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Determining basal ice-sheet conditions in the Dome C region of East Antarctica using satellite radar altimetry and airborne radio-echo sounding

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ABSTRACT. Large subglacial lakes manifest themselves as flat regions on the ice surface. ERS-1 satellite radar altimetry of the Dome C region of East Antarctica was analyzed to correlate unusually flat areas on the ice surface with known locations of subglacial lakes identified from airborne radio-echo sounding (RES) data. The mean length of subglacial lakes which have an expression in the ice-sheet surface was ~8.3 km, whilst those that did not exhibit a surface morphological manifestation had a mean length of ~3.3 km. Thus, lakes up to about 4 km in length are unlikely to be detected from satellite radar altimetry of the ice surface. Given that the spacing of radio-echo flight tracks within the SPRI–NSF–TUD Antarctic database is 50–100 km in many areas, a number of subglacial lakes probably lie undetected beneath the ice sheet. RES information from two large, flat surface regions within Dome C, and a further flat area located at 80° S, 127° E, indicates the absence of subglacial lakes beneath the ice-surface features. However, these areas are characterised by relatively strong radio-echo returns which may indicate the presence of water-saturated basal sediments. We suggest that (1) blankets of water-saturated basal sediments may cause similar surface morphological features to those produced by subglacial lakes; and (2) misidentification of subglacial lakes from satellite altimeter observations of the ice-sheet surface is possible without the support of RES information relating to the ice-sheet base. Furthermore, our study indicates a lack of subglacial lake signals from RES data over relatively thick regions of East Antarctica such as the Adventure Subglacial Trough. We conclude that subglacial water produced in such regions may be transported by a basal hydrological system, driven by overburden pressure, to less thick regions of the ice sheet where subglacial lakes have been identified.

INTRODUCTION AND BACKGROUND

Antarctic subglacial lakes were discovered over 20 years ago from analysis of ice-penetrating radar (e.g. Oswald and Robin, 1973; Robin and others, 1977; McIntyre, 1983). A radio-echo sounding (RES) database, used by these authors and acquired by the SPRI–NSF–TUD (Scott Polar Research Institute, University of Cambridge, U.K.; National Science Foundation, U.S.A.; Technical University of Denmark) collaboration, is held at SPRI. Subglacial lakes appear as bright (typically 10–20 dB stronger than reflections from an ice–bedrock interface), flat, mirror-like signals that are easily distinguishable from reflections from the surrounding bedrock in the time-continuous RES records. A recent systematic analysis of the RES database led to the determination of subglacial lake locations (McIntyre, 1983; Siegert and others, 1996). In total, 77 subglacial lake-type RES reflectors were identified. The majority of the lakes (70%) were located at or near (<400 km from) major ice divides. Moreover, 54 individual RES lake signals were found beneath the Dome C–Ridge B region of East Antarctica. Here several lake reflectors were located relatively close to each other (<20 km). However, unless RES flight tracks cross one another there is no way of determining from these data, whether lake reflectors located relatively close together represent information from the same or different subglacial lakes.

The largest known Antarctic subglacial lake is located at, and extends 230 km north of, Vostok station, central East Antarctica. This subglacial lake is around 50 km wide and several hundred metres deep (Kapitsa and others, 1996). An accurate ERS-1 satellite radar altimeter topographic map of the ice-sheet surface reveals an unusually flat area directly above the location of the lake (as determined from RES measurements; Kapitsa and others, 1996). It has been observed further that the border of this flat surface region correlates extremely well (theoretically within 5 km, the maximum aircraft navigational error during 1970s Antarctic RES investigations, and practically around 1 km) with the location of the lake margin measured in several individual RES flight-lines over this lake. Consequently, the aerial extent of the Vostok lake can be determined accurately from a surface map derived from satellite radar altimetry. Moreover, it was shown that satellite altimeter information relating to flat surface regions can be used to establish whether two or more individual RES data that display subglacial lake features, but that do not overlap spatially, are derived from a single lake (Kapitsa and others, 1996).

Previous investigations of satellite radar altimeter information from the ice sheet above subglacial lakes (Cudlip and McIntyre, 1987; Ridley and others, 1993) identified the relationship between ice-surface morphological features and subglacial water beneath. However, the inaccuracy and poor spatial coverage of the available altimetric data used in these studies meant that the aerial extent of the two subglacial lakes investigated (at Vostok and Terre Adélie) could not be determined with certainty.

The association between ice-surface morphology and subglacial lakes is, in one sense, an indirect one since it is basal shear stress that controls the ice-sheet surface profile and not solely the existence of subglacial water. Also, there may be a size of lake below which no flat region is manifested on the ice surface (Shoemaker, 1990; Ridley and others, 1993).

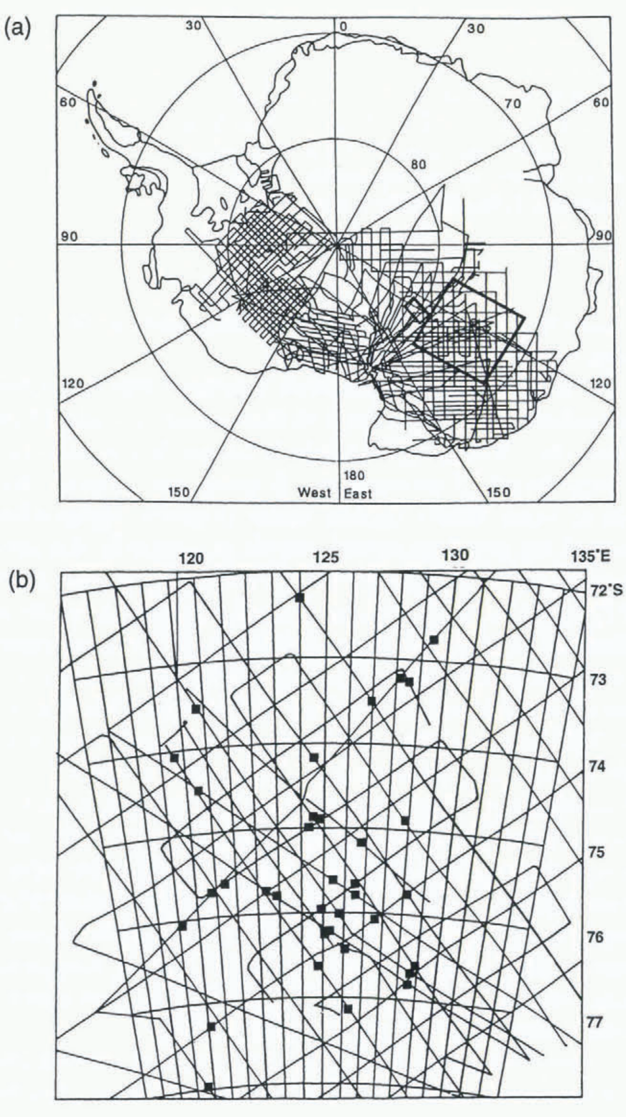
The aim of this paper is to present recent ERS-1 satellite radar altimeter data from the Dome C region, in order to ascertain information regarding the surface manifestation of the numerous subglacial lakes that have been found from analysis of RES data in this area of Antarctica. Any combination of RES lake reflectors representing the same lake is subsequently identified. Thus, basal ice-sheet conditions are inferred from analysis of ice-sheet surface morphology and RES information relating to the base of the ice sheet.

It should be noted that although we locate Dome C Station, as in Paterson (1994), at 74.5° S, 123.2° E, we consider the centre of the Dome C region to be situated at the summit of this locale at 75.1° S, 123.4° E (identified from ERS-1 satellite data and referred to later in Figures 1c and 3a).

THE DISTRIBUTION OF SUBGLACIAL LAKES BENEATH THE DOME C REGION

Siegert and others (1996) analyzed the extensive analogue RES database of Antarctica, held at SPRI, in order to determine the presence and location of subglacial lakes. From this work, 77 subglacial lake-type reflectors were observed (other than the seven that exist for the Vostok lake). This number includes 13 more lake reflectors than in previous investigations (e.g. Robin and others, 1977; Steed, 1980; McIntyre, 1983). Information about the location of these lake reflectors indicates that ~70% are located near (<400 km from) major ice divides. Specifically, 41 of the 77 RES lake reflectors, that have been discovered to date, originate from the Dome C region of central East Antarctica. Within our study, 36 or the 41 lakes that exist around the Dome C region are examined, since five of the Dome C lakes lie outside of our study area (Fig. 1). The minimum lengths of Antarctic lakes were measured by calculating the horizontal extent of the subglacial-lake radio-echo reflections (by assuming a constant air speed of 300 km h^{-1}, unless indicated otherwise in flight records). The mean minimum length of Antarctic subglacial lakes was calculated at 11.5 km, although the majority of lakes have minimum lengths of less than 10 km (Siegert and others, 1996). Within Dome C, the mean length of subglacial-lake RES records is 6.1 km (Fig. 2a).

Basal topography is related to the location of subglacial



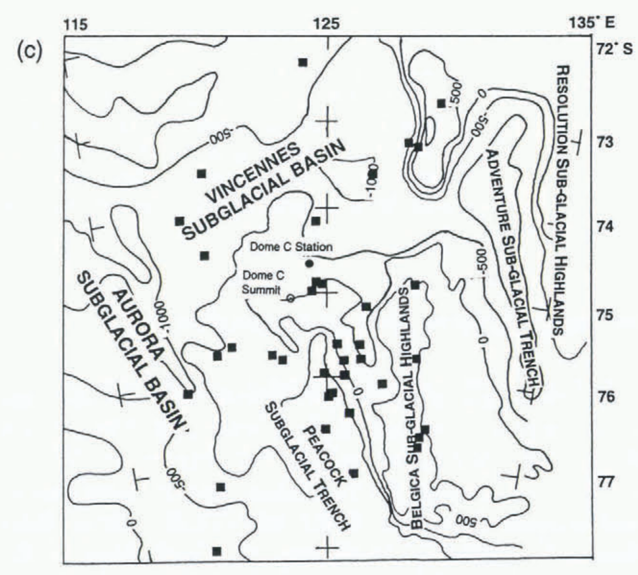


Fig. 1. (a) Location of RES survey airborne flight-lines from the SPRI–NSF–TUD collaboration (Drewry, 1983). Two boxes are illustrated in the diagram. The larger of the two denotes the Dome C region of Antarctica in which ERS-1 satellite altimeter data originate (Fig. 3). The second box indicates a region to the south of Dome C where further RES information is available from an anomalously flat surface region (referred to in Figure 5). (b) Subglacial lake distribution within Dome C, identified from airborne RES data (after Siegert and others, 1996). The locations of survey flight-lines within the Dome C region are also indicated (after Drewry, 1983). (c) Bedrock elevation at the base of the ice sheet around Dome C (after Drewry, 1983). Dome C Station (filled circle) and Dome C Summit (open circle) are located. In all figures, locations of subglacial lakes are denoted as squares.

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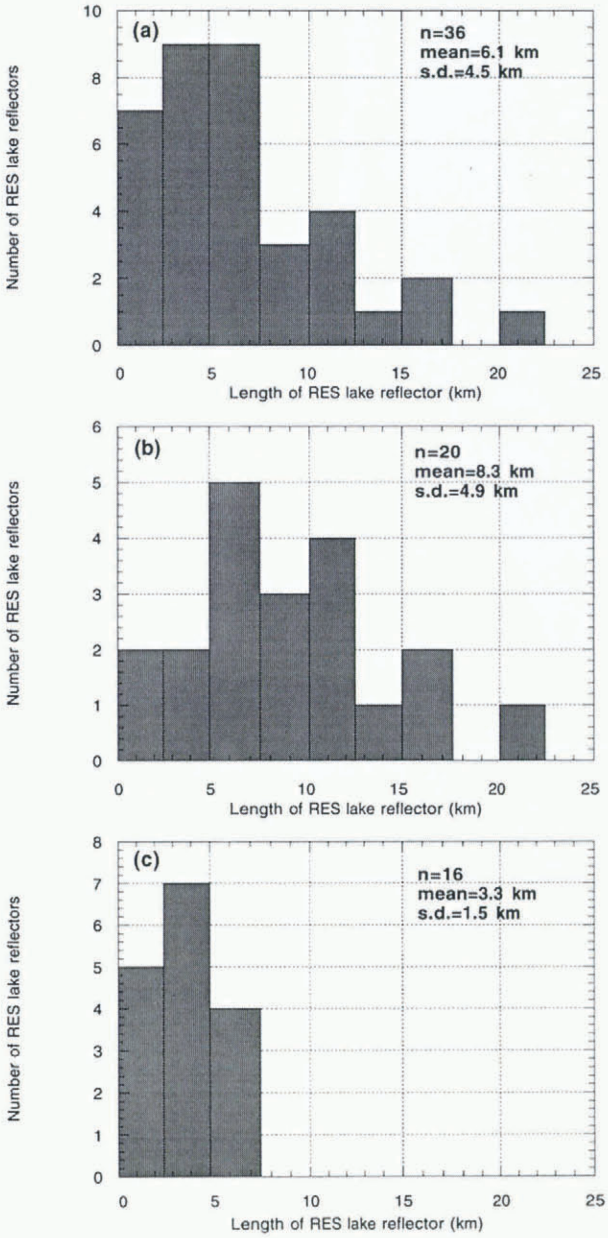

Fig. 2. Minimum length of RES subglacial lake records identified in Figure 1. The minimum length of subglacial lakes is determined from the time-dependent length of the lake signal within the airborne RES data, assuming a constant aircraft speed of 300 km h^{-1} (Siegert and others, 1996). (a) Total population of subglacial lake records above the 3000 m contour around Dome C. (b) RES lake records originating from beneath flat regions in the ice-sheet surface. (c) RES records of subglacial lakes which do not exert a noticeable influence on the ice surface.

lakes in that, assuming a relatively flat ice surface, they usually occur beneath thick ice (>3 km), where the base of the ice sheet is at the pressure-melting point (Robin, 1955; Huybrechts, 1992; Siegert and Dowdeswell, 1996). Because of this, concentrations of subglacial lakes around Dome C are found within the Peacock Subglacial Trench, and the Vincennes and Aurora subglacial basins (Fig. 1c). However, no lakes have been observed within the Adventure Subglacial Trench. Exceptions to the usual occurrence of lakes beneath deeper ice are found over the Belgica Subglacial Highlands where several lake-type reflectors were identified on RES records and the slope between Belgica and Peacock Subglacial Highlands (Fig. 1c).

Although about 50% of the Antarctic ice sheet was sounded during the 1970s by the SPRI–NSF–TUD collaboration (Fig. 1a), flight-line spacing of 50–100 km over much of this area (Drewry, 1983) means that a number of lakes (with minimum dimensions around, or less than, the 10 km scale) may exist between flight-lines and, consequently, could not be recorded within the inventory of Siegert and others (1996).

Analysis of ERS-1 satellite radar altimetric data from East Antarctica provides information on (1) the existence of flat surface regions that may correspond with subglacial lakes located between RES flight-lines, (2) the surface area of known subglacial lakes, identified from the calculated area of the flat surface feature (as in Kapitsa and others (1996) for the Vostok lake), and (3) the minimum size of known subglacial lakes which cause the formation of a flat region within the ice-sheet surface. In addition to these points, if ice-surface morphological features are identified where corresponding RES data indicate that no subglacial lake exists, the same RES data may be used in order to determine the appropriate, alternative ice-sheet basal conditions.

SUBGLACIAL LAKES AND ICE-SURFACE MORPHOLOGY AROUND DOME C

ERS-1 satellite altimeter data around Dome C

Satellite radar altimetry measures the average surface height along the satellite ground-track across a circular footprint some 5 km in diameter (Rapley, 1990). Altimetric data have been used successfully for a number of ice-sheet surface applications (e.g. Cudlip and McIntyre, 1987; Zwally and others, 1989; Ridley and others, 1993; Kapitsa and others, 1996), but their general suitability for continuous surface mapping is limited because of the longitudinal spacing of the ground-tracks (typically 80–200 km). However, during the Geodetic Phase of the ERS-1 altimetric mission (April 1994–March 1995), the satellite conducted two 168 day repeat cycles, the second of which was offset by half a cycle from the first. This led to a ground-track spacing at 75° S of 2 km which, combined with an along-track sampling every 335 m, provides a complete coverage of the ice sheet. The surface elevation measurements are interpolated to form a horizontally two-dimensional grid which is used to produce an accurate digital elevation map of the ice-sheet surface. Individual altimetric measurements have a precision, in ERS-1 ice mode, of ~50 cm (Scott and others, 1994). Each 2 km grid element contains two crossing satellite ground-tracks and some 78 measurements which are averaged for a cell precision on the mean height of ~12 cm rms. The accuracy of the cell mean height is determined by the knowledge of the satellite orbit, which is known to ~8 cm (Scharroo and Visser, in press), and the surface slopes which in this region are at most 0.08°. This results in an rms accuracy of 25 cm per gridcell.

ERS-1 satellite radar altimetry from the geodetic mission over the Dome C region of East Antarctica is provided in Figure 3a. According to a number of authors, the presence of a subglacial lake is indicated by an interruption in the otherwise regular contours of the ice surface (e.g. Cudlip and McIntyre, 1987; Ridley and others, 1993; Kapitsa and others, 1996). However, where the regional surface slopes are low, as around the summit of Dome C, it is difficult to discri-

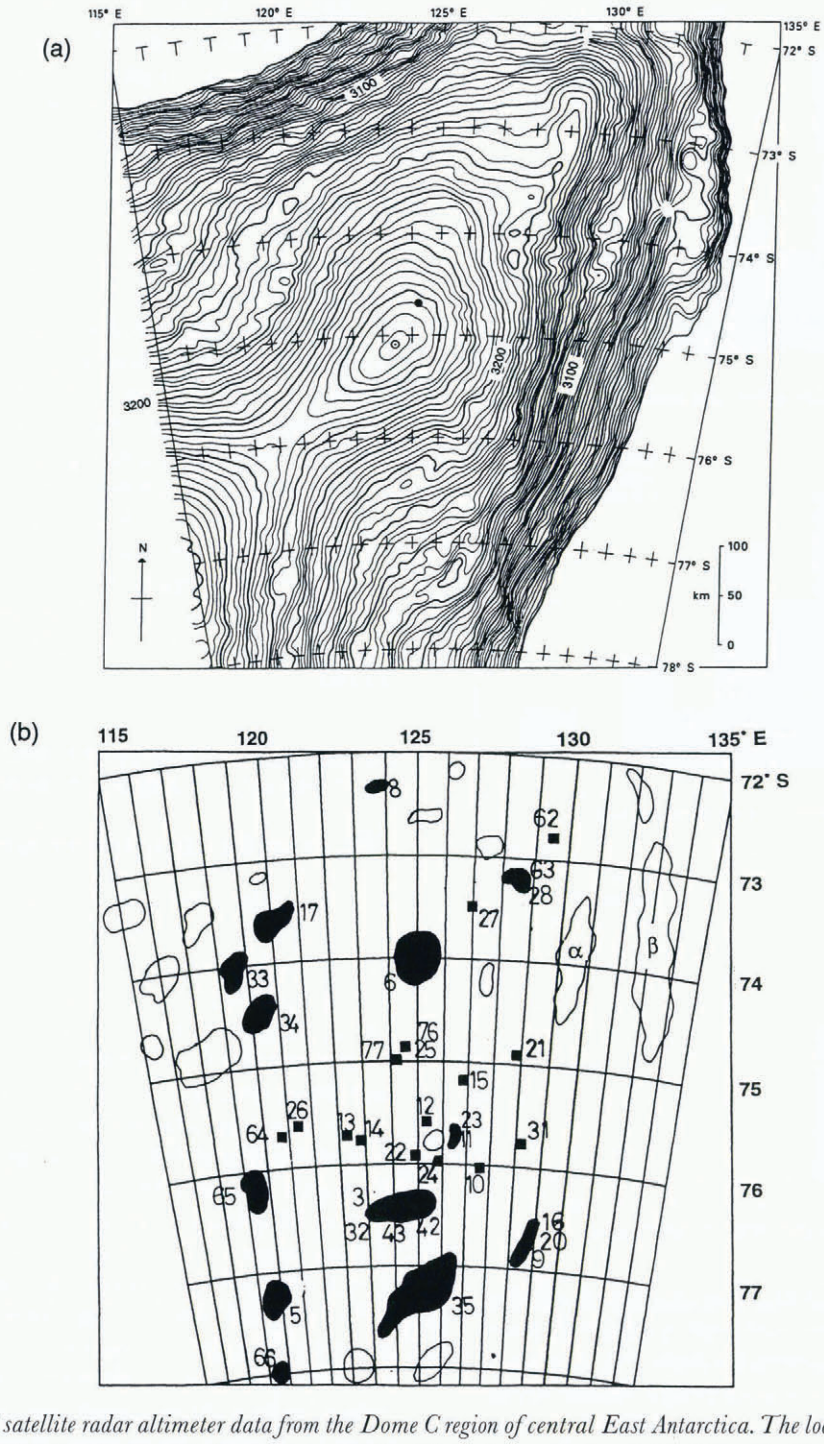

Fig. 3. (a) ERS-1 satellite radar altimeter data from the Dome C region of central East Antarctica. The locations of subglacial lakes with respect to "flat regions" on the ice surface are indicated. Contours are given in 2 m intervals. Dome C Station (filled circle) and Dome C Summit (open circle) are located. (b) The spatial coverage of flat surface regions determined by restricted areas of surface slope less than 0.01°. Those flat regions representing subglacial lakes (identified through analysis of RES data) are shown as black regions, whereas flat regions, beneath which RES data show no subglacial lake, are not filled. Flat regions α and β, referred to in the text, are noted.

minate between surface gradient changes that may be due to the presence of a subglacial lake, and the surrounding, unaffected surface morphology.

Quantification of "flat" regions within the ice-sheet surface

Several flat regions on the ice surface can be observed in Figure 3a. We quantify such regions by assuming that a "flat ice-surface area" has a maximum gradient of no more than 0.01° (Fig. 3b). Further, the direction of surface slope either side of the lake must be similar (thus eliminating flat regions located at the ice divide). This value can be justified given that the maximum gradient of the ice surface over the Terre Adélie lake is 0.01° (Cudlip and McIntyre, 1987). We consider that the extremely flat surface region above the Vostok subglacial lake (0.01–0.004°) may be unrepresentative of surface slopes above subglacial lakes in general, because of the unusually large size (10 000 km^2) of this particular lake (Kapitsa and others, 1996). Thus, if we chose a "flat region" as that which has a slope of <0.004°, we would expect to miss the surface expression of several subglacial lakes. Conversely, under our procedure for determining flat surface regions, we include a broad range of extremely flat surfaces, with end-member situations being the ice surface slopes at the (1) Vostok and (2) Terre Adélie subglacial lakes.

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After consideration of the locations of subglacial lakes with respect to flat surface regions around Dome C, several of the RES lake-type reflectors were found to originate from the same subglacial lake (Fig. 3). Lakes which have two or more RES flights over these flat regions are indicated as such in Table 1. This has implications for the subglacial lake inventory of Siegert and others (1996), in that five of the lakes presented in their list contain detections from two or more RES flights. Consequently, the number of subglacial lakes that exist in the Dome C region above the 3000 m contour, is reduced from 36 "lake reflectors" to 28 "lakes" as a result of our investigation.

Several RES lake-type reflectors are located close to each other, but with no obvious surface feature associated with them. We suggest that these reflectors represent individual lakes. We cannot discount, however, the possibility that such lakes may be connected either by subglacial channels or by narrow sections of a single lake (e.g. lakes 13 and 14, Table 1).

Matching the location of RES lake-type reflectors with flat surface features

Analysis of the satellite radar altimeter map and the locations of subglacial lakes beneath Dome C shows that 20 of the 36 RES lake reflectors within the region defined by the altimeter map lie beneath an ice-sheet surface with slopes of less than 0.01°. Histograms representing the distribution of lengths of RES lake reflectors which lie beneath flat surface regions, and those which do not, show that, in general, larger lakes occur beneath flat regions (Fig. 2). The mean minimum length of RES lake-type reflectors beneath flat regions is ~8.3 km, whilst it is ~3.3 km if no surface expression is detected. Consequently, the occurrence or other-

Table 1. Information about known subglacial lakes located in the Dome C region (adapted from Siegert and others, 1996). Information includes geographical coordinates, observed lake length from RES data, lake length recorded from satellite surface altimetry of ice surface (if different to that measured from RES data) and the thickness of overlying ice (after Siegert and others, 1996)

*Lake No.**	*Latitude*	*Longitude*	*Length (RES)*	*Length (satellite)*	*Distance to Dome C*§	*Ice thickness*
	°S	°E	m	m	km	m
3 (32) (42) (43)	76.57	124.80	5000	72 000	168	3621
5	77.20	119.27	10 000	20 000	248	3835
6†	74.13	124.58	10 000	55 000	104	4094
8	72.31	123.94	10 000		300	3254
9 (20) (16)	76.94	129.40	5000	40 000	240	3011
10†	75.94	127.41	5000		148	3449
11 (23)	75.81	126.56	8500		104	3860
12†	75.65	125.60	5000		80	3399
13†	75.87	122.66	5000		72	3364
14†	75.84	122.82	2000		74	3400
15†	75.14	126.98	2000		96	3447
16 (9) (20)	76.75	129.82	2000	40 000	232	3061
17	73.45	119.54	15 000		200	3924
20 (16) (9)	76.63	129.92	1800	40 000	232	3009
21†	74.91	128.90	700		148	3890
22†	75.97	124.95	3700		104	3168
23 (11)	75.78	125.97	3000		100	3162
24	75.69	126.48	4200		124	3650
25 (76)†	74.96	124.61	3500		32	3360
26†	75.61	120.39	2700		100	3057
27	73.4	126.90	6700	50 000	196	4010
28 (63)	73.17	128.35	15 100		248	4148
31	75.82	129.03	3000		168	3069
32 (3) (42) (43)	76.40	126.03	2900	72 000	164	3500
33	74.03	118.50	8500	50 000	180	4092
34	74.46	119.37	6700	50 000	128	3932
35	77.12	126.30	8400		232	3741
42 (43) (3) (32)	76.19	125.18	5000	72 000	132	3881
43 (3) (32) (42)	76.20	125.30	10 000	72 000	132	3886
62	72.74	129.41	2000		304	3828
63 (28)	73.14	128.41	20 000		252	4171
64†	75.76	119.71	2500		116	3574
65†	76.07	118.11	5000		172	3733
66	78.00	118.60	14 100		324	3341
76 (25)†	74.92	124.65	3500		36	3360
77†	74.92	124.19	1900		28	3225

* Lake numbers denote those assigned within the subglacial lake inventory of Siegert and others (1996). Where subglacial reflectors are observed to lie within the same flat surface region or very close to each other, the lake numbers previously identified from the RES data are provided in parentheses. Consequently, lake numbers in parentheses may be thought of as representing the same lake.

† RES lake data which do not have an associated ice-surface feature.

§ The distance of subglacial lakes to Dome C refers to the summit identified from ERS-1 satellite data rather than the Dome C Station coordinates (Fig. 3a).

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wise of flat ice-sheet surface regions which are attributed to the manifestation of subglacial lakes is controlled by the size of the lake (Fig. 2). This has implications for the minimum size of subglacial lakes that can be detected from satellite information, and leads to a suggestion that there may be more subglacial lakes (≤4 km in length) which lie undetected between the 50–100 km separations of the RES flight-tracks.

Measurements of lake extent from satellite data have implications for the calculated minimum length of lakes, determined previously from RES data. We assume that the shape of the ERS-1-derived flat surface regions, if associated with lake-type RES reflectors, represents the shape of subglacial lakes (e.g. Kapitsa and others, 1996). Where RES data are available, the edge of the subglacial lakes corresponds well with the margin of the flat surface region. Consequently, where the ERS-1-derived lake dimensions are larger than those detailed in RES data, the minimum lengths and approximate areas are recorded directly from the ice-surface features (Table 1; Fig. 3).

Lakes which exhibit a surface expression tend to be located away from the Dome C ice summit (in relative proximity to the ice divide), whilst those which do not have an associated surface feature are generally located closer to the summit. We acknowledge that this relation may be influenced by our quantification of what constitutes a flat ice surface, since it does not allow for flat areas over ice divides to be included. However, we regard the clear size distinction between the two types of subglacial lake (those which lie beneath a flat region and those which do not) as evidence supporting the notion that small lakes (≤4 km) which exhibit no ice surface manifestation are located closer to ice divides (Fig. 4). For instance, subglacial lakes with dimensions no greater than 6 km are located within 100 km of the centre of Dome C. However, both small (<6 km) and large (>6 km) lakes are observed to occur further than 100 km from the Dome C summit (Fig. 4).

Within the satellite altimeter map, two obvious flat regions can be observed where Siegert and others (1996) had previously determined that there are no RES data which indicate the existence of subglacial lakes. These flat regions are noted as α and β in Figure 3b. Re-examination of the Antarctic RES database from these particular regions shows that the smooth mirror-like reflectors associated with subglacial water bodies are not present within the RES data across these regions. However, consideration of bedrock morphology established from the RES database indicates that these flat surface regions lie over the Adventure Subglacial Trough, where thick (>4 km) ice occurs. The RES information shows relatively bright returns from the ice–substrate interface that may indicate the presence of subglacial water. This is compatible with the notion that relatively thick ice in central Antarctica will be subject to pressure-melting at the base. However, the absence of a mirror-like reflector from the RES data means that this subglacial water is not being trapped within a subglacial hollow. Therefore, we can infer that, assuming the generation of subglacial water, transport of water through an as yet unknown basal hydrological system is occurring beneath Dome C.

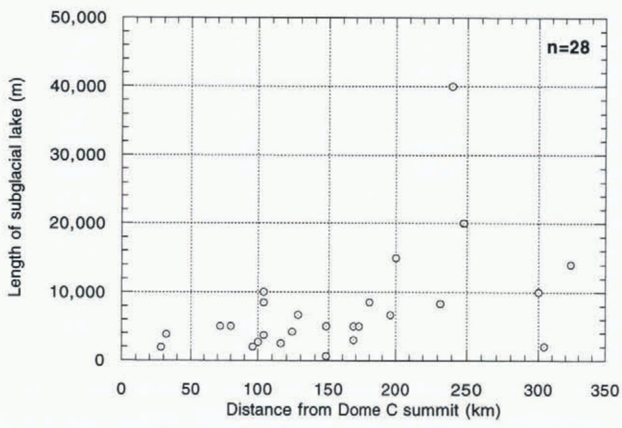

Fig. 4. Minimum length of subglacial lakes (determined from RES observation and the extent of surface features within the ice surface), against distance of the lake from the central region of Dome C. The central region of Dome C is assumed as the summit, highlighted in Figure 3a by an open circle.

Extent of subglacial lakes around Dome C

The surface area of subglacial lakes which possess a surface expression can be established by calculating the aerial extent of the flat surface region. However, for the remaining 16 RES lake-type reflectors that do not occur beneath flat regions on the ice-sheet surface, an estimate of the lake surface area has to be made. We assume that these relatively small subglacial lakes are circular in shape. Their areas can, therefore, be determined by letting the minimum length of the lakes (from RES records) describe the diameter of the lake. It should be noted that the determination of lake area by this means represents a minimum value. Using the above procedure, we estimate that ~15 000 km^2 of the ice-sheet base around Dome C is occupied by subglacial lakes. This value represents 6% of the total ice-sheet base beneath the 3000 m surface contour.

ADDITIONAL FLAT REGIONS ON THE ICE-SHEET SURFACE

In addition to the flat ice-sheet surface regions identified at Dome C (this paper), Vostok station (Ridley and others, 1993; Kapitsa and others, 1996) and Terre Adélie (Cudlip and McIntyre, 1987), an inspection of the Antarctic ERS-1 satellite altimeter data has revealed a relatively large flat region which appears to be analogous to that in the Vostok area (Fig. 5a). This surface feature is located at 80° S, 127° E, and has a surface slope of 0.02° within a regional surface dip of 0.09° (Fig. 5a). The surface slope is twice the value used in our criterion for flat region identification, but the sudden change in slope from that of the surrounding ice sheet (which is similar to that observed over the Vostok lake) means that it should be investigated as a potential surface feature resulting from the presence of a subglacial lake. However, no subglacial lakes were identified in this region from previous inspections of the Antarctic RES records (Oswald and Robin, 1973; Steed, 1980; McIntyre, 1983; Siegert and others, 1996). Because of this, the available raw RES data for the flat-surface area in question were reanalyzed.

The RES data for this region indicate a relatively undulating basal return (Fig. 5b) which suggests that a subglacial lake is not present in this area (reflections from subglacial lakes are unusually flat or mirror-like). However, the RES signal does show relatively bright subglacial returns which

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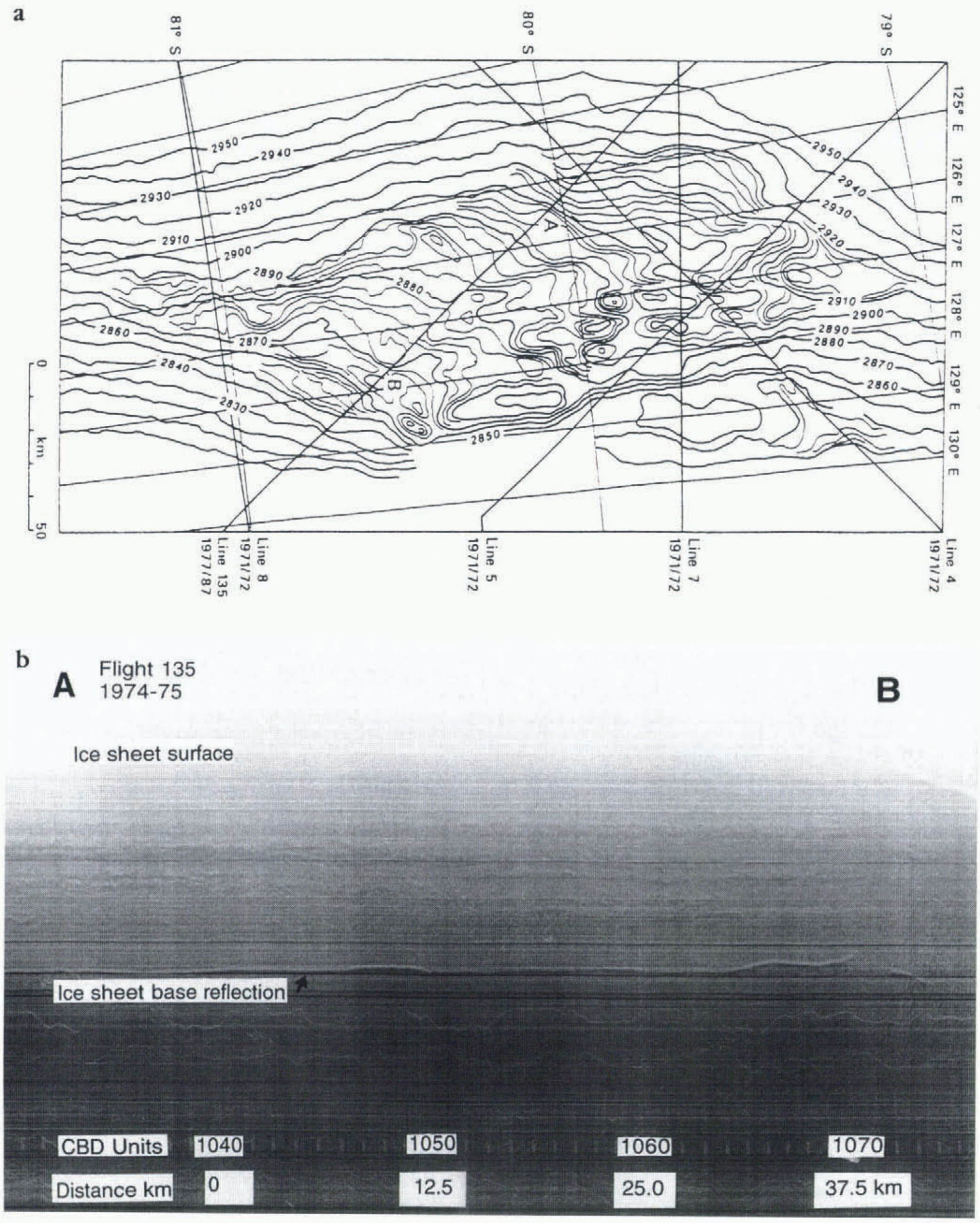

Fig. 5. (a) ERS-1 satellite altimeter data from an unusually flat region to the south of Dome C. RES flight-lines around this region are shown. Contours are given in 2 m intervals where the ice surface is relatively flat, and in 10 m intervals elsewhere. (b) Airborne RES information from flight No. 135, 1978–79. The location markers A and B refer to those indicated in (a). The basal reflection is identified as the non-flat line above the label "Ice-sheet base reflection". The location of this flat surface region is provided in Figure 1a. The sub-parallel wavy lines in the lower half of (b) represent scratches on the original RES negative used to obtain the photograph.

may be indicative of electromagnetic reflections in the presence of water at the ice-sheet base. We suggest that the flat region on the ice surface may be caused by a reduction in the basal shear stress (similar to that which occurs over subglacial lakes) due to the existence of geotechnically weak water-saturated basal sediment. Unfortunately, single e/m pulse RES data that would provide quantitative information about the power of RES returns are not available for this region. Because of this, our identification of "bright" returns remains a qualitative one.

If water-saturated sediments are capable of inducing flat regions on the ice surface (appearing similar to those formed by subglacial lakes), then we can conclude that the identification of subglacial lakes cannot be made through the interpretation of satellite radar altimeter data alone. However, satellite radar altimeter data can help to determine areas where subglacial lakes may exist, and where additional RES data are required to confirm the presence of significant subglacial water bodies.

It is evident from our study of the surface morphology of Dome C that relatively small (~8 km) subglacial lakes and, possibly, regions of water-saturated basal sediments exhibit an influence on the dynamics of the East Antarctic ice sheet. Modern numerical ice-sheet models of Antarctica do not account for the presence of such lakes and their influence on ice-sheet behaviour (e.g. Huybrechts, 1992). However, given that there are at least 28 subglacial lakes of this kind beneath the Dome C area (Fig. 1), this dynamic influence may be a significant one in terms of the flow of ice within this region. If numerical ice-sheet models are to be used in the identification of glacial response to climate change, it is essential that the ice velocity calculated within the model is determined accurately. It becomes important, therefore, that the existence of subglacial lakes is acknowledged and accounted for within models of Antarctic ice flow.

SUMMARY AND CONCLUSIONS

It is known that subglacial lakes can exhibit an expression within the ice sheet directly above them in the form of extremely flat surfaces compared with the surrounding slope of the ice mass (Cudlip and McIntyre, 1987; Ridley and others, 1993; Kapitsa and others, 1996). With this in mind, newly available ERS-1 satellite radar altimetry of the Dome C region of central East Antarctica was used to determine regions of the ice surface that are unusually flat. Such regions were quantified by having slopes of less than 0.01°. Several of these areas correlate well with the locations of known subglacial lakes (Figs 1 and 3; Siegert and others, 1996). However, there are two notably flat regions where no subglacial lakes have been observed, and 16 subglacial lake-type reflectors which lie beneath undisturbed regions of the ice surface.

Our investigation allows the aerial extent of water masses at the base of the Dome C region to be calculated at $\sim$15 000 km^2. This value represents $\sim$5% of the total basal area specified within the 3000 m satellite-derived contour (Fig. 3). We propose that an area of subglacial water such as this, which causes zero shear stress at the ice–water interface, would influence the flow of the ice sheet in this region (as is evident from the ice surface morphology).

The mean length of subglacial RES lake-type reflectors that did not have an associated flat surface region that was detectable by the ERS-1 altimeter was $\sim$3.3 km, compared with the $\sim$8.3 km mean length of those which did. Bearing in mind the 50–100 km width of RES flight paths used in the Antarctic RES survey performed by the SPRI–NSF–TUD collaboration in the 1970s, it is possible that a number of small ($\leq$4 km) subglacial lakes lie undetected beneath the Antarctic ice sheet.

RES data from the ice base beneath two flat surface regions within the Dome C district (identified as α and β in Figure 3), and a further large flat region located at 80° S, 127° E (Fig. 5), do not indicate the existence of subglacial lakes. However, the relatively high strength of these RES signals suggests the existence of basal water and, conceivably, water-saturated basal sediments. The low yield stress of such material would influence the ice-sheet dynamics in a manner similar to the negligible basal stress above subglacial lakes. Consequently, the ice surface morphology above regions of deforming sediment may be comparable with surface features above subglacial lakes. In addition, the absence of subglacial lakes within deep troughs where basal melting is likely to be occurring, such as the Adventure Subglacial Trough, suggests that the transport of water must be occurring at the base of the central Antarctic ice sheet.

We conclude that subglacial lakes cannot be identified unequivocally from satellite radar altimeter data alone. Furthermore, a significant number of relatively small lakes may lie undetected beneath the East Antarctic ice sheet because they are located in between RES flight tracks from the 1970s. Although unusual surface features indicative of those over subglacial lakes can be investigated further by RES work to determine the presence of subglacial water, since small ($\leq$4 km) subglacial lakes do not exert an expression on the ice surface they may only be detected by chance coverage by new RES flights.

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