Antarctic Science 8 (3): 281–286 (1996)

An inventory of Antarctic sub-glacial lakes

M.J. SIEGERT[1], J.A. DOWDESWELL[1], M.R. GORMAN[1] and N.F. MCINTYRE[2]

[1]*Centre for Glaciology, Institute of Earth Studies, University of Wales, Aberystwyth, Dyfed SY23 3DB, UK*
[2]*Earth Observation Sciences Ltd, Broadmede, Farnham Business Park, Farnham, Surrey GU9 8QL, UK*

Abstract: An extensive analogue database of 60 MHz radio-echo sounding records of Antarctica (covering 50% of the ice sheet) is held at the Scott Polar Research Institute, University of Cambridge. This database was analysed in order to determine the presence and location of Antarctic sub-glacial lakes. In total, 77 sub-glacial lake-type records were identified, 13 more than detected in previous studies. An inventory of these sub-glacial lakes includes geographical coordinates, minimum length and overlying ice thickness for each lake. Information concerning the location of these lakes indicates that the majority (~70%) are found in the proximity of ice divides at Dome C and Ridge B within East Antarctica.

Received 15 November 1995, accepted 10 April 1996

Key words: Antarctic ice sheet, radio-echo sounding, RES

Introduction

Lakes beneath the Antarctic ice sheet were first reported from airborne radio-echo sounding (RES) records by Oswald & Robin (1973). Several other studies of Antarctic 60 MHz RES data, acquired as part of the SPRI-NSF-TUD (Scott Polar Research Institute, University of Cambridge, UK; National Science Foundation, USA; Technical University of Denmark) joint research programme between 1967 and 1979 (Drewry 1983) (Fig. 1), have identified up to 64 areas of bright, mirror-like reflections (Fig. 2), interpreted as representing water beneath the ice sheet (Robin *et al.* 1977, Steed 1980, McIntyre 1983). The lakes identified in these studies were discovered during the reduction of radio-echo sounding data from several regions of Antarctica.

In this contribution, we present an inventory of Antarctic sub-glacial lakes which is derived from a systematic re-analysis of the entire SPRI-NSF-TUD Antarctic RES dataset, undertaken with the specific aim of identifying the full set of sub-glacial water bodies present along these ~400 000 km of RES flight track over the Antarctic ice sheet (Fig. 1). Geographical coordinates, ice thickness and length of mirror-like reflections are presented for the set of Antarctic sub-glacial lakes for the first time.

RES and characteristics of sub-glacial water bodies

Airborne RES at 60 MHz has been used successfully to penetrate to the base of ice over 4 km thick in Antarctica (e.g. Robin *et al.* 1977, Drewry 1983). This is possible because ice is relatively transparent to radio waves at this frequency (Johari & Charette 1975), especially when it is several tens of degrees below freezing, as is the case for most of the Antarctic ice sheet.

The strength of reflection from the bed depends to a first order upon the difference between the dielectric properties of the ice (dielectric constant $\varepsilon = 3.2$), and the dielectric properties of the sub-ice material. As the dielectric constant of water ($\varepsilon = 81$) is very different from typical bedrock ($\varepsilon = 4–9$), a much stronger reflection is obtained from an ice-water interface compared with an ice-rock interface. This difference is further increased by the relatively rough character of an ice-bedrock interface, which scatters energy and further reduces echo strength.

Sub-glacial lakes are identified on 60 MHz RES records by the presence of the following characteristics (Fig 2.):

(i) strong reflections from the ice sheet base, which appear bright on film records and are typically 10–20 dB stronger than adjacent ice-bedrock reflections,

(ii) echoes of constant strength along the track, indicative of an interface which is very smooth on the scale of the RES wavelength, and

(iii) a very flat and virtually horizontal character, with maximum slopes typically less than 1%.

This last property arises from hydrostatic and ice flow mechanisms (Oswald & Robin 1973). Such 'lake' reflections are, thus, highly distinctive, and therefore pose relatively few problems concerning identification (Fig. 2).

It should be noted that accumulations of water-saturated basal sediments may also yield relatively strong electromagnetic wave returns, in some cases similar to those observed from an ice-water interface. Conceivably, such returns may be observed on the RES record as flat horizontal reflections. As a consequence, we do not preclude that some of the 'lakes' identified in this inventory may comprise pockets of water-saturated sediments at the ice-sheet base.

Analysis of Antarctic RES records

RES data from flights over about 7 million km^2 of the Antarctica Ice Sheet (Fig. 1) (Drewry 1983) were recorded in

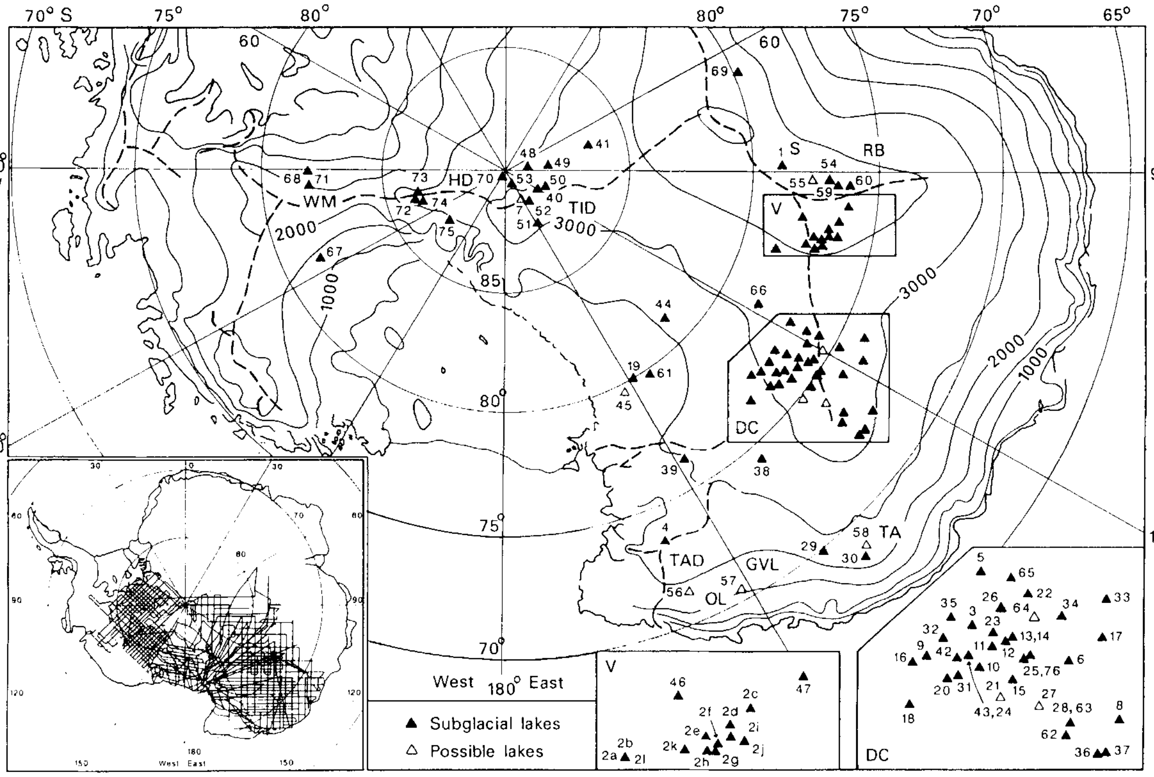

Fig. 1. Locations of subglacial lakes determined from the SPRI-NSF-TUD airborne RES data. The RES flight-lines are inset. The identifying numbers, associated with each lake location, are referred to in Table I. Abbreviations to place names are as follows: DC (Dome C); GVL (George V Land); HD (Hercules Dome); OL (Oates Land); RB (Ridge B); S (Sovetskaya Station); TA (Terre Adelie); TAD (Talos Dome); TID (Titan Ice Dome); V (Vostok Station); WM (Whitmore Mountains).

analogue form on 35 mm negative film as a time-continuous, or Z-scope, record of the received signal (Fig. 2). The full set of film records was examined four times by two individuals working independently over a period of several months. The locations of all possible radar reflections from sub-glacial lakes were noted, using the criteria defined above. Any section of RES film that was found to indicate a relatively flat, bright return (indicative of a radio wave reflection off a basal water layer) was enlarged onto photographic paper. A third person then examined the photographic prints of each possible sub-glacial water body, and a final inventory was agreed after discussion.

The locations of the lakes were then determined using records of the airborne navigation. During the field seasons of 1967–69, the navigation relied upon aircraft avionics and compass inputs, with occasional solar and ground fixes, to determine the location of the aircraft. The records of aircraft navigation during these seasons are analogue recordings of aircraft avionics, log books and flight maps. However, between 1971–79, an inertial navigation system was used on flights, which provided an automatic record of time, latitude and longitude. This system, while subject to a drift of *c.* 1–2 km hr^{-1}, provided very much more accurate and systematic navigation than the previous scheme. Navigation errors in absolute lake locations are a maximum of 5 km and are often considerably less, depending on the distance from the nearest reliable position fix (Drewry *et al.* 1982). These lake locations were compared with the maps of Antarctic sub-glacial lakes prepared by earlier workers (Oswald & Robin 1973, Steed 1980, McIntyre 1983), and any further discrepancies were investigated by further inspection of RES data.

The locations of the 77 sub-glacial lakes, identified as a result of these procedures, are plotted in Fig. 1. It should be noted that the large sub-glacial lake of about 10 000 km^2, located close to Vostok Station in East Antarctica (Fig. 1), was observed on several different RES flights (Oswald & Robin 1973, Robin *et al.* 1977, Kapitsa *et al.* 1996). Similarly, where two observations of sub-glacial lakes are plotted within a few kilometres of one another in Fig. 1, we cannot distinguish whether they are independent water bodies or parts of a single, larger lake (e.g. lakes 25 and 76 (Table I) may well originate from the same sub-glacial lake). For lakes of diameter greater than 10–20 km the presence of a

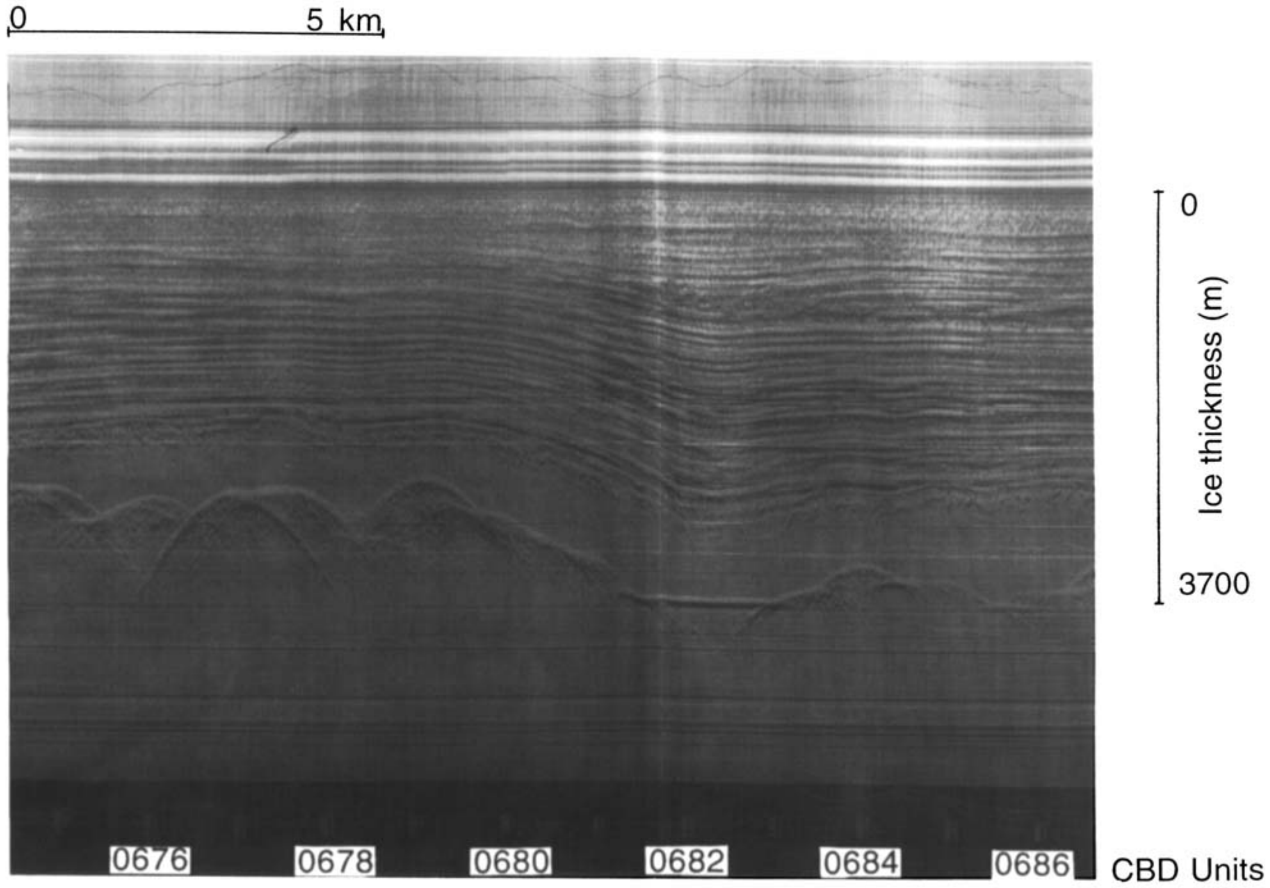

Fig. 2. Sub-glacial lake No. 46, from Flight No. 121 (1974-75) at time 0682. Note the strong, flat, 6.5 km-long reflection off the lake compared with the weaker, undulating signal returned from the surrounding bedrock. Strong downward folding of the ice sheet internal layering is observed directly over the lake. Time is given in CBD units, which are set to zero at aircraft take-off, recording 1 CBD every 15 seconds in the flight thereafter.

continuous, flat and smooth ice-surface, derived from satellite radar altimetry, would provide an independent assessment of this problem (cf. Cudlip & McIntyre 1987, Ridley *et al.* 1993). Consequently, lake records 30 and 58 (Table I), located close to a relatively flat ice-surface in Terre Adélie (identified from Seasat altimeter observations), may also correspond with the same sub-glacial lake (Cudlip & McIntyre 1987).

In addition to information on the latitude and longitude of the set of sub-glacial lakes derived from RES, the length of water body and the thickness of overlying ice were also measured (Table I). Lengths of the sub-ice lake records were calculated by assuming a constant aircraft speed of 300 km hr^{-1}, and may be considered as representing minimum values for water-body dimensions. Ice thicknesses can be measured directly both from the Z-scope data, and individual pulse (A-scope) recordings, by measuring the one-way travel time of the basal reflection and multiplying by the e/m wave velocity within ice (168.5 m ms^{-1}, Glen & Paren 1975). The error in such measurement of ice thickness from RES methods is up to 1.5% of ice thickness (Drewry 1983).

Inventory of sub-glacial lakes

The results of our systematic re-analysis of radio-echo sounding records from approximately half of the Antarctic ice sheet for the presence of sub-glacial lakes are summarized in Table I. This table provides an inventory of data on the latitude and longitude, minimum length and overlying ice thickness for the 77 lake reflections identified from the analogue RES records. The locations of these sub-ice water bodies are shown in Fig. 1.

It is clear from Fig. 1 that the majority of the observed lakes are situated in relatively close proximity to ice divides, where both the surface slope and ice velocity are small. Two clusters of lakes, accounting for 70% of the total lake inventory, are in regions of Dome C and Ridge B in East Antarctica (Fig. 1). In addition, the ice divide stretching from West to East Antarctica (which runs close to the South Pole), has several sub-ice lakes along its length in the areas of Hercules Dome and Titan Dome (Fig. 1).

Although approximately half of the Antarctic ice sheet was sounded by the SPRI-NSF-TUD survey (Fig. 1), flight-line spacing of 50–100 km over much of this area implies that

Table I. Inventory of Antarctic sub-glacial lakes.

Lake No.	Lat., °S	Long., °E	Length, m	Ice thickness, m	Locale
1967-68					
1	78.1	88.5	35 000	4200	Sovetskaya Station
1971-72					
2a	78.48	106.87	5000	3741	Lake at Vostok Station
3	76.57	124.80	5000	3621	Dome C
4	73.28	157.28	3500	2827	Talos Dome
5	77.20	119.27	10 000	3835	Dome C
2b	78.48	106.87	n/a	3741	On ground at Vostok Airstrip
6	74.13	124.58	10 000	4094	Dome C
2c	76.51	101.13	5000	4184	Lake at Vostok Station
(7)	(88.3)	(150)	(5000)	(2807)	(Titan Dome)
8	72.31	123.94	10 000	3254	E of Dome C
9	76.94	129.40	5000	3811	W of Dome C
10	75.94	127.41	5000	3449	W of Dome C
11	75.81	126.56	8500	3860	W of Dome C
12	75.65	125.60	5000	3399	W of Dome C
13	75.87	122.66	5000	3364	W of Dome C
14	75.84	122.82	2000	3490	W of Dome C
15	75.14	126.98	2000	3447	W of Dome C
16	76.75	129.82	2000	3661	W of Dome C
17	73.45	119.54	15 000	3924	E of Dome C
1974-75					
18	76.28	135.31	8040	3214	W Dome C
19	79.93	148.27	8375	2333	E of Byrd Gl. & Transantarctic Mts
20	76.63	129.92	1843	3009	W Dome C
(21)	(74.91)	(128.90)	(670)	(3890)	(Dome C)
22	75.97	124.95	3685	3168	Dome C
23	75.78	125.97	3015	3162	Dome C
24	75.69	126.48	4188	3650	Dome C
25	74.96	124.61	1340	3360	Dome C
26	75.61	120.39	2680	3057	Dome C
(27)	(73.4)	(126.90)	(6700)	(4010)	(W of Dome C)
28	73.17	128.35	15,075	4148	W of Dome C
29	69.71	140.95	2848	2269	George V Land
30 (58)	68.44	136.87	2680	4011	Terre Adelie
31	75.82	129.03	3015	3069	W of Dome C
32	76.40	126.03	2881	3500	W of Dome C
33	74.03	118.50	8543	4092	E of Dome C
34	74.46	119.37	6700	3932	E of Dome C
35	77.12	126.30	8375	3741	W of Dome C
36	71.81	128.35	1340	2994	NE of Dome C
37	71.79	128.2	1340	3021	NE of Dome C
38	74.04	139.92	1608	3285	W of Dome C
39	75.73	148.86	6700	3010	W of Dome C
40	88.5	120	3350	3100	Titan Dome
41	87	075	3183	2943	W of Titan Dome
42	76.19	125.18	4958	3881	W of Dome C

Inventory of sub-glacial lakes includes geographical coordinates, observed length and the thickness of overlying ice. The order of lake entries is chronological, based on the date of the flight from which each is recorded. Parentheses indicate that the RES record may contain a sub-ice lake reflection, but identification is not certain. It should be noted that this inventory represents RES returns from single flight-lines over lake surfaces, and that some of these data may correspond to the same sub-glacial lake (e.g., reflection no. 25 & 76 may represent reflections off the same sub-glacial lake).

Lake No.	Lat., °S	Long., °E	Length, m	Ice thickness, m	Locale
43	76.20	125.30	10,050	3886	W of Dome C
44	81.84	133.47	2680	2641	E of Transantarctic Mts
(45)	(79.43)	(154.13)	(6700)	(2036)	(E of Transantarctic Mts)
46	77.4	100.4	2412	3709	W of Ridge B
47	76.8	97.5	1608	3715	W of Ridge B
48	88.73	64.52	3350	2997	S of Titan Dome
49	88.36	70.54	5360	3027	S of Titan Dome
50	88.37	112.68	3350	3068	Titan Dome
51	87.61	148.62	8040	3062	Titan Dome
52	88.71	136.88	1876	3070	Titan Dome
53	88.42	144.50	1675	2741	Titan Dome
54	77.1	92.5	3350	3784	Ridge B
2d	77.0	104.5	43,550	3812	Lake at Vostok Station
55)	(78)	(99)	(11,725)	(3399)	(Ridge B)
2e	77.6	105.0	26,800	3805	Lake at Vostok Station.
(56)	(71.13)	(155.68)	(10,050)	(2347)	(Oates Land)
(57)	(70.47)	(151.60)	(1675)	(2418)	(Oates Land)
2f	77.18	104.82	30,150	3800	Lake at Vostok Station
2g	77.12	103.99	3350	3857	Lake at Vostok Station
2h	77.4	102.80	3350	3883	Lake at Vostok Station
2i	76.70	102.10	6700	3842	Lake at Vostok Station
2j	76.56	102.13	15,075	3911	Lake at Vostok Station
58 (30)	68.8	136.2	43,550	4224	Terre Adelie
59	77.1	92.5	1340	3481	Ridge B
60	76.8	93.5	1340	3426	Ridge B
61	79.15	144.3	5025	2580	W of Transantarctic Mts
62	72.74	129.41	2010	3828	Dome C
63	73.14	128.41	20,010	4171	Dome C
(64)	(75.76)	(119.71)	(2512)	(3574)	(Dome C)
65	76.07	118.11	5025	3733	Dome C
66	78.00	118.60	14,070	3341	S of Dome C
67	81.4	119.0 W	2010	3200	W of Whitmore Mts
2k	77	102	241,200	n/a	along length of Lake at Vostok Station
1977-78					
68	82.06	98.95 W	1675	2894	Whitmore Mts.
2l	78.48	106.87		3741	Aircraft circling over Vostok Station
69	79.04	67.73	6700	2500	Dome A
1978-79					
70	89.97	161.56 W	50,250	2778	South Pole
71	82.99	94.92 W	1340	3200	Whitmore Mts
72	86.36	106.17 W	1675	2814	Hercules Dome
73	86.43	105.56 W	1340	2906	Hercules Dome
74	86.77	111.26 W	1675	3960	Hercules Dome
75	87.77	125.30 W	5025	2315	Hercules Dome
76 (25)	74.92	124.65	3484	3360	Dome C
77	74.92	124.19	1943	3225	Dome C

some additional lakes may be present between existing flight-lines. Similarly, no data were available for the remainder of the ice sheet. Analysis of high-accuracy satellite radar altimeter data will be used in future investigations (during the next two years) of larger sub-glacial lakes over the remaining portion of Antarctica (J.K. Ridley, personal communication 1995).

Our inventory provides important information for several pieces of further work. First, the inventory provides coordinates for the locations of sub-glacial lakes, and an indication of the minimum size of the lake. This may be useful for the identification of ice surface topographical features, using satellite radar altimetry, associated with sub-glacial lakes. Secondly, Antarctic sub-glacial lakes provide an important boundary condition for the thermal analysis of the ice sheet, in that the basal temperature of the ice sheet over sub-glacial lakes may be assumed to be at pressure melting point (Siegert & Dowdeswell in press). Thus, the location of sub-glacial lakes may be important to the understanding of heat flow at the base of the Antarctic ice sheet.

Acknowledgements

We thank Dr Gordon Robin for commenting on a draft of this paper and Prof Dr Heinz Miller and Dr David Vaughan for providing constructive and helpful reviews. We also thank the Director of the Scott Polar Research Institute, University of Cambridge, for his support of this project. Funding for this research was provided by NERC Grant GR9/1418.

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