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Three-dimensional ice sheet structure at Dome C, central East Antarctica: implications for the interpretation of the EPICA ice core

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Abstract: Airborne radar data acquired in 1995 by the Italian Antarctic Programme over Dome C in central East Antarctica were processed to develop maps of internal isochronous ice sheet layering around the EPICA ice core site. Three internal layers were traced continuously across the radar-survey area at ice depths of 1–2 km. The maps reveal that the ice core site is located where internal layers are near horizontal to depths of at least 2 km. The Italian radar data do not resolve internal layers below 2 km. However, radar data collected over this part of East Antarctica in the 1970s show the internal layers to depths of up to 4 km. These internal layers reveal the regional structure of ice to the west of Dome C. Layers from both surveys are dated through an existing chronostratigraphic link between the Vostok ice core site and Dome C. The pattern of internal layering at Dome C reflects relatively steady conditions of ice flow and accumulation for the last 100 000 years. However, for ice older than this we show that there is significant local variation in the thickness between internal layers and the ice-sheet base. Our maps provide an indication of the structure of the ice sheet from which the EPICA deep ice core will be taken.

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Key words: East Antarctica, ice cores, radar layering

Introduction

In 1998, the European Project for Ice Coring in Antarctica (EPICA) began extracting an ice core at the summit of Dome C in central East Antarctica. This ice core will, over the next few years, sample the whole ice column (3250 m thick) and will provide detailed palaeoclimate information over several glacial–interglacial cycles (Jouzel *et al.* 1996). Crucial to the interpretation of the ice core is the 3-D structure of the ice sheet since it may provide an insight into the present day and past flow of ice. The location of the EPICA coring site was established after a detailed airborne radar survey, undertaken by the Italian Antarctic Programme, revealed the ice surface and subglacial topography (Fig. 1) (Tabacco *et al.* 1998). The Italian radar survey covered a 80 × 120 km region of Dome C, using 33 transects aligned in a grid with a 5–10 km spacing (Fig. 1). However, the isochronous internal layering that was also recorded in this survey did not play a significant role in the location of the ice core. By analysing internal layers from these Dome C radar data, we have calculated the spatial distribution of three isochrons around the ice core site revealing an accurate representation of ice sheet structure at this location.

The relatively small area covered by the Italian radar survey means that the wider pattern of internal layering must be determined from another source. Previous investigations of internal radar layering at Dome C used analogue radar data collected in the 1970s by the Scott Polar Research Institute (SPRI) (Drewry 1983, Siegert *et al.* 1998, Hodgkins *et al.* 2000). Although the SPRI radar data cover a large area of Dome C, they are limited to eight transects separated by between 25 and 75 km. Thus, the spatial quality of 3-D layering extracted from the SPRI data is restricted. However, along individual radar lines, the SPRI data can be used effectively to determine patterns of internal layering. In this paper, we analyse one SPRI radar line, aligned across the crest of the Dome C ice divide, to provide information on the internal layering outside the study area of the Italian radar survey.

Processing radar data

Internal radar layers occur when there is a change in the dielectric properties of ice (see Fujita *et al.* 1999 for a recent review of the causes of radar layering). At ice depths greater than 1 km, near the centre of an ice sheet, internal layers are caused primarily by acidic bands of ice formed by an aerosol deposit on the ice surface from a large volcanic event (Fujita *et al.* 1999). The apparent thickness (separation) of a radar layer is dependent on the pulse width of the radio wave. The resolution of the Italian radar data is limited by the radio-wave pulse width of 1 μs, which represents about 40 m in ice. The vertical resolution of the Italian radar data is also limited by the digitizing frequency, which records pixels at about 8 m intervals. Our findings should be considered with these limitations in mind. Tabacco *et al.* (1998) judge their radar

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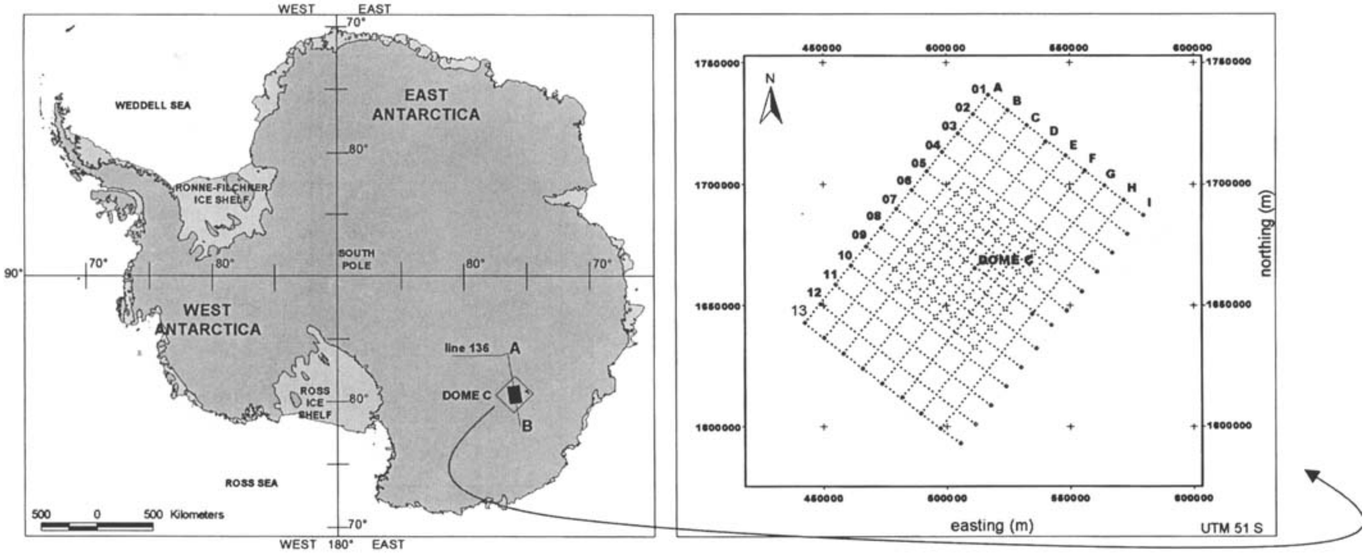

Fig. 1. The location of Dome C and the position of Italian and SPRI radar lines used in the analysis of internal layering. The arrangement of the Italian radar survey of Dome C is also provided.(numbers and letters refer to flight legs). Note that the survey area has been rotated by approximately 135° counter-clockwise in the right hand diagram, and in all later diagrams, so that the North arrow is vertically aligned.

data to be accurate to ± 25 m of ice thickness, whilst the accuracy of the SPRI data has been estimated at 1% of ice thickness (e.g. Rose 1978), which corresponds to about 30 m at the EPICA ice core site.

Internal radar layers are often continuous over large distances in Antarctica. Several of such layers have been traced between Dome C and Vostok Station (Siegert *et al.* 1998) and between Vostok Station and Titan Dome (near South Pole) (Siegert & Hodgkins 2000). We were able to trace three internal layers continuously across all flightlines in the Italian radar survey (Fig. 1) using methods discussed in Hodgkins *et al.* (2000). The depths of these layers were extracted from the radar data, and used to construct maps of isochronous surfaces. In doing so, the 3-dimensional structure of the ice sheet was established.

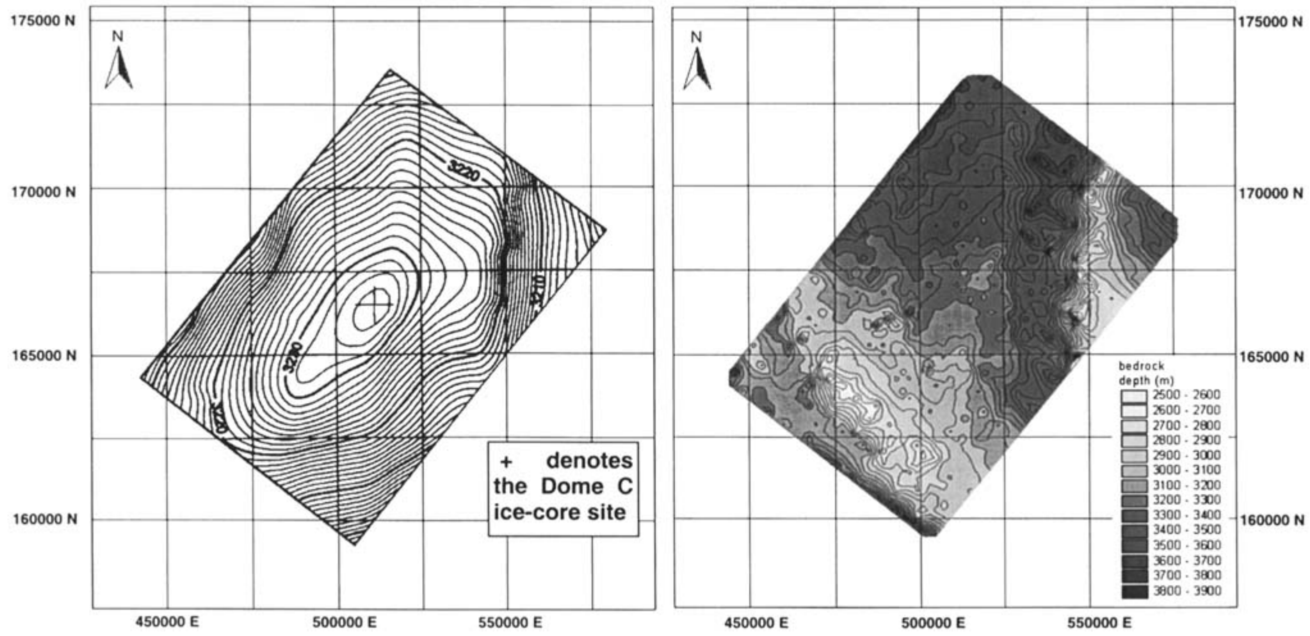

Fig. 2a. Ice-sheet surface across Dome C, established from ERS-1 altimetry. Contours provided in 1 m intervals. **b.** Subglacial bed elevation in the Dome C region, derived from Italian radar data. Adapted from Tabacco *et al.* (1998) and Rémy & Tabacco (2000).

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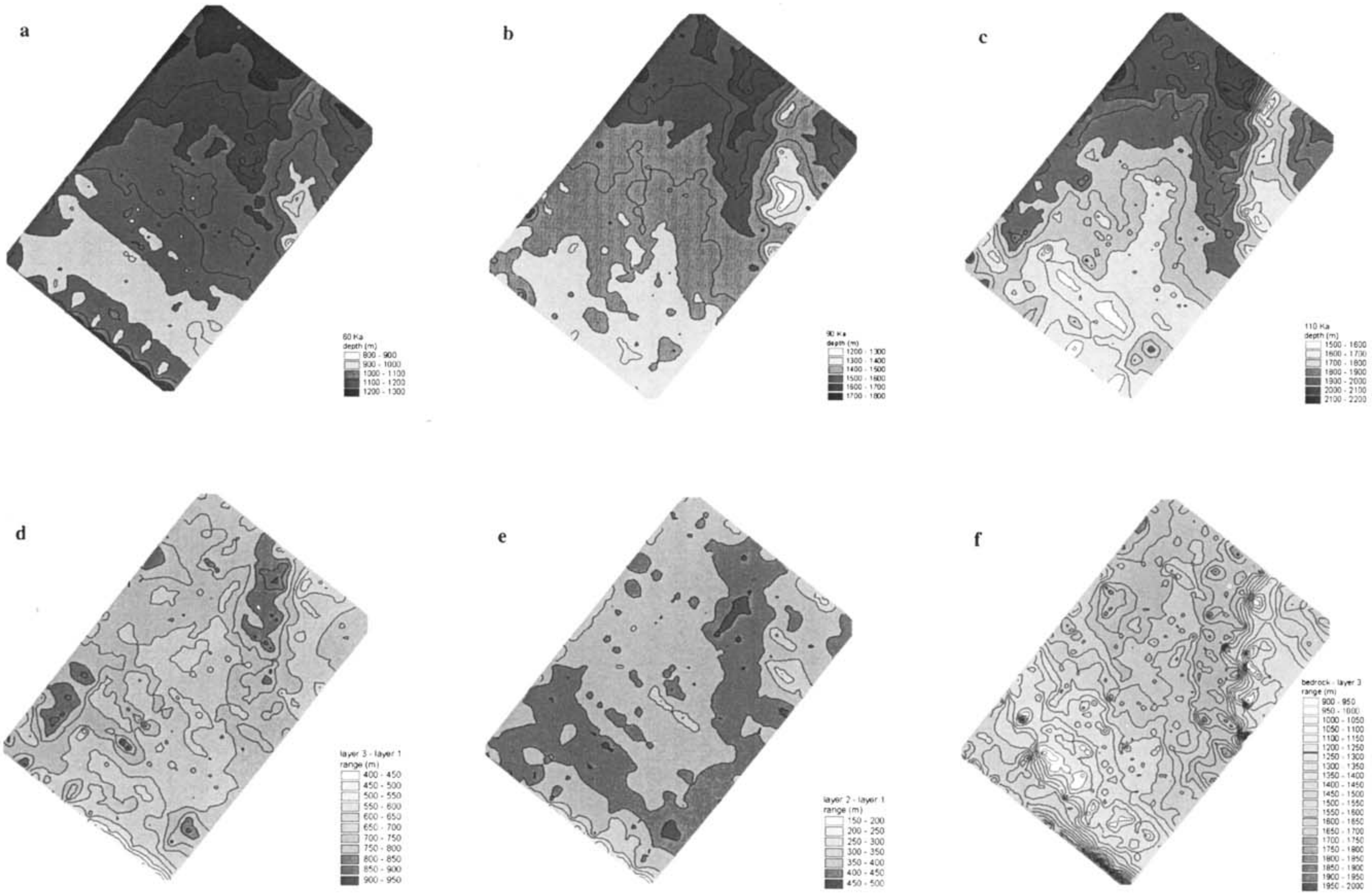

Fig. 3. Maps of internal layering across the Italian radar survey region. **a.** Layer 1 (*c.* 60 ka), **b.** Layer 2 (*c.* 90 ka), **c.** Layer 3 (*c.* 110 ka). Also provided is the variation in ice thickness between internal layers across the survey region as follows. **d.** Layer 1 and Layer 3, **e.** Layer 1 and Layer 2, **f.** Layer 3 and bed. When viewing these maps it should be remembered that the resolution of the Italian radar data is limited by (1) the radio-wave pulse width of 1 μs, which represents about 40 m in ice and (2) the digitizing frequency, which records pixels at about 8 m intervals.

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The pattern of internal layering is affected by the flow of ice over bed topography, the accumulation of ice and, in some circumstances near an ice divide, the non-linear flow of ice (Vaughan *et al.* 1999). The bed influence on isochrons is greatest in the lower parts of the ice sheet. In the upper regions of the ice sheet the pattern of internal layering is influenced more by past rates of ice accumulation. The surface of the ice sheet may still retain a signature from the underlying bed, but this will be damped in accordance with Budd & Carter (1971), such that the further up the ice column one goes, the less the impact of the bed relief on internal layering becomes. By analysing the normalized depth of internal layers (i.e. the depth of an internal layer as a fraction of the total ice thickness), the effect of the bed can, to an extent, be taken out.

Local 3-D structure of the ice sheet around the EPICA site

The ice-sheet surface and subglacial bed elevations across Dome C were established from ERS-1 altimetry and two ground-based GPS surveys carried out in 1993 and 1995 (Tabacco *et al.* 1998) (Fig. 2). The large-scale subglacial topography within the Italian radar survey area includes two large subglacial ridges (that are branches of the Belgica Subglacial Highlands in the south, and the Resolution Subglacial Highlands in the north), each with amplitudes of over 500 m. The ridge in the northern side of the survey, trending northwards, has a 500 m deep, 15 km wide trench along its western flank (Fig. 2). Detailed maps of the internal layering across the Italian radar survey area are provided in Fig. 3. Internal layers ride over both of these ridges converging vertically over the crests and diverging in the valleys. For example, the thickness between internal Layer 1 and Layer 3 over the ridge within the Resolution Subglacial Highlands is 600 m, whereas over the adjacent trench it is as much as 800 m (Fig. 3d).

The summit of Dome C is located between the two ridges, above the Vincennes Subglacial Basin. The exact location of the EPICA drill site is above a region where the ice sheet base undulates smoothly with amplitudes of around 300 m and lengths of around 10 km (Fig. 2). Internal layers are extremely planar across this part of the basin, and the thickness between Layer 1 and Layer 3 varies by only about 50 m. The Italian radar data show that the EPICA ice core will sample layers of ice with a virtually horizontal alignment (the actual gradient is around 1 in 300 from south-west to north-east) to depths of at least 2000 m below the ice surface (Fig. 3). The radar data acquired in the Italian survey cannot usually resolve internal layers below this depth.

Ages are assigned to our isochron maps from the stratigraphical correlation between the Vostok ice core site (and therefore the depth–age function calculated for the ice core) and Dome C, detailed in Siegert *et al.* (1998). Layer 1 has an age of *c.* 60 ka, layer 2 is *c.* 90 ka and Layer 3, the lowest layer traceable in the Italian radar data, is aged *c.* 110 ka.

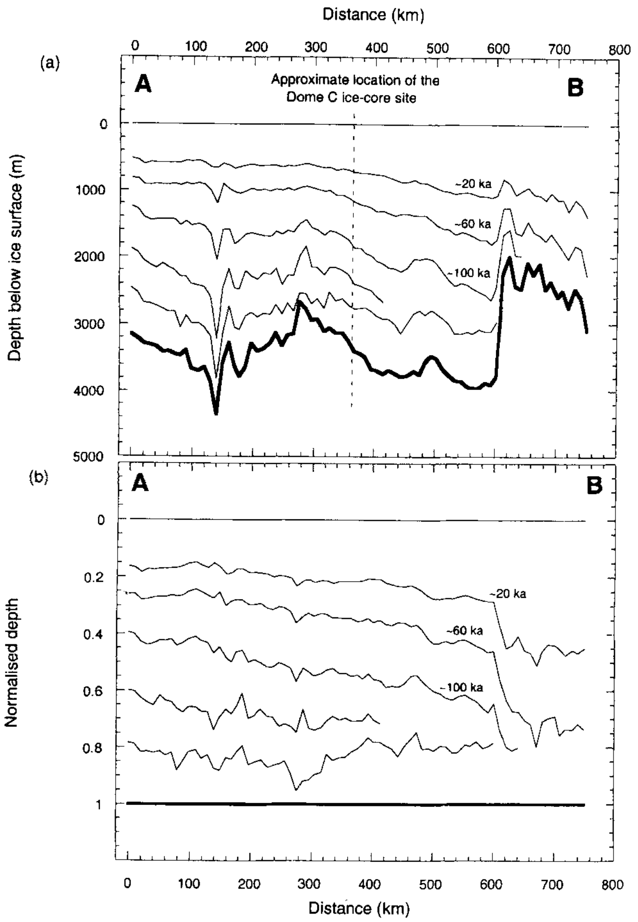

Fig. 4a. The spatial distribution of internal layers along a SPRI radar transect from the Aurora Subglacial Basin to the Resolution Subglacial Highlands. The three uppermost internal layers correspond to isochrons at *c.* 20 ka, *c.* 60 ka and *c.* 100 ka. No date is assigned to the deepest internal layers since they are below the part of the ice sheet covered by the Vostok to Dome C stratigraphic link in Siegert *et al.* (1998). The location of the EPICA ice-core site is indicated. **b.** Normalized depths of internal layers.

The relief displayed in our three maps of internal layering gets greater with ice depth, as expected. Near the base of the ice sheet, the relief shown in the internal layers matches well to the bed relief.

Regional variation in internal layering

By analysing internal layers across the ice sheet using the SPRI radar data, we are able to detect the deep regional isochronal structure of the ice-sheet around Dome C. One 800 km long SPRI transect across Dome C (Fig. 1) is particularly useful because it is aligned along the crest of the ice sheet. We can therefore be confident that ice flow will be parallel to this SPRI transect.

Between the Aurora Subglacial Basin (the left hand margin of the radar transect in Fig. 4a), 400 km to the south-west of

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the EPICA ice core, and the Belgica Subglacial Highlands (150 km to the south-west), the normalized depth of all internal layers is generally deeper towards Dome C (Fig. 4b). Widespread variation in ice thickness between internal layers in the upper 2 km of the ice sheet is likely to be due mainly to changes in accumulation over time across the radar transect.

The SPRI radar data show that all normalized internal layers dip downwards from 300 km west of Dome C to the EPICA ice core site (Fig. 4). The normalized pattern of internal layering indicates that, over the past 100 ka, 20% more ice (relative to total ice thickness) has built up at the ice core site compared with ice currently located over the Aurora Subglacial Basin, at the south-western end of the radar transect. Further downstream over the Vincennes Subglacial Basin, internal layers above the 100 ka isochron continue this steady pattern of divergence in normalized depth, suggesting that the increase in accumulation from south-west to north-east in the last 100 ka has been steady over this period across the Dome C region.

However, below the 100 ka isochron there is a very distinct change in internal layers from the south-west of the Belgica Subglacial Highlands to those across the Vincennes Subglacial Basin. Whereas over the highlands they are aligned similarly to younger layers above, over the basin they are non parallel to the younger internal layers. Around the EPICA ice core site, the internal layers older than 100 ka diverge from the ice-sheet base, and converge with layers above (Fig. 4). This results in a decrease in ice thickness between the 100 ka isochron and the lowest measurable internal layer of 50% from the start of the transect (over the Aurora Subglacial Basin) to the EPICA ice-core site.

The normalized pattern of internal layering for ice younger than 100 ka is largely unaffected by large-scale topography, with the exception of the very large subglacial hill located 250 km to the north-east (downstream) of the EPICA ice core site. Above this hill the 100 ka isochron is located close (< 300 m) to the ice base (Fig. 4). The thickness of ice older than 100 ka is controlled to a large extent by subglacial topography. Around the EPICA ice-core site there is over 1.5 km of ice older than 100 ka. However, over the subglacial hill downstream of the ice core site, there is less than 300 m worth of ice older than 100 ka.

Conclusions

Accurate maps of internal ice-sheet layering have been produced around the EPICA ice core site. Three isochronous planes were traced, with ages of 60 ka, 90 ka and 110 ka assigned through a correlation with the Vostok ice core (Siegert *et al.* 1998). The radar data used to construct these maps do not resolve internal layers older than 110 ka. However, radar data collected in the 1970s resolve deeper internal layers well. Our analysis of internal radar layering across the Dome C ice divide reveals a number of features about the ice sheet relevant to the interpretation of the EPICA ice core.

- The internal layer maps show that near-horizontal ice layers are to be expected in the EPICA ice core to depths of at least 2 km (to an age of around 110 ka).
- Regional internal layers around Dome C submerge, and diverge from each other in vertical section, from west to east across the ice core site, largely as a consequence of the pattern of ice accumulation (Fig. 4), with little noticeable effect from subglacial topography.
- The pattern of internal layering for ice older than *c.* 100 ka is similar to younger layers above across the Aurora Subglacial Basin, but distinctly different downstream across the Vincennes Subglacial Basin. The transition between these two patterns is related to subglacial topography (the two basins being separated by a branch of the Belgica Subglacial Highlands).
- Below *c.* 2 km at the EPICA ice core site, the structure of the ice sheet changes from that affected by the past accumulation of ice, to that controlled to a large degree by subglacial topography and, probably, former ice flow.

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