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Determination of the surface and bed topography at Dome C, East Antarctica

The recent Greenland experiences, GRIP and GISP2 (Hodge and others, 1990; Hempel and Thyssen, 1993; Jacobel and Hodge, 1995), have confirmed the importance of surface topography, bed morphology and internal layer geometry in the selection of the best site for a deep drilling project. The ideal drill site would be marked, at the same time, by a flat surface at the regional summit (topographic dome), by a flat bed morphology, by continuous and horizontal internal layering and by absence of basal melting areas. This correspondence describes the topographic and radar measurements that were carried out in 1993 and 1995 over Dome C region, East Antarctica, as part of the site selection process for the deep drilling project EPICA (European Project for Ice Coring in Antarctica) — Dome C (Jouzel and others, 1996).

The first detailed topographic map at Dome C (contour interval 5 m), obtained by radar altimetry from the European remote-sensing satellite ERS-1, was provided by F. Rémy (Brisset and Rémy, 1996). A topographic dome roughly centred at 75°09′ S, 123°06′ E was evident; this position is about 65 km south of the old Dome C location (Drewry, 1983) corresponding to the U.S.A. Dome C camp. Because of the relative inadequacy of ERS-1 data in respect of the accuracy needed for drill-site location, it was decided to carry out a ground-based topographic survey in order to obtain a new topographic map over the dome area.

Previous radar data (Bentley and others, 1979; Drewry, 1983; unpublished data from Scott Polar Research Institute (SPRI)), concerning a 50 km × 50 km grid close to the old U.S.A. camp, on the northern side of the topographic dome, were acquired and analyzed. The data evidenced: (a) ice thickness of 3000–4000 m; (b) a very complex bed morphology; (c) continuous internal layering with a featureless lower zone of hundreds of metres; (d) three subglacial lakes, 3200–3400 m deep from surface, located about 20 km north of the dome summit. Because of the partial coverage of the dome area, and the inadequacy of the past radar data in respect of navigation system and grid spacing, it was decided to carry out a new airborne and ground-based radar survey in order to obtain new detailed information.

TOPOGRAPHIC SURVEY

During December 1993, topographic and geodetic measurements were carried out. The centre of the topographic dome obtained by ERS-1 was monumented and located in absolute geographic coordinates utilizing the DORIS system (Vincent, 1994). Around this point a global positioning system (GPS) survey was carried out in order to obtain a detailed topographic map of the summital area (Cefalo and others, 1994). The measurements were carried out in kinematic mode, using two Trimble 4000SEs, the first installed on a snowcat (rover), the second one (master) located close to the DORIS beacon, in order to have a good reference position for differential processing of data. To avoid passive trajectory, the survey was carried out on a "star" grid, centred on the DORIS point, composed of six rectangular isosceles triangles, with cathetus length of 20 km, rotated from each other by 60°. The total length of the GPS profiles was about 400 km. In 1995, another topographic map of a larger area (contour line interval 1 m), obtained by a newly available series of ERS-1 data which was merged with 1993 GPS data, was worked out by F. Rémy and R. Cefalo (Fig. 1); this map shows the asymmetry of the dome structure and suggests a regional ice divide oriented northeast–southwest.

RADAR SURVEY

The radar equipment was designed and built by M. R. Gorman of SPRI, Cambridge, U.K., in a development funded by the Italian Antarctic Programme (PNRA); some minor modifications and adjustments (balun, antennas, addition of GPS system, radio-frequency pulse alimentation) were carried out by an Italian team (F. Corbelli and A. Passerini). The radar utilises a digital pulse generator to generate a 60 MHz pulse of switchable duration (0.3 or 1.0 μs), at about 1 mW peak power. This is amplified by a solid-state power amplifier to more than 2 kW peak power. The receiver consists of a solid-state low-noise preamplifier, followed by a switchable-bandwidth successive-detection logarithmic amplifier. The dynamic range of this amplifier is 80 dB, and the output is digitised to 8 bit resolution, acquiring 512 samples spaced by 100 ns, for a total time range of 51.2 μs. The digitised data pass via an RS232 serial link to the control computer (IBM-compatible 80386SX, 40 MB hard disk).

The calibration test of the overall system shows a system performance of 150–160 dB (not including antenna gain), depending on pulse length and bandwidth settings. The same radar equipment was deployed both by aircraft and by snowcat. For airborne survey we employed a Twin Otter aircraft; a GPS Trimble 4000SSE system (L1 and L2 frequency), with geodetic antenna mounted on the fuselage, was installed and linked to the radar. The aircraft radar antennas used were folded dipoles under each wing, with one used for transmit, the other for receive. Antenna gain is estimated at 8.2 dB. For ground survey we used a snowcat, modified by a PNRA team (R. Buccolini and L. Blasi) and suited for GPS antenna and radar installation. The radar antenna was installed on a non-metallic sledge (designed and built by P. Godon, Institut Français pour la Recherche et la Technologie Polaire, Plouzane) to be towed by the snowcat. A master GPS station, synchronised with the rover, was installed at Dome C camp to enable differential correction of data.

Radar measurements were carried out on three grids (Fig. 2). The "big grid", used for airborne survey, is an 80 km × 120 km rectangular grid, with a spacing of 10 km between flight-lines, centred on the summit point, with the longer side parallel to the apparent dome axis. The "small grid", co-centred with the previous one, is a 50 km × 50 km square grid (line spacing 10 km), shifted by 5 km from the lines of the "big grid" in order to obtain in the central part of the area a final coverage with a spacing of 5 km between the flight-lines. The geometry of the "star grid" for ground-based measurements was similar to that used during the 1993 topographic survey. The total airborne survey length was about 2800 km, the ground-based one about 300 km. The grids were designed to have a large number of crossover check points between all the radar lines; we totalled about 240 crossover points.

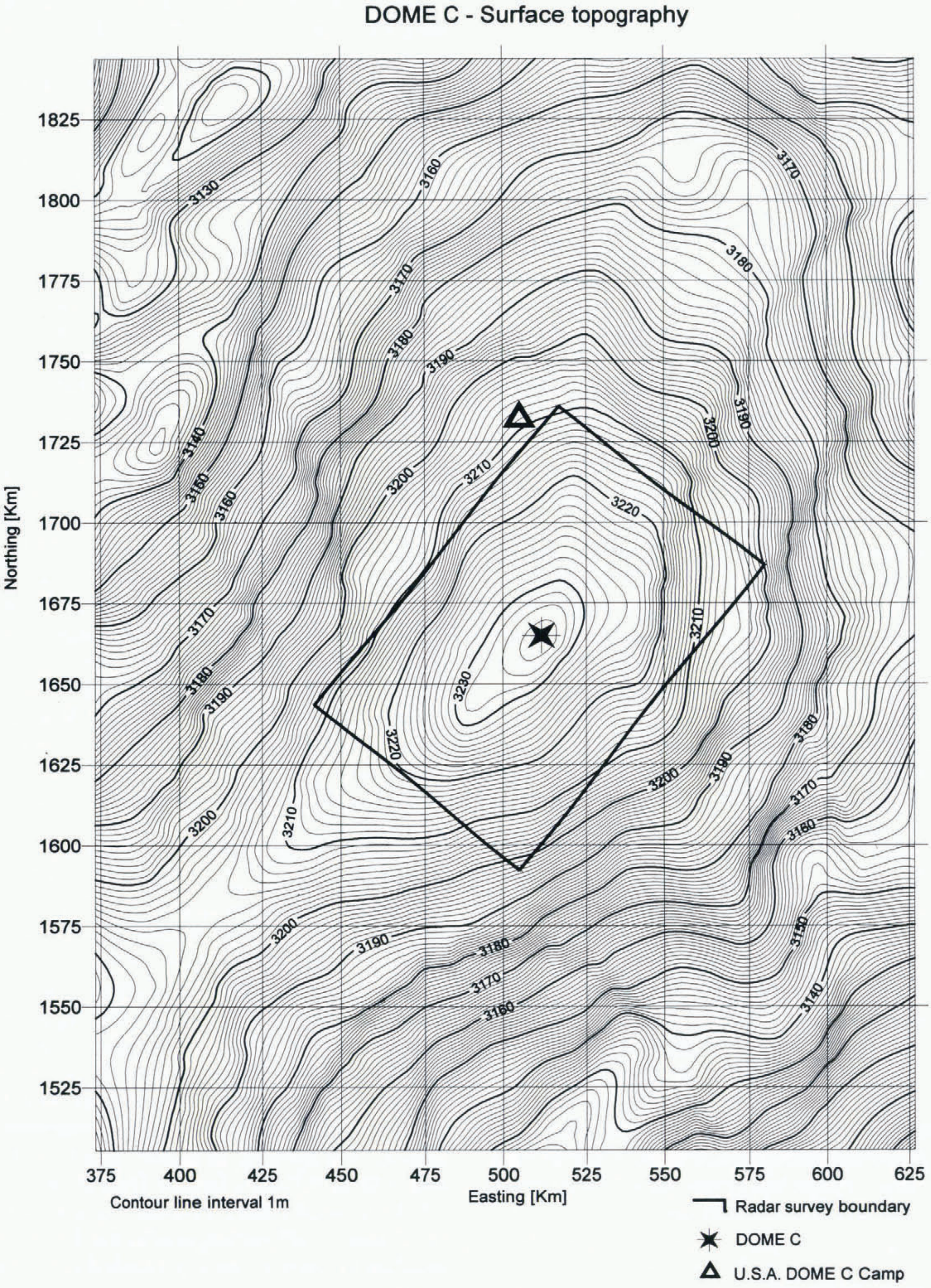

Fig. 1. Surface topography by ERS-1 and GPS.

RADAR DATA AND PROCESSING

The radar survey consisted of 34 profiles by air and 21 by ground. The airborne survey was achieved in four flights, with a cruising speed of 100–120 knots (185–220 km h^{-1}), at 1000 ft (305 m) average elevation over the surface (controlled by radar altimeter). Data were acquired using a pulse length of 1 μs, with an acquisition rate of 1 record/3 s, that is, 1 record/150–185 m. About 14 000 records were acquired by air. The ground-based survey was carried out with a travelling speed of 4–10 knots (7.5–18.5 km h^{-1}), with an acquisition rate of 1 record/6–15 m; in total, about 30 000 records were acquired. All the radar data were located by a synchronised GPS system with a precision in x, y coordinates of better than ± 20 m (only pseudo-range differential corrections were done).

All the radar profiles were processed with a software package specially designed for the new radio-echo sounder. A constant electromagnetic-wave propagation velocity of 168 m μs^{-1} was assumed (Robin, 1975; Patterson, 1981; Bogodorosky and others, 1985). Thickness value was determined to the nearest value of digit sample on the record, with a digitising error of ± 100 ns for both surface and bed reflections. This corresponds to an rms uncertainty of about ± 12 m in thickness. No corrections for higher velocity in the firn were calculated, which implies that all thickness values will be underestimated by very approximately 30 m. It is not possible to improve this estimate without informa-

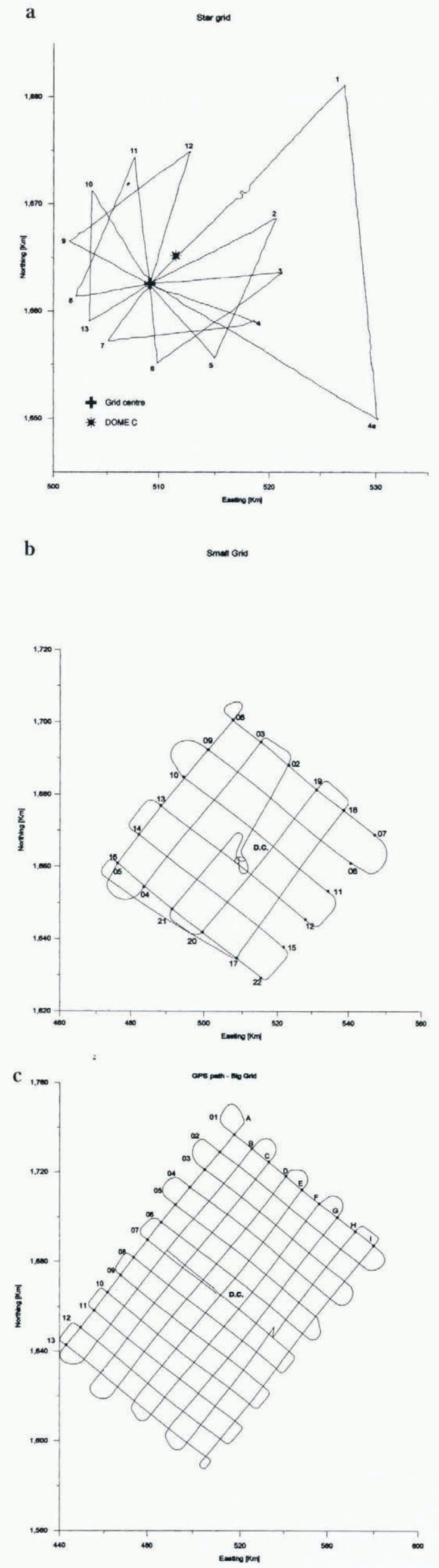

Fig. 2. Location of GPS tracks of radar grids. (a) GPS path "big grid"; (b) "small grid"; (c) "star grid".

tion on firn thickness and the density profile. Good-quality radar records were obtained over all the grids, with strong and unambiguous bottom returns; measured ice thickness was 2500–4000 m. Internal layering is apparent everywhere, mostly from 800 to 2800 m depth below surface. Normally the layering follows the bed topography with reduced amplitude; a featureless lower zone of about 700–800 m occurs over the deeper bed areas. The featureless zone is reduced to less than 300 m where the bed topography is higher. Four subglacial lakes were detected. One of them, at 74.91° S, 124.65° E, corresponds to Lake No. 25 of the inventory produced by Siegert and others (1996); the lake closest to the dome summit (74.95° S, 123.76° E) is about 20 km northeast. Examples of airborne radar lines are shown in Figure 3a–c. A ground-based radar line, located near the centre, is shown in Figure 4. Here the flat bed morphology appears to vary within a range of less than 100 m, at the mean ice depth of 3250 m. Horizontal and continuous layering is observed down to 2200 m depth; below this, until about 2500 m, the layering appears more irregular, and below this depth the internal layering disappears.

Comparative ice-thickness values at each crossover point of all the airborne and ground-based radar profiles (more than 220 points) were calculated; they presented differences of less than 10 m, i.e. less than the estimated accuracy in thickness determination. A first grid with averaged values of crossing points was calculated. Over the whole area, 3800 ice-thickness values were calculated, about 1800 (spacing 1500 m) on the flight-lines and about 2000 (spacing 150 m) on ground-based ones. Different gridding methods were used; each gridding result was compared with the crossover-point dataset. The best results were obtained by the minimum curvature method that gave minimum differences with the crossover-point depth.

In order to calculate the bed topography, a new detailed surface map of the "big grid" area (minimum curvature gridding) was worked out (Cefalo and others, 1996). This map was obtained by merging the 1994 ERS-1 data with all the GPS and DORIS values. Slight differences with the Cefalo 1994 map were observed and the new summit of the dome was fixed at 75°06′06″ S, 123°23′42″ E. By subtracting thickness values from the surface topography a bed map was obtained (Fig. 5). A tridimensional view of the area with surface and bed topography is presented in Figure 6. The maps are World Geodetic System 1984 ellipsoid (WGS84) referenced, and elevation values refer to height above ellipsoid (HAE).

CONCLUSIONS

With regard to the main aim of the work, i.e. the drilling-point selection, we can conclude:

Bed topography

The plateau located over the central part of the area (at a mean elevation corresponding to zero HAE) is bounded eastward by a well-defined system composed of a deep valley and a parallel sharp ridge oriented north–south. South and southwest it is surrounded by a complex chain of mountains reaching a maximum altitude of about +500 to +700 m. Northward the plateau is bordered by a system of smooth hills (reaching a maximum altitude of +100 m), then gently deepens to −300 m without prominent obstacles.

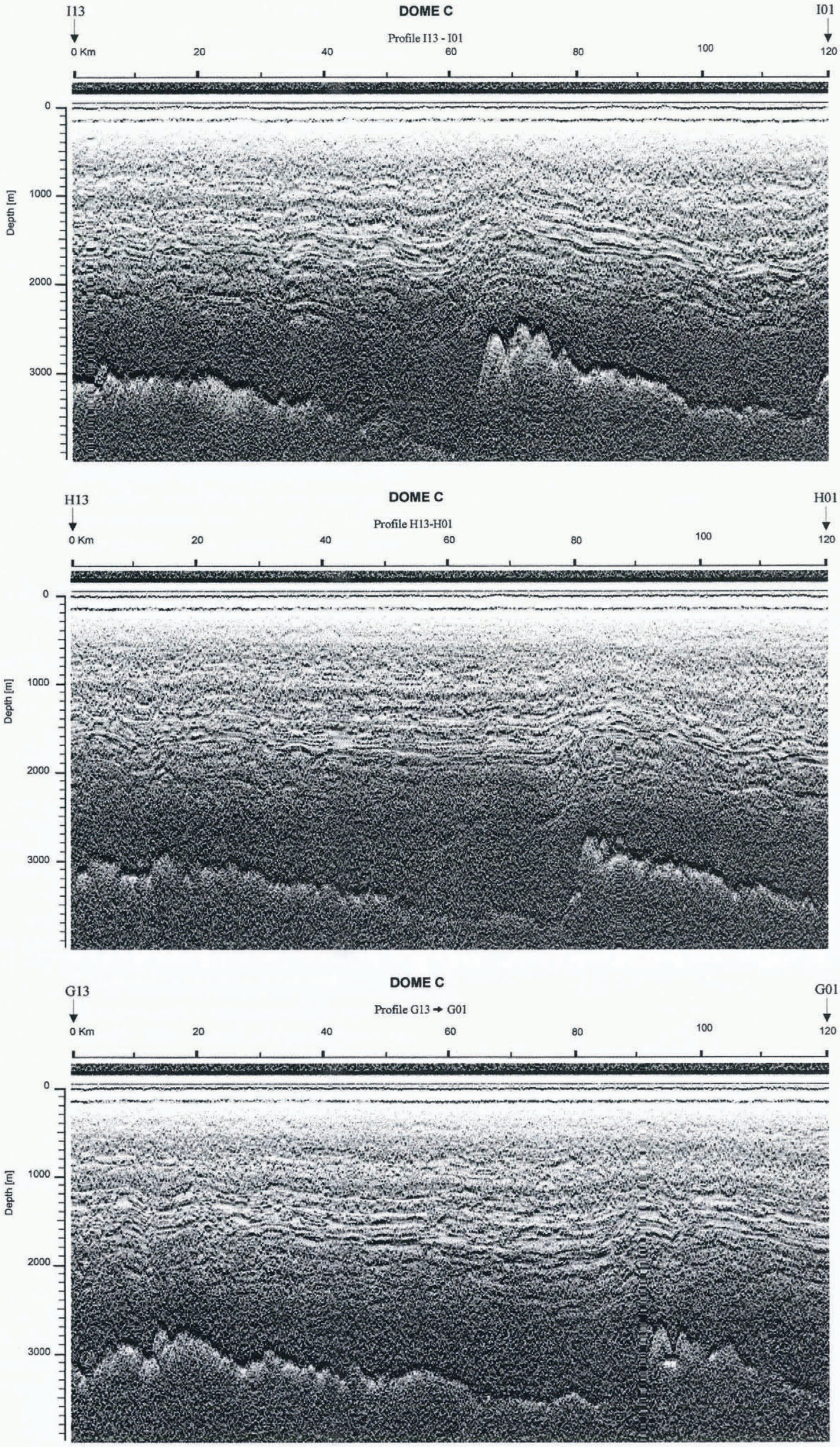

Fig. 3. Examples of airborne radar records. For flight location see Figure 2a.

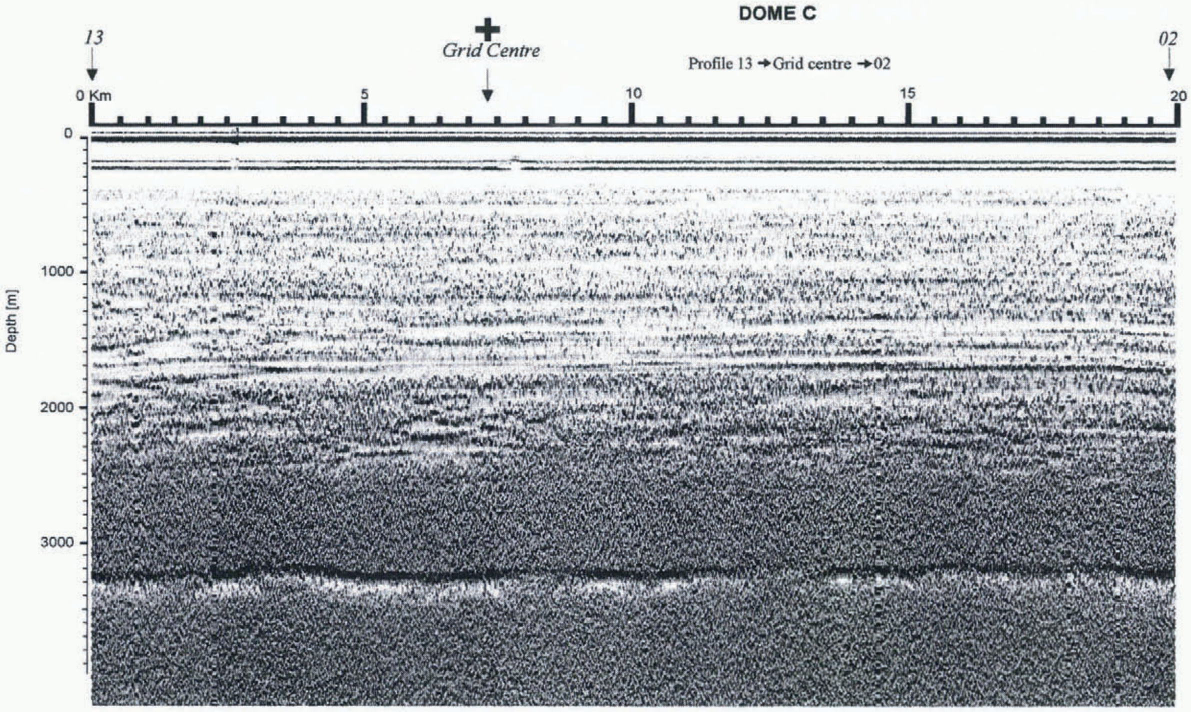

Fig. 4. Example of ground-based radar records. For profile location see Figure 2c.

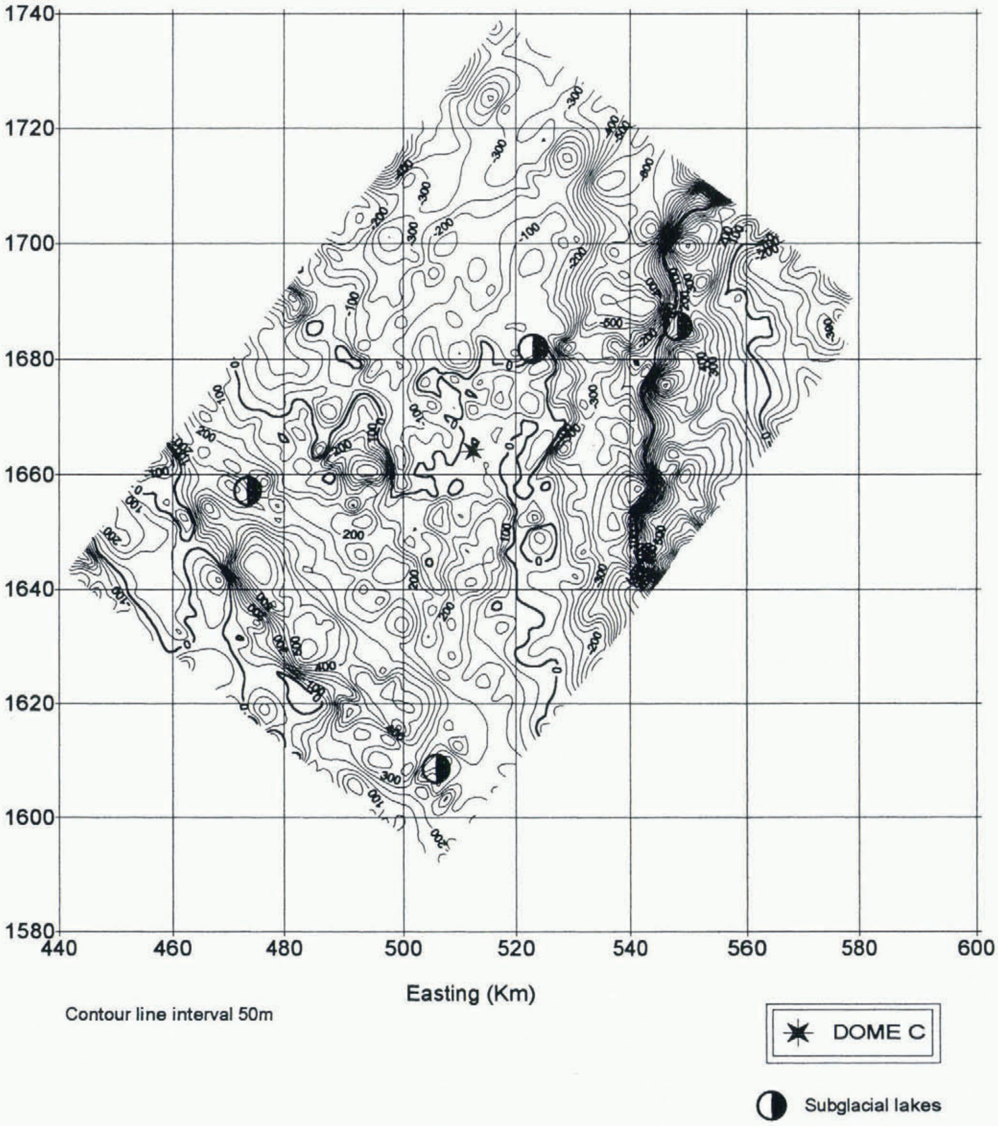

Fig. 5. Bed topography. Height above WGS84.

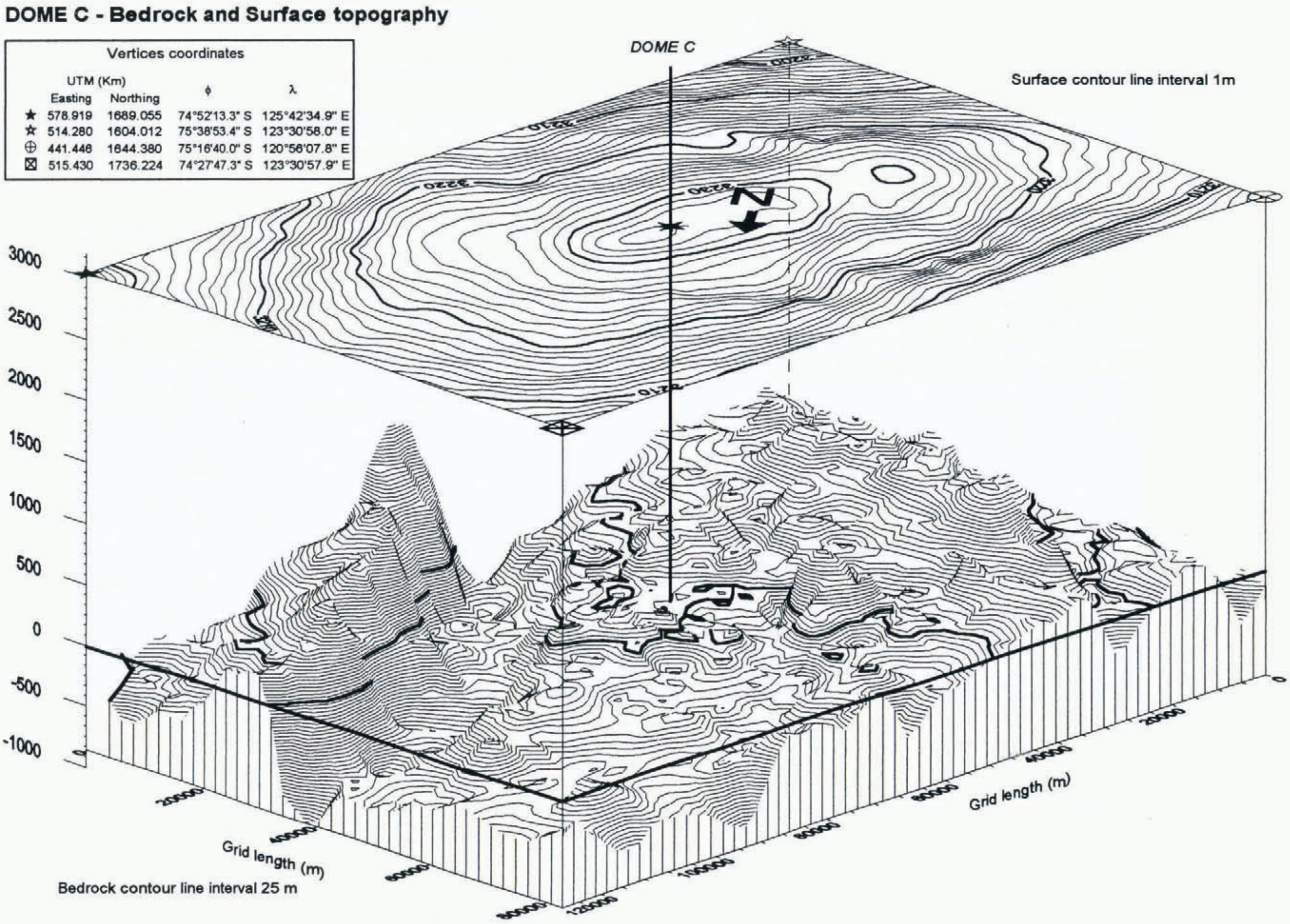

Fig. 6. Tridimensional view of surface and bed topography. Height above WGS 84 (bold line on bed topography indicates ellipsoid elevation).

The north–south valley, with a width of about 15 km, deepens northward from −200 to −600 m; its eastern side is steeper than the western one. The altitude of the main four summits of the north–south ridge ranges from +400 to +700 m. The relative elevations of valley plateau and valley ridge are respectively about 400 and 1000 m; the morphologic appearance suggests a tectonic-fault angle depression.

Surface topography

The dome surface and the topographic summit (3233 m HAE) is defined. The lowest surface altitude (see Fig. 1) is 3100 m, giving a maximum surface altitude range of 130 m over the entire 80 000 km^2 area. In the central sector, over the bedrock plateau, the surface slope values are less than 0.0001. A good correlation between the surface slope and the main morphological features of the bedrock is evident over the whole area.

Internal layering

Over the central area, internal layering is continuous and horizontal until about 2200 m depth; two main reflectors with strong echoes at 1700–1800 and 2100–2200 m depth are observed; discontinuous layers from 2200 to 2500 m are occasionally detected. Over areas with complex morphology, internal layers follow the bed topography with smoothed slope; on the restricted areas over the ridges, the continuity of internal layering is interrupted.

Subglacial lakes

The four subglacial lakes detected by the present radar survey, and all the other lakes of Siegert and others' (1996) inventory are located in marginal areas with respect to the central part of the dome. The closest one is about 20 km distant from the dome summit.

Final conclusion

The area close to the topographic summit has, at the same time, flat bed morphology, horizontal internal layering and no subglacial lakes. Considering in addition that the central bedrock plateau is protected and isolated by local ridges, we conclude that the summit dome area can be considered a good location for the drilling project. The proposed Dome C drilling site is: coordinates 75°06′06″ S, 123°23′42″ E; elevation 3233 m; ice thickness 3250 ± 25 m.

ACKNOWLEDGEMENTS

We dedicate this work to the memory of the crew of Twin Otter C-GKBD and its captain, J. C. Armstrong. They were en route to the Italian station to work with us at Dome C. All were killed when the aircraft crashed on take-off from Rothera Station on the night of 23 November 1994. Perpetual honour to their memory. We thank the French-Italian logistic team, and P. Delay (traverse leader), P. Godon and U. Ponzo for their decisive and enthusiastic support.

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SIR,

Comments on "Some comments on climatic reconstructions from ice cores drilled in areas of high melt" by Roy M. Koerner

Koerner (1997) presents an interpretation of ice-core data collected from the circumpolar Arctic. As a member of a Russian research team, I was involved in the coring and study of some of the ice cores referenced in his paper. The results of our research were published in the Russian scientific literature. This letter presents relevant data not included in Koerner (1997), and corrects a few inaccuracies. This additional information should contribute to a clearer understanding of the complexity of the ice-formation processes in glaciers subjected to intensive melting.

DATA

Lomonosovfonna. Three locations were studied along the ice divide on Lomonosovfonna. In the southern part of the plateau at 1025 m a.s.l., Zinger and Mikhalev (1967) determined the average accumulation rate to be 988 mm w.e. a^{-1} for the period 1957–64. The 201 m ice core was recovered in 1976 in the northwest part of the plateau at about 1080 m a.s.l.; results were published in Gordienko and others (1981). Because the thickness of the ice is unknown, the time-scale based on stable isotopes remains questionable. The firn–ice transition at the 1976 drilling site was in the depth range 27–32 m (Zagorodnov, 1985). In addition, a 135 m ice core was recovered in 1982 from a site (about 1000 m a.s.l.) approximately 10 km south of the 201 m core. This borehole was plumb from surface to bottom (Zagorodnov and others, 1984). Melt features comprised 34% of the glacier sequence, and the 1975–82 balance was 620 mm w.e. a^{-1}; for the period of 1962–82 the average balance was 658 mm w.e. a^{-1} (Zagorodnov and Samoylov, 1985). Note that Koerner (1997, table 1) gives the balance for the 1976 drilling site as 820 mm w.e. a^{-1}.

Austfonna. The elevation of the drilling site on the Austfonna summit was close to 750 m a.s.l. (Dowdeswell, 1986; Dowdeswell and others, 1986; Arkhipov and others, 1987; Dowdeswell and Drewry, 1989). The 566.7 m ice core was recovered from a plumb borehole. Mass-balance data for the drilling site are presented in Table 1. Assuming that the tritium peak at 14 m was from 1963 (Vaykmyae and Punning, 1989), the average (27 year) mass balance was 526 mm w.e. a^{-1}; without tritium data the average (5 year) balance was 598 mm w.e. a^{-1}. Both these values are lower than 794 mm w.e. a^{-1} given by Koerner (1997, table 1).

The melt scale for the Austfonna record appears to be incorrect and the curve given by Koerner (1997, corrected fig. 4) appears shifted. Using data from Tarussov (1992), and assuming that the profile was digitized from Zagorodnov and Arkhipov (1990) or from Kotlyakov and others (1990), with a net accumulation of 794 mm w.e. a^{-1} (Koerner, 1997, table 1), the Austfonna melt record presented by Koerner (1997) cannot be reproduced; melt values exceed the net accumulation. A similar problem exists in the Akademii Nauk melt record. The original percentage melt record was obtained from two ice cores, one drilled in 1985 (0–561 m) and the other in 1987 (250–761 m). These melt records are internally consistent. Using the melt percentage profile (Kotlyakov and others, 1990) and assuming annual net ac-