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Geophysical investigations of ice-sheet internal layering and deformation in the Dome C region of central East Antarctica

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ABSTRACT. New maps are presented of three internal ice-sheet radio-echo sounding (RES) layers in the region 73.5–75.75° S, 120–127° E (56 000 km^2) around Dome C, central East Antarctica. These layers represent horizons of enhanced acidity resulting from volcanic aerosol deposition, identified from analogue RES data. They are continuous over the entire mapped area, and constitute deformation markers in the ice column. Internal RES layers were initially identified from discrete radar power reflection coefficient profiles and subsequently digitized directly from prints of ice-sheet cross-sections, acquired by continuous RES profiling. Georeferenced vector data are used to generate a 5 km gridcell raster of depth for each internal RES layer, as a basis for contour mapping. Ice deformation in the Dome C region is significant because this is the location of the European Project for Ice Coring in Antarctica. Since internal layers are isochronous, the one-dimensional ice-core data at Dome C can be correlated over the survey area to produce a three-dimensional context.

INTRODUCTION

This paper uses radio-echo sounding (RES) data to provide new, three-dimensional information on internal ice-sheet structure for the Dome Concordia (Dome C) region of central East Antarctica (Fig. 1). An extensive analogue RES dataset of the Antarctic ice sheets, collected by the Scott Polar Research Institute (SPRI)–U.S. National Science Foundation (NSF)–Technical University of Denmark (TUD) consortium between 1968 and 1979, is held in archive at SPRI, University of Cambridge, U.K. (Drewry, 1983). Approximately 50% of the area of the ice sheets is covered by RES flight tracks, with a focus on the western part of East Antarctica. A pervasive feature of the data is the occurrence of strong reflections from within the ice. Several individual internal reflectors are discrete and continuous over distances on the order of 100 km. Electromagnetic (e/m) reflections of this type occur in ice at boundaries of dielectric contrast. The causes of the reflections are understood to be ice-density changes (at depths of < 1000 m) and acid ice resulting from volcanic aerosol deposition. At depths of > 1000 m, radio-echo layering is caused principally by acid labelling of discrete stratigraphic horizons within the ice sheet (Millar, 1981; Siegert and others, 1998b).

The Dome C region (Fig. 1) is of particular interest because of its potential significance for palaeoenvironmental studies. The 2700 m ice core taken from Vostok station, central East Antarctica, has provided benchmark evidence of palaeoclimate for the last glacial–interglacial cycle (Lorius and others, 1985; Jouzel and others, 1989, 1993). A 3300 m ice

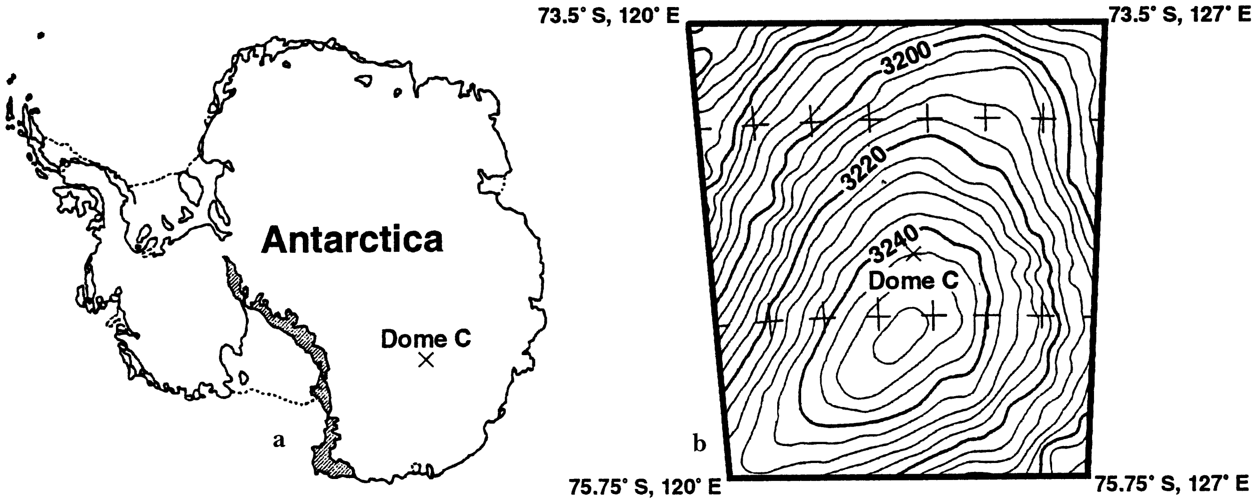

Fig. 1. (a) Location of Dome C. (b) ERS-1 radar altimeter-derived surface elevation in the study area; contours in m a.s.l. (source: Siegert and Ridley, 1998).

core from Dome C (about 550 km from Vostok station) is to be obtained through the European Project for Ice Coring in Antarctica (EPICA) (Jouzel and others, 1996). This is likely to yield similarly important palaeoclimate data. Siegert and others (1998a) traced five prominent internal layers, identified from RES data, for >500 km across the East Antarctic ice sheet, between Vostok and the new ice-core site at Dome C. This correlated the stratigraphy and depth–age relationship between the two sites. The present paper enhances understanding of the glaciological context of the future Dome C ice core by mapping the three-dimensional, internal ice-sheet structure in the region.

A 9600 km^2 area around the Dome C ice-core site has been mapped using 60 MHz radio-echo sounding (Tabacco and others, 1998). In this survey, the surface and subglacial topography was established. Although internal layering was observed in the RES data, no three-dimensional representation of internal ice-sheet structure was developed. The present paper, therefore, represents the first attempt to map RES layering in three dimensions within central East Antarctica, and to identify internal ice-sheet architecture accordingly.

ACQUIRING INTERNAL RES LAYER DATA

Analogue RES data were recorded in two different formats during SPRI–NSF–TUD Antarctic operations: as plots of two-way travel time vs signal strength from single e/m pulses ("A-scope" data; Fig. 2), or as a continuous series of e/m returns where signal strength is identified by brightness rather than an axis variable ("Z-scope" data; Fig. 2). A-scope data were recorded discretely at 15 s intervals; the distance interval varied with the speed of the aircraft, and is referred to as a "CBD unit". Quantitative information about the reflectivity of individual layers is acquired by determining power reflection coefficients (PRCs), which account for the geometric spreading, refraction and dielectric absorption of radio waves in ice, and the two-way antenna gain of the RES apparatus (Robin and others, 1977; Paren, 1981; Siegert and others, 1998b). When plotted as two-way e/m wave travel time against real time, continuously recorded Z-scope data yield ice-sheet pseudo-cross-sections.

Three prominent internal layers were traced across four separate flight-lines in the Dome C region: lines 102, 104, 108 and 136 (Fig. 3a). Each individual flight-line has at least two, and up to four, crossing points along it, which have been used for cross-checking to ensure the correct layers are identified on the Z-scope data. The process of identifying and tracing layers is as follows: calculate PRC profiles from A-scope data at 20 CBD unit intervals along each of the four flight-lines; match three PRC maxima at five check locations (11 individual PRC profiles); use PRC profiles to trace the three PRC maxima along the full length of each flight-line at 20 CBD unit resolution (58 individual PRC profiles); use Z-scope data to trace layers corresponding to the PRC maxima over the full length of each flight-line at 1 CBD unit resolution (this step checks the results of the previous two steps); finally, the three RES internal layers (and the bedrock profile) can be marked on analogue Z-scope data consisting of photographic prints, and digitized. Locations and total ice depths at 1 CBD unit resolution are known from the original flight navigation data, so the actual depth of each layer can be calculated from its fractional depth.

Confidence in the identification of each RES internal layer is high, because of consistency checks from different data formats (A- and Z-scope), and direct tracking from Z-scope prints. Consideration of the digitizing resolution suggests that the absolute accuracy of the determined layer depths is of the order of 100 m; this constitutes only 2.4–4.4% (mean 2.9%) of the ice depth in the study area.

CONSTRUCTING INTERNAL RES LAYER MAPS

Some 930 data points, each matched to the depth of the three internal RES layers and of the bedrock, were acquired by the above procedure, in the area 73.0–76.3° S, 118–132° E. However, in order to achieve the densest coverage of data points centred around Dome C, the mapping exercise focuses on an area delimited by the latitude range 73.5–75.75° S (about 250 km), and longitude range 120–127° E (about 225 km); Dome C is located at 74.6667° S, 123.8333° E, and is therefore very close to the centre of this approximately 56 000 km^2 area (Fig. 3a). Five hundred vector (x, y, z) data points are located within this area (Fig. 3a), where x corresponds to the latitude of the point, y to its longitude and z to the depth of either internal RES layer 1, 2 or 3 or the bedrock. It was decided to map layer depths rather than elevations because the absolute ice-surface elevations derived from the original

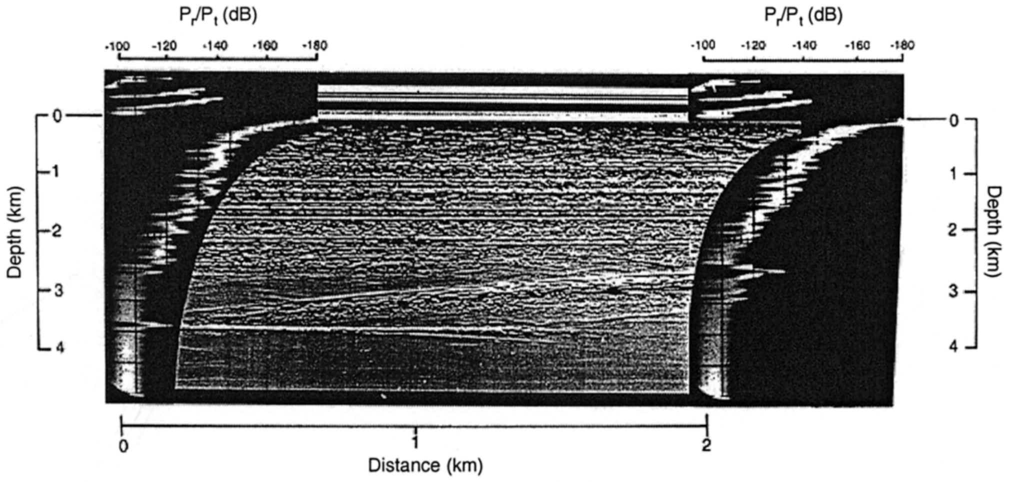

Fig. 2. Sample analogue RES data: a time-continuous "Z-scope" pseudo-ice-sheet cross-section, and corresponding single-pulse "A-scope" returns; P_r/P_t is the amplitude of the received radio wave relative to the transmitted power. The prominent lowermost P_r/P_t peak represents bedrock, which in this example can be traced from left to right, decreasing in depth.

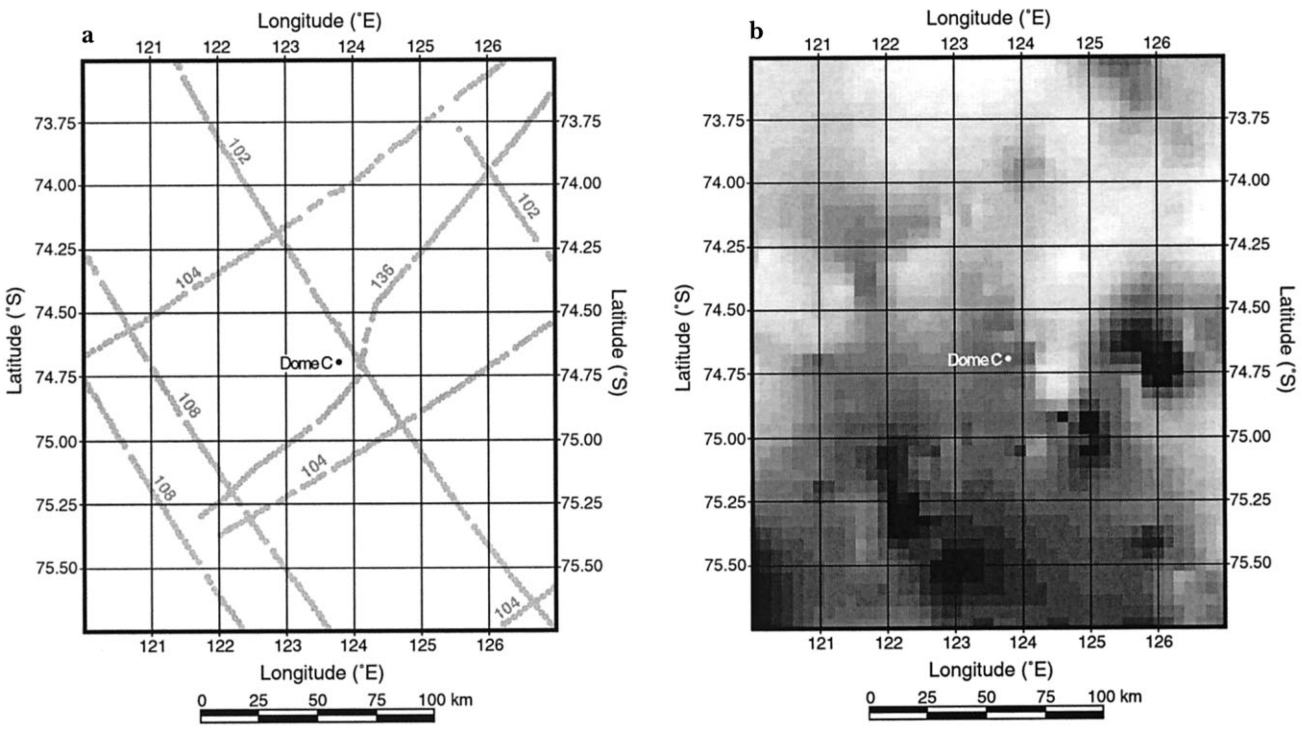

Fig. 3. (a) Location of data points within the study area. There are 500 latitude/longitude (x, y) locations, each with the depths of three internal RES layers and the bedrock (z). Flight-line numbers are indicated. (b) 5 km grid raster derived from bedrock depths; lighter shading indicates greater elevation/shallower depth. There are 50 gridcells in the latitudinal direction and 45 cells in the longitudinal direction. A similar raster was generated for each of the three RES internal layers as well as the bedrock, as the basis for contour mapping (see Figs 4 and 5).

flight navigation data are less reliable than the relative depths that may be determined from the RES data (and than recently acquired European Remote-sensing Satellite (ERS-1) surface elevation data). From these vector files, raster files were generated using an iterative minimum-curvature algorithm, in which a two-dimensional cubic spline function is used to fit a surface to the input depth values. Three grid resolutions were examined: 2 km (125 × 111 cells), 5 km (50 × 45 cells) and 10 km (25 × 23 cells). The vector data were not sufficiently densely spaced to justify a 2 km gridcell resolution, while the contours generated from the 10 km gridcell raster appeared unduly generalized. Contour maps were therefore generated from 5 km gridcell rasters (Fig. 3b). The raster was contoured by linear interpolation. Input raster values were pre-smoothed by a weighted average method to remove jagged anomalies and outliers in contouring. Figure 4 presents the final contoured depth maps for each of the three RES internal layers and the bedrock. Note that the necessary interpolation from irregularly spaced vector data suggests the reliability of the contour maps decreases towards the centres of "data-sparse" areas.

DISCUSSION

Ice deformation

Valuable applications of DEMs of ice-sheet internal layers may be as initial boundary conditions in dynamic models of ice-sheet flow, or as final boundary conditions in inverse-modelling procedures. While the flow rate of an ice column decelerates quasi-exponentially towards bedrock, *cumulative* deformation is greatest near the bed, where ice residence time is greatest as a result of the low flow rates. Beneath a large ice sheet, patterns of deformation will be complicated by large-scale variations in bedrock topography, thermal regime, strain history of the ice column (which reaches a maximum thickness of >4000 m in the mapped area) and residence time: the age of ice at 2200 m depth at Dome C is >145 000 years (Siegert and others, 1998a). Therefore, internal RES layers are an indicator of internal deformation, which can be resolved at a fine scale over large areas. A measure of the extent to which each internal RES layer has been deformed is given by the range in depth of the layer and the standard (rms) deviation of the depth of the layer within the mapped area. The data in Table 1 confirm that both of these measures increase with depth. Two ice-sheet cross-sections across the Dome C area are illustrated in Figure 5. These reveal a trend towards increasing resemblance to the bedrock profile with internal RES layer depth, which is consistent with the data in Table 1.

Ice-core studies

Ice cores necessarily require as complete, detailed and undisturbed a stratigraphy as possible. Because of logistical and resource implications, this is an operational as well as

Table 1. Descriptive statistics for internal RES layer and bed depths

Statistic	*Latitude*	*Longitude*	*Layer 1 depth*	*Layer 2 depth*	*Layer 3 depth*	*Bed depth*
	°S	°E	m	m	m	m
Minimum	73.509 5	120.014 6	732	1298	1594	2254
Maximum	75.748 0	126.989 6	1689	2673	3072	4093
Range	–	–	958	1374	1478	1839
Mean	–	–	1158	1801	2286	3423
Std dev.	–	–	201	306	328	346

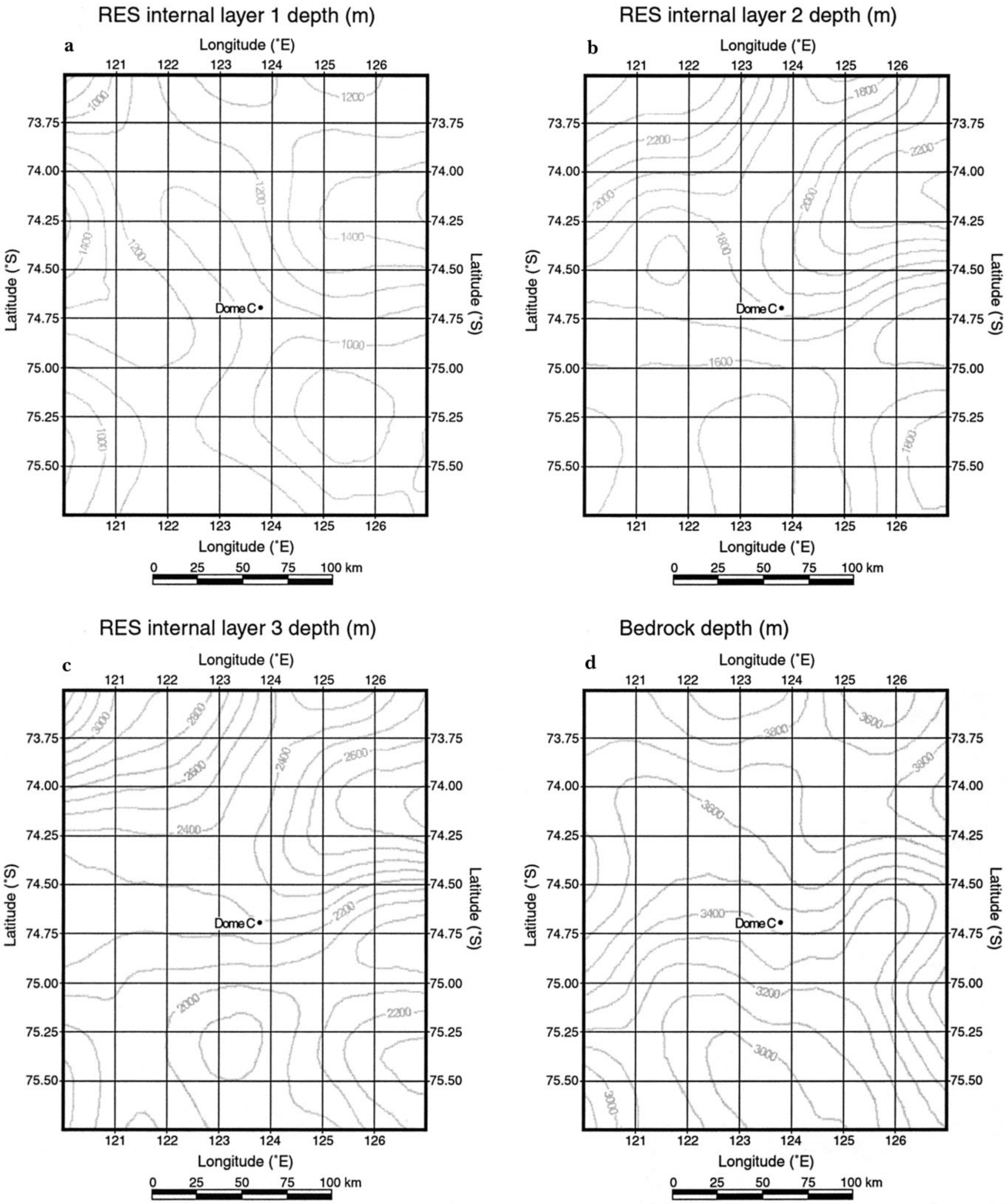

Fig. 4. (a) Depth of RES internal layer 1 (age 76 700 BP). (b) Depth of RES internal layer 2 (age 107 200 BP). (c) Depth of RES internal layer 3 (age 144 300 BP). (d) Depth of bedrock. Contours in metres. Ages are from radio-echo layer correlation with the Vostok ice core (Siegert and others, 1998a).

a scientific issue. The mapping of internal RES layers, as deformation markers, is therefore a valuable tool for ice-core studies. This is particularly true when the layers, which are inferred to be isochrons, can be dated (e.g. Siegert and others, 1998a), allowing ice from specified time intervals to be targeted.

Ice-core data are, by their nature, one-dimensional. However, ice within such cores is unlikely to have been deposited without subsequent three-dimensional movement. Ice divides are known to migrate because of interaction between ice loads, bedrock, surface elevation and accumulation. Thus, there is no guarantee that the EPICA ice core, drilled at the summit of Dome C, will sample ice from the ancient ice divide. At depth, the EPICA core may retrieve ice which has been subject to horizontal shearing that occurs away from the ice divide. This investigation now makes it possible to place the EPICA ice core within the three-dimensional context of the regional ice-sheet architecture.

At the site of the Dome C ice core, internal RES layers show that ice below about 1000 m has been subject to hori-

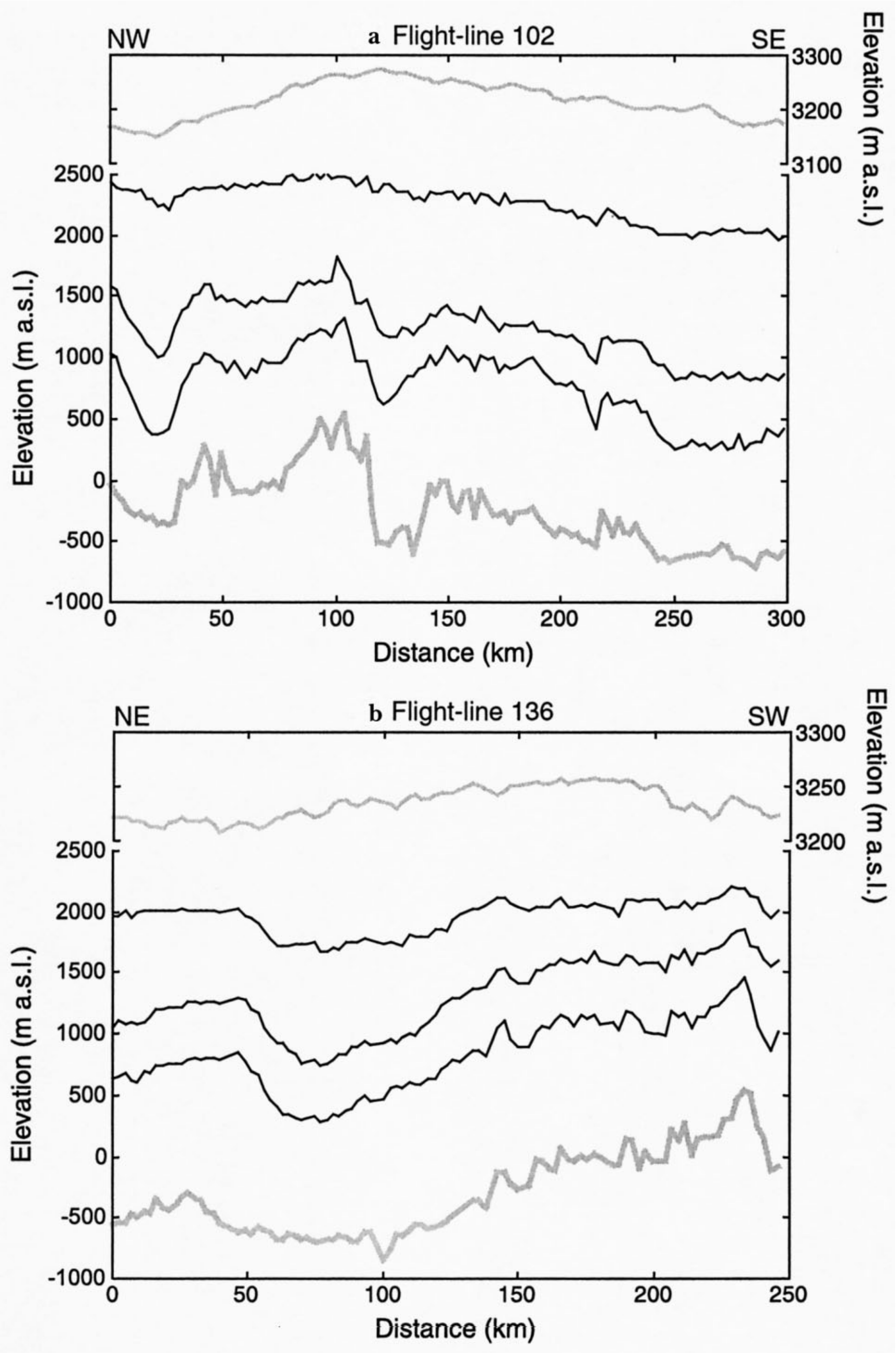

Fig. 5. Cross-sections showing ice surface, RES internal layers 1–3 and bedrock profiles in the study area along (a) flight-line 102 and (b) flight-line 136. Locations are given in Figure 3a. Note the separate scale for the ice-surface elevation on each profile.

zontal shearing, since the layers slope by 0.5–1.0°. Thus, unlike ice at the Vostok core, which is located over an extremely flat subglacial lake, ice from the Dome C core may be significantly sheared and strained due to subglacial bedrock relief. The maps presented here can provide a basis for determining the strain history of the ice column below Dome C. It should be noted that directly below Vostok station, internal layers are virtually horizontal (Siegert and others, 1998b).

CONCLUSIONS

Maps have been presented of three ice-sheet internal RES layers in a 56 000 km^2 region around Dome C, central East Antarctica. These maps can provide boundary conditions for three-dimensional ice-sheet models, taking advantage of information on internal ice-sheet structure and deformation, and allow ice-core data to be extrapolated over large areas (cf. Siegert and others, 1998a). In particular, they enable comparisons to be made between Dome C and other deep ice-core sites. RES layers from beneath Vostok station indicate that ice layering is virtually horizontal at the ice-core site. This is because the ice core is located over an extremely flat subglacial lake. At Dome C, however, where the ice-core site is located over bedrock, the maps of RES layers presented here indicate that ice below 1000 m is dipping by 0.5–1.0°. It is concluded that ice 1000–2000 m below the surface is, or has been, subject to deformation. This finding will be important when ice from the core is examined, and these maps will provide the glaciological context with which to identify the deformation history of the ice core and the Dome C region in general.

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REFERENCES

Drewry, D. J., *ed.* 1983. *Antarctica: glaciological and geophysical folio.* Cambridge, University of Cambridge. Scott Polar Research Institute.

Jouzel, J. *and 9 others*. 1989. A comparison of deep Antarctic ice cores and their implications for climate between 65,000 and 15,000 years ago. *Quat. Res.*, **31** (2), 135–150.

Jouzel, J. *and 16 others*. 1993. Extending the Vostok ice-core record of palaeoclimate to the penultimate glacial period. *Nature*, **364** (6436), 407–411.

Jouzel, J., G. Orombelli and C. Lorius. 1996. European Project for Ice Coring in Antarctica (EPICA). *Terra Antartica*, **3** (1), 49–54.

Lorius, C. *and 6 others*. 1985. A 150,000-year climatic record from Antarctic ice. *Nature*, **316** (6029), 591–596.

Millar, D. H. M. 1981. Radio-echo layering in polar ice sheets. (Ph.D. thesis, University of Cambridge.)

Paren, J. G. 1981. Correspondence. Reflection coefficient at a dielectric interface. *J. Glaciol.*, **27** (95), 203–204.

Robin, G. de Q., D. J. Drewry and D. T. Meldrum. 1977. International studies of ice sheet and bedrock. *Philos. Trans. R. Soc. London, Ser. B.*, **279** (963), 185–196.

Siegert, M. J. and J. K. Ridley. 1998. Determining basal ice-sheet conditions in the Dome C region of East Antarctica using satellite radar altimetry and airborne radio-echo sounding. *J. Glaciol.*, **44** (146), 1–8.

Siegert, M. J., R. Hodgkins and J. A. Dowdeswell. 1998a. 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** (7), 1019–1022.

Siegert, M. J., R. Hodgkins and J. A. Dowdeswell. 1998b. Internal radio-echo layering at Vostok station, Antarctica, as an independent stratigraphic control on the ice-core record. *Ann. Glaciol.*, **27**, 360–364.

Tabacco, I. E., A. Passerini, F. Corbelli and M. Gorman. 1998. Correspondence. Determination of the surface and bed topography at Dome C, East Antarctica. *J. Glaciol.*, **44** (146), 185–191.

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