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Penetration of Antarctic subglacial lakes by VHF electromagnetic pulses: Information on the depth and electrical conductivity of basal water bodies

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Abstract. Owing to the high level of absorption of very high frequency radio waves in water, previous investigators of airborne radio echo sounding (RES) data from Antarctica have assumed that the depth of subglacial lakes cannot be measured directly by this method. However, we have identified a number of RES returns from beneath the ice-water interface at the surface of eight subglacial lakes that we have interpreted as being reflected from the lake floor. The returns allow us to measure the depth of subglacial lakes, since the velocity of radio waves in water (33.4 m μs^{-1}) is relatively unaffected by electrical conductivity. Attenuation of radio waves within water is controlled largely by its electrical conductivity. Consequently, by examining the decay of the radio wave amplitude with depth we can gain information about the conductivity of subglacial water bodies. Our results indicate that the minimum water depths of eight subglacial lakes vary between 8 and 21 m. The lakes from which our depth measurements were taken are distributed widely around the ice sheet. Thus it may be concluded for the first time that Antarctic subglacial water bodies are generally at least several meters in depth. By examining the attenuation of radio waves through subglacial water, the electrical conductivity of the water is estimated to be extremely low (i.e., fresh pure water).

1. Introduction

The number, spatial distribution, and minimum size of subglacial lakes beneath the Antarctic Ice Sheet have been determined from analysis of analogue airborne radio echo sounding (RES) information [*Siegert et al.*, 1996], held at the Scott Polar Research Institute (SPRI), University of Cambridge. Very high frequency (VHF) radio wave reflections off subglacial lakes are easily identifiable in 60 MHz RES records, compared with those from other regions of the ice sheet base. In particular, the presence of (1) strong returns from the ice sheet base, which appear bright on film records and are typically 10-20 dB stronger than ice-bedrock reflections, (2) echoes of constant strength along the flight track, indicative of an interface which is very smooth on the scale of the RES wavelength, and (3) a very flat and virtually horizontal character, with maximum slopes typically around 1:150, are indicative of reflections off subglacial lakes [*Siegert et al.*, 1996]. In total, 77 subglacial lake-like reflectors have been observed within the RES data set, ~90% of which are located beneath thick ice (>2.5 km), in proximity to, or within 200 km from, the ice divides at Dome C, Ridge B, Talos Dome, Titan Dome, and Hercules Dome (Figure 1).

In recent years a number of independent studies have enhanced our understanding about the formation, size, and distribution of Antarctic subglacial lakes [e.g., *Oswald and Robin*, 1973; *Robin et al.*, 1977; *Shoemaker*, 1990; *Kapitsa et al.*, 1996; *Siegert et al.*, 1996; *Siegert and Dowdeswell*, 1996; *Dowdeswell and Siegert*, 1999]. Furthermore, our knowledge of ice sheet dynamics over subglacial lakes (where basal shear-stress is effectively reduced to zero) has increased with the availability of accurate surface elevation maps from the ERS 1 satellite [*Kapitsa et al.*, 1996; *Siegert and Ridley*, 1998a]. However, as yet, little information has been gathered with regard to the water depth of Antarctic subglacial lakes.
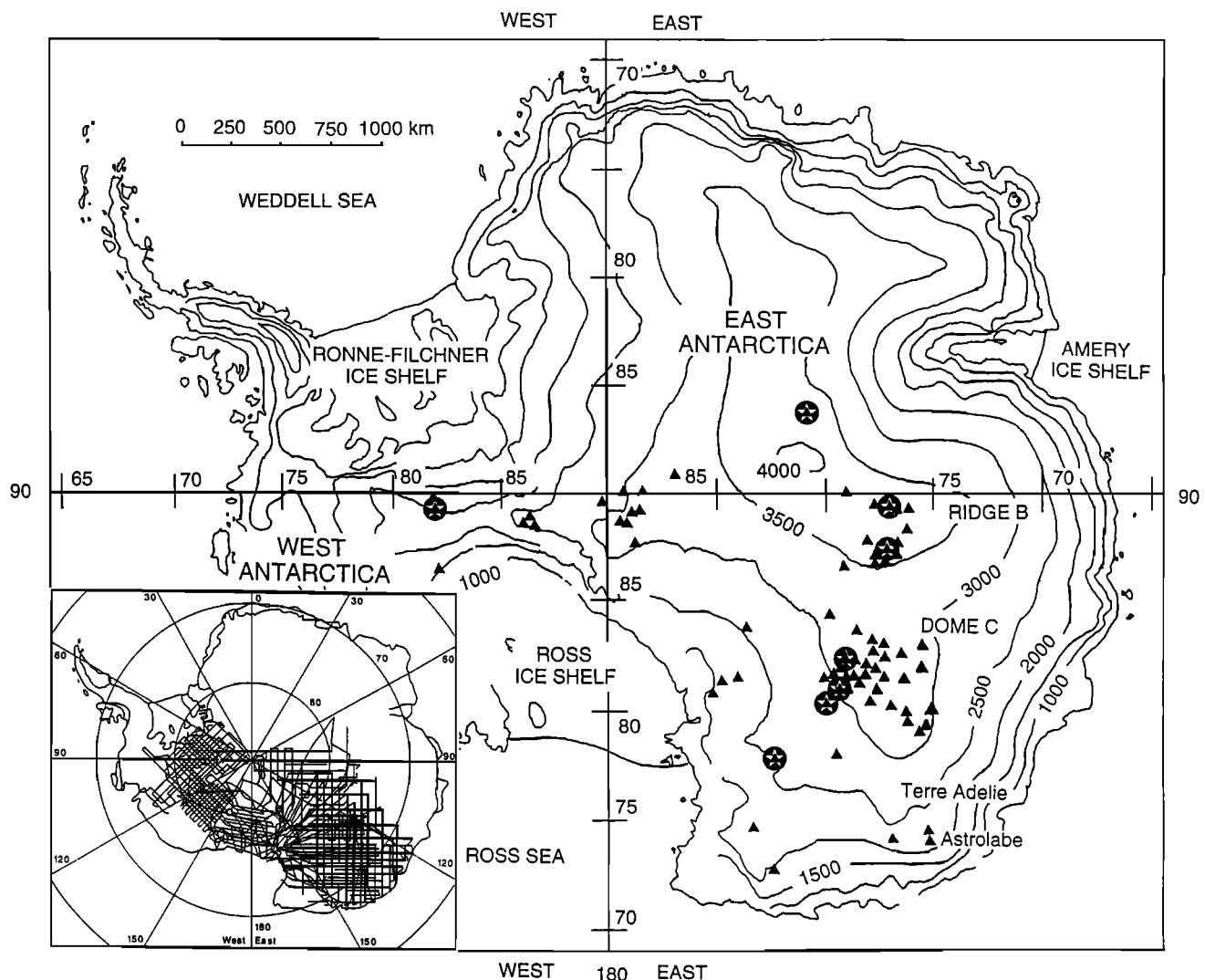
Figure 1. Spatial distribution of Antarctic subglacial lakes [after *Siegert et al.*, 1996]. Locations of subglacial lakes which have RES records from the lake floor are indicated by a circle around the triangle.

The one previous direct measurement of a subglacial water depth was recorded during a 1964 seismic experiment at Vostok Station, central East Antarctica, from which the water depth of the southern end of Lake Vostok has been recorded at 510 m [*Kapitsa et al.*, 1996]. Other research on the water thickness of subglacial water bodies has been less specific than that of *Kapitsa et al.* [1996]. For example, *Drewry* [1986] calculated the "skin depth" necessary for radio reflection in freshwater to be 6.5 m at 60 MHz and, since no lake floor reflections had been observed at the time, concluded that this value represented the minimum thickness of an Antarctic subglacial freshwater layer. In addition, *Bogorodskiy et al.* [1985] suggested that the gradient of bedrock bordering a particular subglacial lake beneath Dome C, measured from RES data, indicates that the water depth of the lake is of the order of tens of meters rather than centimeters. Further, *Shabtaie et al.* [1987] indicated that water bodies beneath Ice Stream C are between several centimeters to meters in

thickness, from consideration of power reflection coefficients obtained from the ice-base interface. However, *Shabtaie et al.* [1987] did not observe radio wave reflections from the floor of the water bodies, and so their investigation did not constitute direct evidence for subglacial water thicknesses.

Here, we present direct measurements of the water depth of eight subglacial lakes, from evidence held within existing 60 MHz RES data of the Antarctic Ice Sheet. In addition, our analysis of radio wave power returns provides estimates of the electrical conductivity of Antarctic subglacial water bodies.

2. Identification of Lake Floor Reflections

Airborne RES data are provided in two formats. The first is graphs of radio wave power against two-way travel time (or depth) known as A scopes. The second is formed by stacking multiple A scopes together in a time-dependent
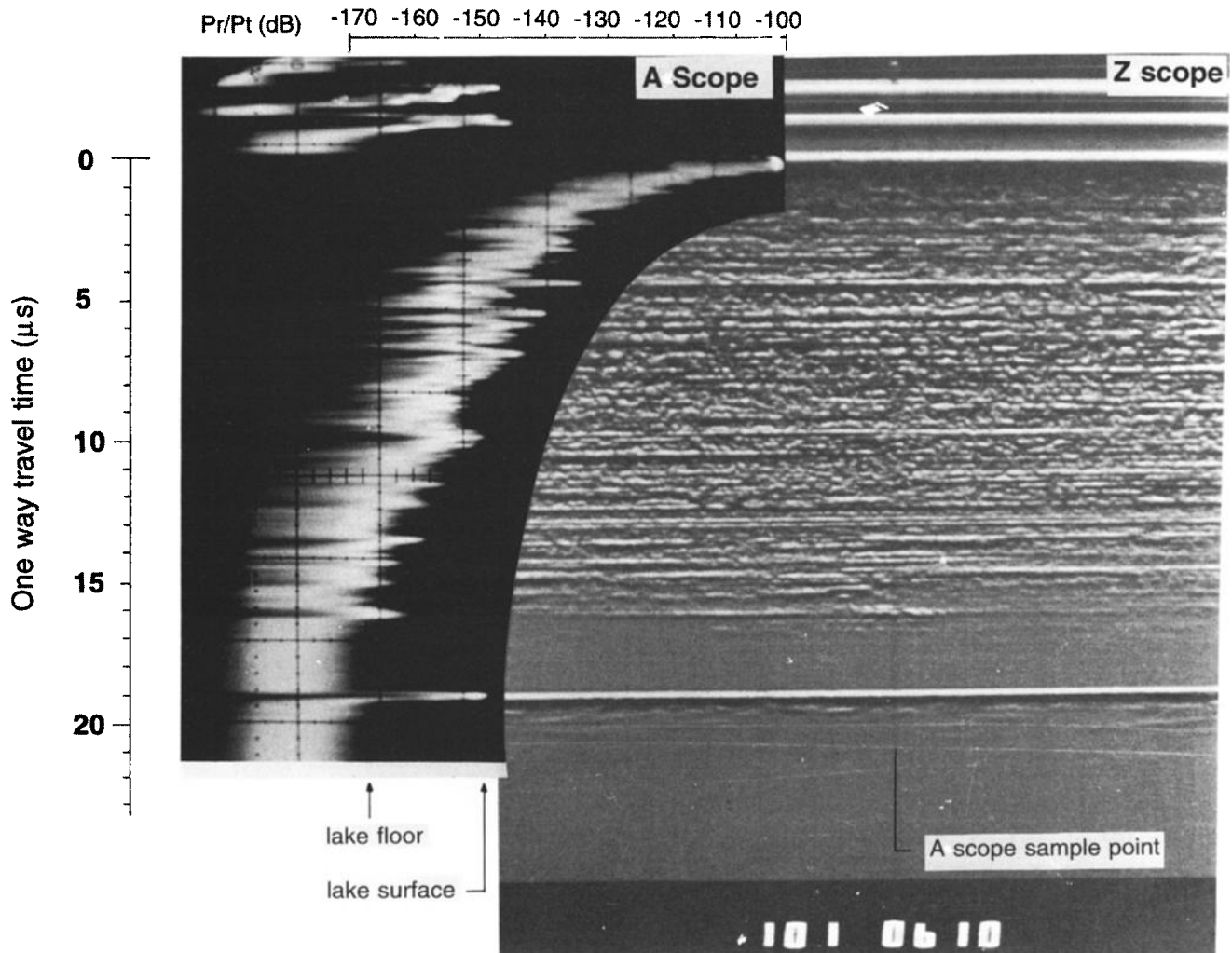
Figure 2. A scope and Z scope RES data illustrating a reflection from the lake floor. The Z scope data can be used to trace the lake floor return across the ice sheet, while the A scope data can be used to derive information about the power return from the reflected radio wave. These data can then be used to quantify the conductivity and, hence, purity of the lake water. The data shown are from a 1974 flight line 101, located to the west of Dome C.

manner to yield a pseudo cross section of the ice sheet known as Z scopes. Careful inspection of the 60 MHz RES records of 77 subglacial lakes, collated by *Siegert et al.* [1996], showed that up to eight separate ice-water reflectors are followed shortly (~0.5 μs) by a relatively strong anomalous "secondary reflection". We are able to identify these secondary reflections on A scope mode in one case (Figure 2) and Z scope RES data in all eight cases (e.g., Figures 3, 4, and 5).

These secondary reflections are from the floor of subglacial lakes. Several alternative origins of secondary RES returns "beneath" the ice-water interface are shown to be inconsistent with our data. For example, the returns cannot be derived from side reflections off surrounding bedrock. Also, multiple radio wave reflectors do not cause the signals that we record. Further, the reflection is not caused by an instrumental phenomenon. Our rationale for falsifying origins other than subglacial lake floor reflections for radio wave returns after that from the ice-water interface are now discussed.

2.1 Subglacial Lake Sidewall Reflectors

Radiowave reflections from an ice-bedrock interface not located directly beneath the transmitter/receiver may be recorded if the interface is steep enough for a normal reflection to occur because the beam width of the radio wave pulse is about 30°. Such reflections are characterized by a hyperbolic shape in Z scope data (analogous to hyperbolae in seismic data). For the case of RES data from subglacial lakes, these reflections may be important due to the relatively steep bedrock sides that have been observed at the edges of subglacial lakes (sidewalls). However, there are a number of reasons which suggest that the secondary reflections observed after ice-water interfaces in a number of subglacial lake RES data are not due to sidewall reflectors.
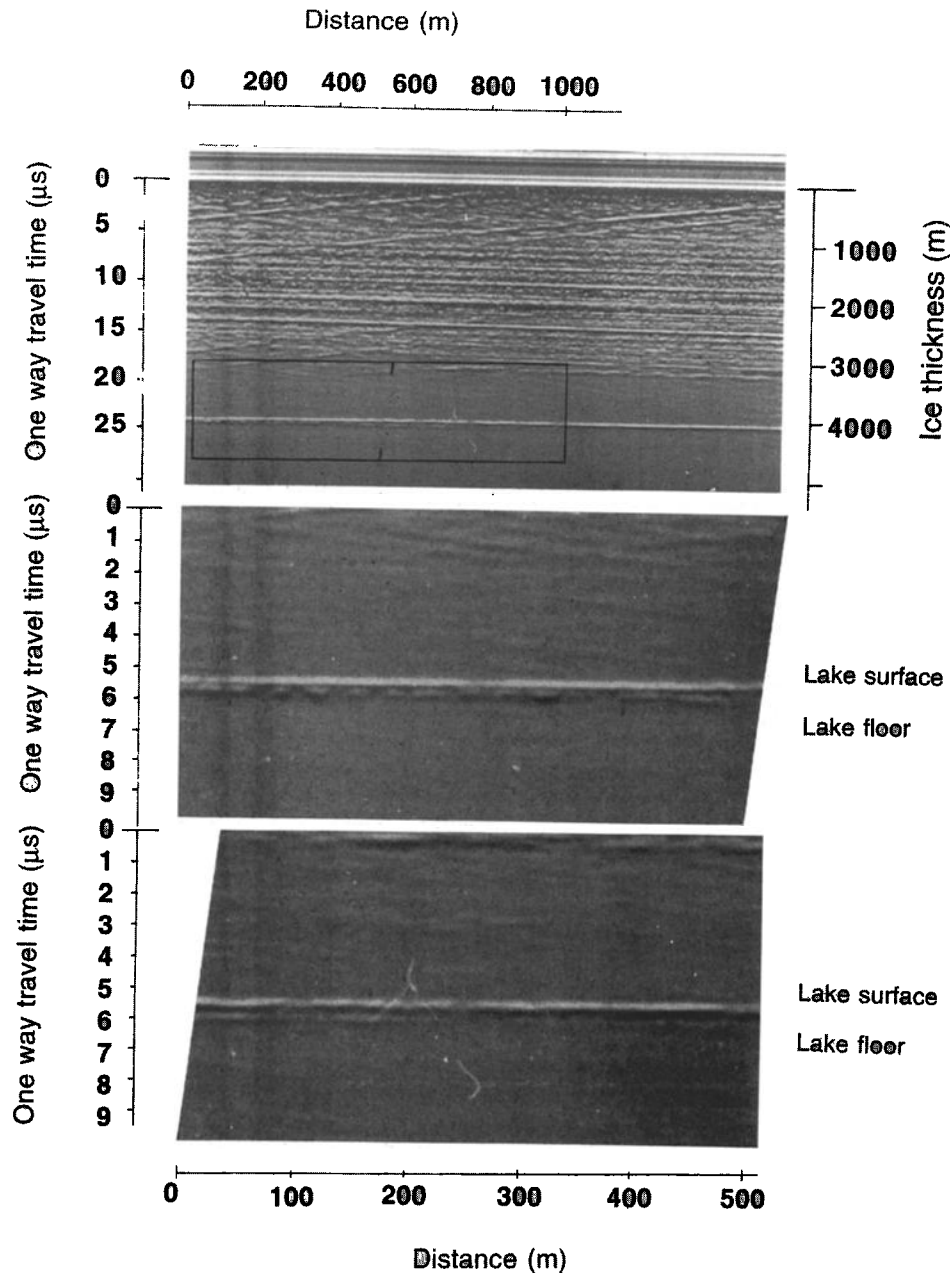
Figure 3. An example of Z scope RES data from a subglacial lake where VHF radio wave reflections from the subglacial lake floor can be observed. The full-sized radio echo sounding data are provided with an enlargement of the ice-water interface beneath. From the enlarged section of RES data, the subglacial lake floor reflections can be observed about 0.2-0.4 μs after the ice-water interface of the lake surface. The data are from the 1974 flight line 123, and are located at the northern end of the Vostok Station subglacial lake [*Siegert and Ridley*, 1998a].

First is a lack of hyperbolae in RES data that would be expected from sidewall reflections. Such hyperbolae are easily recognizable in appearance in Z scope data and do not necessarily decay with depth very rapidly. However, secondary reflections beneath those of the ice-water interface that we have observed are not hyperbolic in form. A good example of the difference between true lake floor and hyperbolic-type reflections is illustrated in Figure 4, where the lake floor signal is recorded as an undulating return beneath the flat lake surface and the sidewall

reflection is shown as a more steeply dipping return that originates from above the lake surface. Second, we witness considerable and rapid deterioration of the signal strength with depth in the lake floor returns, indicating that they are not generated by reflections off lake sidewalls. Figure 4 demonstrates that sidewall hyperbolae penetrate to significant "apparent" depths in the RES data.

It should be noted that hyperbolae from side reflections from the ice sheet base, other than those aligned along the flight track, are not often observed in other nonlake regions
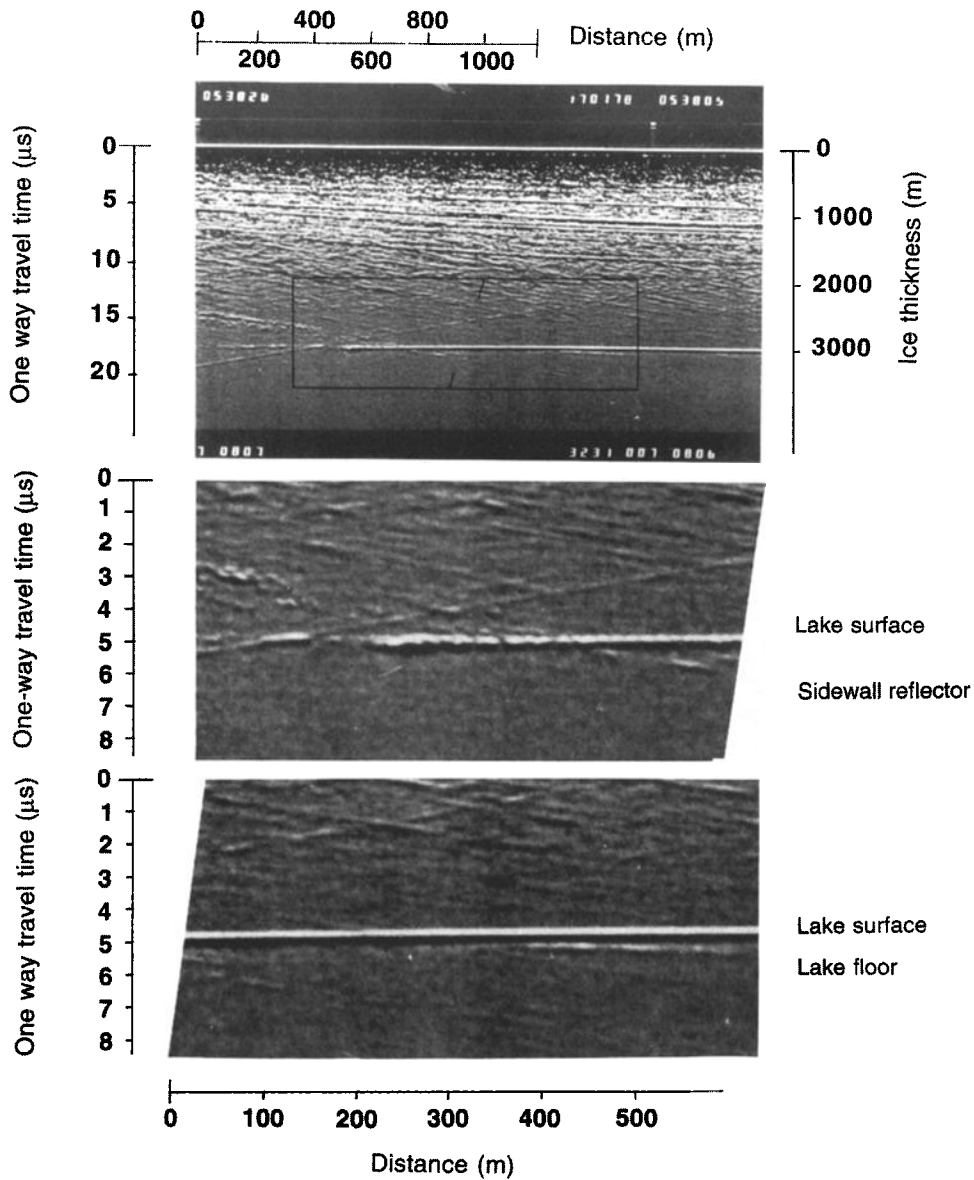
Figure 4. Z scope RES data from 1978 flight line 007, located within the Whitmore Mountains area of West Antarctica. The full Z scope image has been enlarged in the lower two photographs across the ice-water interface of the subglacial lake surface. The data show the difference between true lake floor reflectors (gently undulating returns around 10 m below the lake surface) and those from sidewalls (hyperbolic-type pattern starting above the level of the lake and ending well below the lake surface).

of the ice sheet. This may be due to the relatively narrow lateral beam width of the transmitted radio wave pulse, precluding the possibility of side reflectors. Thus it can be concluded that secondary returns after those from the subglacial lake surface are not due to side reflections from the ice-bedrock interface at or above the lake edge.

2.2 Subglacial Crevasses

Radio wave reflections from a crevassed glacier base above subglacial water are recorded after the ice-water interface [e.g., *Shabtaie et al.*, 1987]. However, the reflections from such crevasses are hyperbolic in Z scope mode data. Reflections presented here, which we interpret

from the lake floor, are not hyperbolic and, thus, are not due to an irregular ice-water interface.

2.3 Multiple Reflectors

Internal ice sheet layers observed through RES, separated by tens of meters, are caused by ancient acidic snow deposits over the ice sheet surface. Such deposits are thought to result from an aerosol product derived from previous volcanic material in the atmosphere [*Millar*, 1981; *Siegert et al.*, 1998]. The presence of multiple radio-wave-reflecting horizons within the ice sheet has significance to our interpretation of the subglacial reflections. It is possible, in a manner similar to that understood in
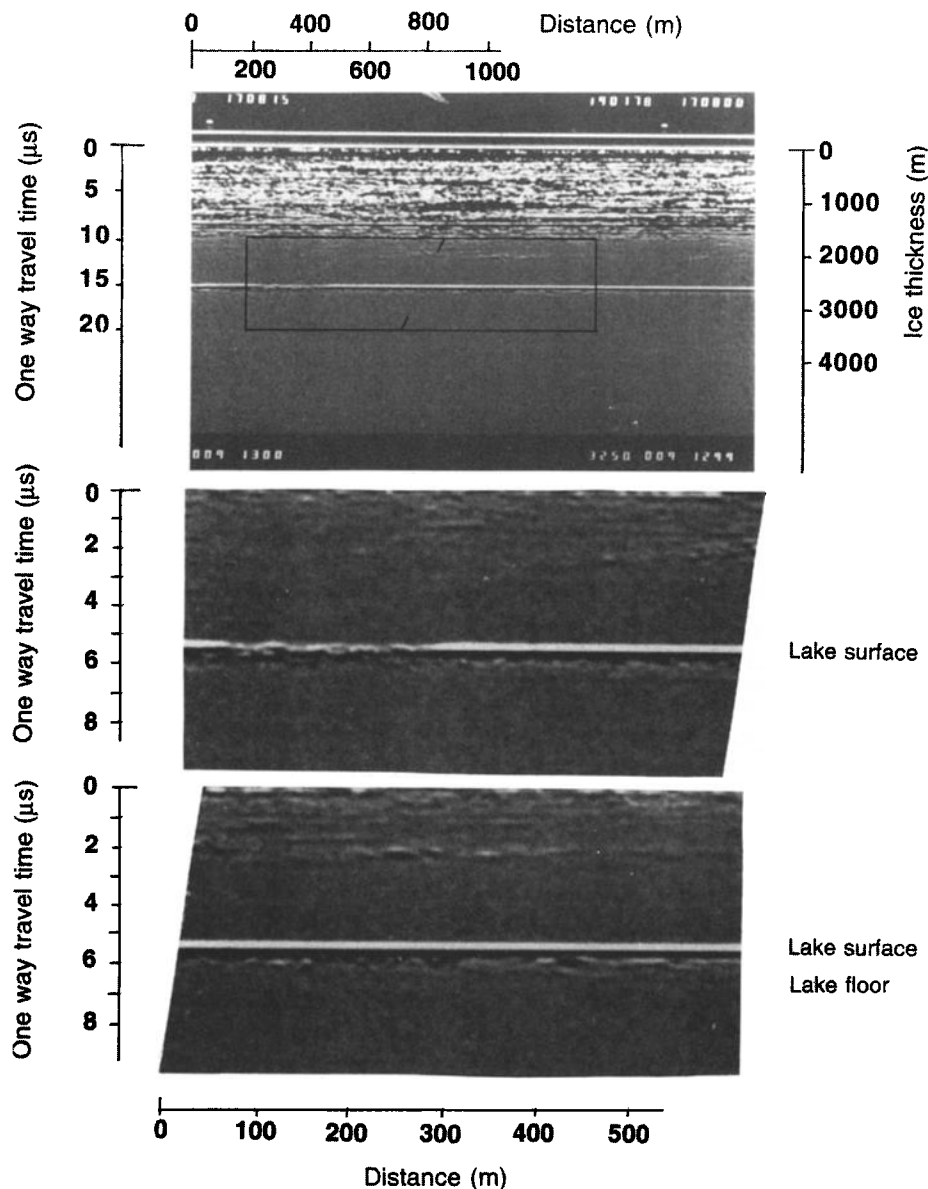
Figure 5. Z scope RES data from 1978 flight line 009, located within Dome A, central East Antarctica. The full Z scope image has been enlarged in the lower two photographs across the ice-water interface of the subglacial lake surface. The data display a distinctive lake-floor signal which slopes downward from left to right. The signal begins just above the level of the lake where the strong, flat returns from the lake surface are interrupted by a rough signal typical of an ice-bedrock contact.

seismology, that multiple reflections may result from radio waves reflecting between closely spaced reflecting layers. In this process, a relatively faint secondary arrival would be observed after the first wave is received. However, both returns would exhibit the same spatial form (since the only reflectors that are different between the two pathways are uniform internal radio echo layers). The reflections beneath the subglacial lake returns do not mimic those of the ice-water interface (which are extremely flat). Instead, they are undulating in spatial character, a feature that indicates the secondary reflectors are not caused by a "multiple" event.

2.4 Receiver Recovery or Other Instrumental Phenomenon

A further possible explanation for the "lake floor" reflections is that they are simply a manifestation of irregularities in the instrument system. For example, the instrument may be susceptible to "recovery overshoot" from the strong echo reflected from the ice-water interface. The strongest argument against this possibility is the several hundreds of kilometres of lake-type radio reflections which are recorded without a small trailing pulse. It is also difficult to postulate an instrumental

explanation which could account for the change in delay of the trailing pulse, given that the primary ice-water echo is of unvarying strength.

2.5 Lake Floor Reflections

Having demonstrated that secondary returns cannot be caused by sidewall reflectors or multiple returns, the only plausible solution to these reflections is that they are caused by radio wave reflections off the floor of a subglacial lake. In such reflections we would expect (1) an undulating spatial character and (2) sharp decay with depth in the power of the reflection due to the dielectric properties of water (referred to later). Both these features are observed within the secondary reflections beneath those of the ice-water interface of a number of subglacial lakes, which we interpret to be caused by reflections off the lake floor.

In some circumstances we expect the subglacial lake surface to be interrupted as the bedrock rises above the level of the lake. A good example of this is illustrated in Figure 5, where the secondary reflection can be seen to slope from just above the lake surface (where the otherwise smooth lake return becomes disturbed, weak, and irregular due to the rough nature of the substrate surface) to 15 m or so beneath the lake.

An important point to note is that our observations of "secondary radio wave reflections" beneath the ice base represent unequivocal evidence for the existence of subglacial water bodies.

3. Propagation of Radio Waves Through Ice and Water

Our identification of subglacial lake floor reflections is a consequence of the propagation of VHF radio waves in water. For ice sheets the RES technique works by emitting and receiving a radio wave propagating near orthogonally to the ice surface. Since the slope of an ice-water interface above a subglacial lake is generally low (<1°), we can assume that the radio waves we identify as lake floor reflections have propagated in this orthogonal manner. Thus, we can model the transmission and reflection of radio waves at the ice-water and water-substrate interface in a simple one-dimensional manner.

Electromagnetic wave velocity (v) is related to the dielectric property of the substance within which the wave propagates. The relation is given as [Glen and Paren, 1975]

$$v = \frac{c}{\sqrt{\kappa}}, \tag{1}$$

where c is the velocity of light and κ is the dielectric constant of the substance (dimensionless). For ice, κ is between 3 and 4.3, which gives a range of radio wave velocity of 173-145 m μs^{-1}. Glen and Paren [1975] give the dielectric constant of glacier ice as 3.17, which yields a propagating velocity of 168 m μm^{-1} for radio waves in ice sheets and glaciers. For water, κ is 80.4, which corresponds to a radio wave velocity of 33.4 m μs^{-1}. Equation (1) can,

therefore, be used in conjunction with information gained from RES data on the travel times of radio waves through ice and water to determine ice thickness and water thickness where a lake floor reflection is recorded.

The dielectric constant of water does not change significantly with salinity or temperature so that we can estimate the propagating velocity of radio waves within subglacial lakes as 33.4 m μs^{-1}, regardless of the electrical conductivity of water (M.I. Kennett, personal communication, 1995)

The attenuation of radio waves within water is related to its electrical conductivity. Consequently, by measuring amplitudes of radio waves reflected from the floors of sub ice lakes of known water depth, information about the attenuation of radio waves within the lake water can be established. The attenuation of a radio wave within a medium is given by

$$A = A_0 \exp(-BZ), \tag{2}$$

where

$$B = \pi\sigma f\mu_0, \tag{3}$$

A_0 is the initial amplitude of the radio wave, Z is the distance traveled through the medium, σ is the electrical conductivity (mhos m^{-1}) particular to the medium, f is the radio wave frequency (60 MHz in the case of our RES data), and μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ N A^{-2}).

Both RES data sources (A scope and Z scope) provide (1) measurements of subglacial lake depths and (2) information concerning the power of lake floor reflections. A scope data provide semiquantitative information with regard to the amplitude of the reflected radio waves and can be used to establish the conductivity of the water mass. From consideration of the one A scope record available, we are able to estimate the conductivity of the lake water.

4. Lake Floor Radio Wave Reflectors and Depths of Subglacial Lakes

In total, reflections from the base of eight different subglacial lakes were recorded (e.g., Figures 2 and 3). From the raw RES information provided, one-way travel times for radio waves through the water bodies can be measured accurately (to within 1.5%). From these data, assuming that the radio wave velocity within water is 33.4 m μs^{-1}, we can calculate the distance traveled by the radio wave in water and, hence, determine the water depth of these subglacial lakes to an accuracy of 1.5% (Table 1). Because as depth increases so the potential for RES reflection of the lake floor decreases, we interpret measurements of subglacial water depth by this RES method as representing minimum values.

We calculate the water depths of seven subglacial lakes to be between 8 and 21 m (Table 1). These are the first measurements of water depth for seven of these lakes. This information has implications, given the occurrence of up to

Table 1. Water Depth of Eight Subglacial Lakes, Measured From Radio Wave Reflections From the Lake Floor.

Latitude, deg S	Longitude, deg E	Ice Thickness, m	Water Depth Maximum, Minimum, m	Geographic Location
71.81	128.35	2994	21.6, 12.0	NE Dome C
77.1	92.5	3784	17.7, 15.5	Ridge B
77.04	104.5	4079	11.9, 7.9	Vostok (Figure 3)
82.06	-98.95	2894	15.8, 12.6	Whitmore Mountains. (Figure 4)
79.04	67.73	2500	17.1, 13.3	Dome A (Figure 5)
76.28	135.31	3214	16.7, 12.0	West Dome C
74.03	118.50	4092	17.6, 12.35	East Dome C
76.63	129.92	3009	18.7, 15.0	West Dome C

Also provided are the location of the lake, and the thickness of the overriding ice sheet. Maximum and minimum water depths are calculated from the deepest and shallowest lake floor reflectors, respectively.

77 lake like reflectors beneath the Antarctic Ice Sheet, for estimating the volume of water housed beneath the Antarctic Ice Sheet.

The remaining lake is the 510 m deep Vostok Station lake. The seismic measurement from which the water depth was calculated was taken from the opposite end of the lake from where we have identified RES reflections from the lake floor. In their interpretation of the subglacial topography at Vostok Station, *Kapitsa et al.* [1996] noticed the bedrock elevation bordering the lake at both ends and suggested that the lake, at its northernmost end, is likely to be only a few meters deep. The RES information we have gathered confirms *Kapitsa et al.*'s [1996] inference and supports the notion that the average water depth of this lake is several hundred meters.

Measurements of the lateral extent of subglacial lake floor reflectors indicate that there are less than 0.5 km worth of subglacial lake floor record held within the SPRI RES database. It is interesting to note that the total length of the database is in excess of 400,000 km, a figure which illustrates the scarcity of lake floor information within the data set. The length of a 250 ns radio wave pulse is 8 m in water. This marks the minimum depth from which clear basal reflections are expected. The lack of more records of radio wave reflections from the base of subglacial lakes in the SPRI archive can be interpreted in two ways. First, lake depths are commonly less than 8 m. Second, lake depths are usually greater than ~20 m (below which the radio wave is attenuated completely). Our results on their own are unable to solve this problem. However, when one considers that subglacial lakes are often several kilometers in length, for the former interpretation to be correct, the subglacial topography cannot vary vertically by more than 8 m along the entire length of the lake (i.e., the topography must be very flat and horizontal). Inspection of the topography around subglacial lakes shows this assumption to be completely invalid for the rest of the known ice sheet base. We see no reason why the topography should suddenly change below the water surface, and so we can conclude that most lakes are deeper than the maximum 20 m that we have measured. It is for this reason that

subglacial base radio wave reflections are not seen often in RES data.

Another possible reason why more basal reflections than those listed in Table 1 are not observed within the RES data set may be that water-saturated sediments exist beneath most lakes. These sediments may have a low electromagnetic wave impedance relative to that of an ice-bedrock interface, such that no radio wave signal is reflected from the water-sediment interface.

Radio wave reflections from the lake floors are generally not seen at the edges of subglacial lakes. However, it is probable that in such regions the water depth can be between 8 and 21 m, suggesting that observable lake floor reflections are likely. Such reflections are not observed in RES records because most sidewalls of subglacial lakes are relatively steep (e.g., gradients of 0.1-0.01), yielding nonnormal reflectors. A reflection will only be observed when the water-substrate interface is relatively horizontal, and this is most likely to occur on the top of subglacial perturbations in the center shallow regions of lakes. Even if the gradient is low enough to permit a normal-type reflector (e.g., a gradient of 0.01), it would take 800 m of constant slope at 0.01 for the lake floor to reach the required 8 m depth to allow a lake floor observation. As has been stated, there are few precedents for such morphology within surrounding bedrock. A final point to note is that the edges of many subglacial lake radar records are associated with hyperbolic-shaped tails from surrounding bedrock that may make interpretation difficult.

The 77 known subglacial lake RES reflectors are distributed widely around the Antarctic Ice Sheet, with significant concentrations beneath ice domes at Dome C (~70%), Titan Dome (~10%), Ridge B (~8%), and Hercules Dome (~5%) (Figure 1). The coordinates of the eight subglacial lakes where VHF radio wave penetration to the lake floor has been detected are provided in Table 1. The wide spatial distribution of these lakes allows us to infer that conclusions drawn from our investigation are relevant to the entire ice sheet. We therefore suggest that subglacial water depths of at least 10 m are commonplace beneath the central regions of the Antarctic Ice Sheet.

5. Water Quality of Subglacial Lakes

Measurements of the decay of the radio wave amplitude with water depth allow us to estimate the electrical conductivity of the subglacial water body. However, since the 60 MHz RES database is held in the form of analogue records, the decay of the lake floor reflected signal is difficult to measure accurately. We have one A scope record available with which to estimate the attenuation of radio waves in subglacial lakes (Figure 2). In order to predict electrical conductivity from equations (2) and (3), the variation with depth of the radio wave amplitude must be identified. We can estimate the relative power of the radio wave at the ice-water and ice-substrate interfaces by the following method.

The amplitude reflection coefficient (R) is given by

$$R = \frac{V_1 - V_2}{V_1 + V_2}, \tag{4}$$

where V_1 and V_2 are the radio wave velocity above and below the interface, respectively. The radio wave velocities in polar ice and water are 168 and 33.4 m ms^{-1}. However, because the physical (and therefore electrical) properties of the lake floor are not known, the radio wave velocity through this medium is also unknown. Therefore we determine a range of electrical conductivities for the water, based on a variety of lake floor substances, namely (1) water-saturated sand (radio wave velocity 58 m ms^{-1}), (2) water-saturated silt (95 m ms^{-1}), (3) clay (98 m ms^{-1}), and (4) bedrock (110 m ms^{-1}) [Reynolds, 1997].

From the estimates of the amplitude reflection coefficient at the ice-water and water-substrate interfaces, the relative loss of the radio wave amplitude (A/A_0) could be calculated. Since the depth of the water body can be measured relatively accurately (i.e., 13 m water depth in Figure 2), we can use the radio wave amplitudes of the lake surface and floor reflections to determine the conductivity of subglacial lake water (equation (3)). We estimate the electrical conductivity of Antarctic subglacial lake water for a variety of substrate media, between 3.08×10^{-4} mhos m^{-1} (for water-saturated sand at the lake floor) and 5.36×10^{-4} mhos m^{-1} (for bedrock). The electrical conductivity of fresh water is 10^{-4} mhos m^{-1}. Thus our estimates of electrical conductivity within subglacial lakes show that the water is, qualitatively yet unequivocally, very pure and fresh.

Equation (4) assumes that the ice-water and water-substrate interfaces are flat and smooth. This is probably true for the ice-water interface (as is evident in Z scope records; Figures. 3, 4, and 5), but not necessarily for the lake floor boundary. If the interfaces are rough, then the power reflected at the interface will be scattered. In this case the received power may be different from that returned from a flat interface. One would usually expect a rough surface to yield less radio wave power reflected to the receiver because of scattering. Because a rough interface will scatter the energy nonuniformly in different directions, it is not easy to identify a correction factor to

equation (4) to account for this process. Equation (4) yields "maximum" reflection coefficients, so the electrical conductivity calculated will also be maximum values. Our results therefore represent an upper envelope for the electrical conductivity of Antarctic subglacial lakes. It should be noted that we do not account for a situation in which there is a gradual transition between lake water and the substrate medium because such a transition would not provide a sharp dielectric boundary and would not be conducive to lake floor VHF radio wave reflections.

6. Discussion

Our investigation has demonstrated that subglacial lakes are at least several meters deep, and our results provide the first direct evidence in support of significant volumes of water (between 4000 and 12,000 km^3) beneath the Antarctic Ice Sheet [Dowdeswell and Siegert, 1999]. The presence of water beneath the Antarctic Ice Sheet has implications for the thermodynamic history of the ice sheet. The temperature at the ice sheet base above subglacial lakes is likely to be at the pressure melting value (~-2°C). The ice sheet base is insulated from the very cold ice surface temperatures (~-60°C) by the ice sheet and is kept warm through geothermal heat from the Earth's interior (~50 mW m^{-2}). The rate of subglacial melting beneath Antarctica is of the order of millimeters per year [Kapitsa et al., 1996]. At Dome C, subglacial lakes occupy 10% of the 50,000 km^2 subglacial area [Siegert and Ridley, 1998b] and constitute between 250 and 1250 km^3 of water (depending on the mean thickness of lake water). Assuming that all subglacial melting collects within subglacial lakes, we can use these figures to infer that under a melting rate of 1 mm yr^{-1}, it would take between 5000 and 25,000 years of continual melting to yield the estimated water volumes. If subglacial melting is limited to ice over the lake itself (or if water collected within the lake comes only from ice above it), then it would take between 50,000 and 250,000 years to fill the subglacial lakes up to their present levels. For the Vostok lake, it would take 150,000 years of constant melting at 1 mm yr^{-1} over the 14,000 km^2 area of the lake to form the estimated 2000 km^3 water volume. These simple calculations show that under relatively low rates of subglacial melting, it takes a timescale of the order of a glacial-interglacial cycle to build the estimated water levels beneath the ice sheet.

Such calculations can be interpreted in two different ways. First, it would have taken relatively little time to build up modern lake levels from a situation where no subglacial lakes existed. Further, assuming constant subglacial melting over the next 100,000 years the water volume of subglacial lakes may double in volume and area. This process may dramatically alter the basal conditions of the Antarctic Ice Sheet. For instance, a doubling of the water volume beneath the Antarctic Ice Sheet could lead to widespread decoupling of the lake-bedrock interface and affect the relative stability of the ice sheet. Future

numerical modeling work is required to quantify the interaction between the growth of subglacial lakes and ice dynamics.

On the other hand, if the lakes have been present for several hundred thousand years without much change in water depth, the meltwater produced in that time must have been transported via a subglacial hydrological system to the ice sheet margin where refreezing occurs. The rate of refreezing must be the same as the production of meltwater for steady state to be maintained. As yet there is no direct evidence for the subglacial hydrological system beneath the Antarctic Ice Sheet. However, future numerical modeling studies may provide conceptual information regarding the subglacial hydrology associated with subglacial lakes.

7. Summary and Conclusions

We have analyzed 60 MHz Antarctic RES data from 77 known subglacial lake reflections [*Siegert et al.*, 1996] in order to detect evidence of VHF radio wave penetration to the base of subglacial lakes. In total, subglacial lake floor radio wave reflections were detected in eight cases. Assuming a radio wave velocity in water of 33.4 m μs^{-1} allows direct measurements of subglacial water depths to be made (Table 1). Because of the attenuation of VHF radio waves in water, these water depths (generally between 10-21 m) should be considered as minimum values. The reflection coefficient at the ice-water and ice-substrate interfaces can be estimated from the radio wave velocities in ice, water, and sublake substrate. This information can be used to estimate the conductivity of subglacial water, since water depth can be measured reasonably accurately. We estimate that the conductivity of Antarctic subglacial water bodies varies between about 3-5×10^{-4} mhos m^{-1}; reflecting very fresh water beneath the Antarctic Ice Sheet. Very accurate values of the conductivity of subglacial water are possible to calculate if the reduction of the VHF radio wave signal with water depth can be measured. However, because of the analogue nature of the Antarctic RES database held at the SPRI, exact measurements of the attenuation of the radio wave signal with water depth are difficult to obtain.

References

Bogorodskiy, V.V., C.R. Bentley, and P.E. Gudmandsen, *Radioglaciology*, D. Reidel, Norwell, Mass., 1985.

Dowdeswell, J.A., and M.J. Siegert, The dimensions and topographic setting of Antarctic subglacial lakes and implications for large-scale water storage beneath continental ice sheets, *Geol. Soc. Am. Bull.*, *111*, 254-263, 1999.

Drewry, D.J., *Glacial Geologic Processes*, Edward Arnold, London, 1986.

Glen, J., and J. Paren, The electrical properties of snow and ice, *J. Glaciol.*, *15*, 15-38, 1975.

Kapitsa, A., J.K. Ridley, G. de Q. Robin, M.J. Siegert, and I. Zotikov, Large deep freshwater lake beneath the ice of central East Antarctica, *Nature*, *381*, 684-686, 1996.

Kennett, M.I., An analysis of the scattering of radio waves within a temperate glacier, Ph.D. thesis, Univ. of Bristol, Bristol, England, 1987.

Millar, D.H.M., Radio-echo layering in polar ice sheets and past volcanic activity, *Nature*, *292*, 441-443, 1981.

Oswald, G.K.A., and G. de Q. Robin, Lakes beneath the Antarctic Ice Sheet, *Nature*, *245*, 251-254, 1973.

Reynolds, J.M., *An Introduction to Applied and Environmental Geophysics*, John Wiley, New York, 1997.

Robin, G. de Q., D.J. Drewry, and D.T. Meldrum, International studies of ice sheet and bedrock. *Philos. Trans. R. Soc. London*, *279B*, 185-196, 1977.

Shabtaie, S., I.M. Whillans, and C.R. Bentley, The morphology of ice streams A, B and C, West Antarctica, and their environs, *J. Geophys. Res.*, *92*, 8865-8883, 1987.

Shoemaker, E.M., The ice topography over sub-glacial lakes, *Cold Reg. Sci. Technol.*, *18*, 323-329, 1990.

Siegert, M.J., and J.A. Dowdeswell, Spatial variations in heat at the base of the Antarctic Ice Sheet from analysis of the thermal regime above sub-glacial lakes, *J. Glaciol.*, *42*, 501-509, 1996.

Siegert, M.J., J.A. Dowdeswell, M.R. Gorman, and N.F. McIntyre, An inventory of Antarctic sub-glacial lakes, *Antarct. Sci.*, *8*, 281-286, 1996.

Siegert, M.J., and J.K. Ridley, An analysis of the ice-sheet surface and sub-glacial topography above the Vostok Station subglacial lake, central East Antarctica, *J. Geophys. Res.*, *103*, 10,195-10,207, 1998a.

Siegert, M.J., and J.K. Ridley, Determining basal ice sheet conditions at Dome C, central East Antarctica, using satellite radar altimetry and airborne radio-echo sounding information, *J. Glaciol.*, *44*, 1-8, 1998b.

Siegert, M.J., R. Hodgkins, and J.A. Dowdeswell, A chronology for the Dome C deep ice-core site through radio-echo layer correlation with the Vostok ice core, Antarctica, *Geophys. Res. Lett.*, *25*, 1019-1022, 1998.

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