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A stratigraphic link across 1100 km of the Antarctic Ice Sheet between the Vostok ice-core site and Titan Dome (near South Pole)

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Abstract. Isochronous internal ice-sheet layering, measured from airborne 60 MHz radar, was traced between Lake Vostok and the Titan Ice Dome (100 km from South Pole Station), Antarctica. Three layers were selected between Ridge B and Titan Dome, and between Ridge B and Lake Vostok. This layering can be used to correlate the existing Vostok ice core across 1100 km of the ice sheet interior. Our correlation is also matched to the new EPICA ice-core site, by using an existing radar link between Vostok and Dome C stations. Thus, three East Antarctic ice domes are linked stratigraphically for the first time through internal ice-sheet radar layering. Our results indicate that the basal layers of ice at Titan Dome are around 165,000 years old suggesting that this location and, by inference, the South Pole Station, are prime sites for a high-resolution ice core from the last glacial-interglacial cycle.

Introduction

Deep ice cores from the centres of large ice masses yield detailed paleoenvironmental information spanning several hundred thousand years of recent Earth history. For example, the Vostok ice core holds climate data for the last 420,000 years [*Petit et al.*, 1999]. In order to establish as comprehensive a history of palaeoclimate as possible, records from ice cores separated by several hundred kilometers need to be correlated. To date, Be^{10} markers, volcanic horizons and dust layers within the ice have provided an effective means to compare ice-core information. The use of radar layering not only links ice cores stratigraphically, but details the spatial behaviour of the ice column across the ice sheet.

Internal ice-sheet radar layering at 60 MHz is caused by electromagnetic-wave reflections from boundaries of dielectric contrast. Such boundaries are caused by (1) ice density variations to an ice depth of 800 m (2) horizons of relatively high acidity formed from the aerosol product of large volcanic events contained within ancient snow and (3) crystal orientation fabrics [*Fujita et al.*, 1999]. Internal layers below 800 m observed in 60 MHz radar are believed to be isochronous, and traceable over several hundred kilometers [*Millar,* 1981; *Siegert et al.*, 1998; *Fujita et al.*, 1999]. Radar layers are readily identifiable in the archive of radar data held at the Scott Polar Research Institute (SPRI) in Cambridge. These data cover over 400,000 km of track across 40% of the East Antarctic Ice Sheet.

The Vostok ice core has already been matched to the EPICA ice-core site at Dome C through radar layering [*Siegert et al.*, 1998]. Five internal radar layers were traced along a flightline between Vostok and Dome C. The internal layering showed that 300 m more ice was present at Dome C for the last glacial-interglacial cycle than in the Vostok core. Moreover, the depth-age profile at Dome C (adjusted from Vostok) supported flow model results indicating that the base of the Dome C core would be significantly older than the Vostok ice core base [*Siegert et al.*, 1998]. Thus, internal layer correlation between Vostok and Dome C has provided a useful guide for the EPICA ice core and its relationship to the Vostok core [*Hodgkins et al.*, in press].

Titan ice dome is located about 100 km from South Pole. In this paper, a new internal ice-sheet radar layer link is made between Titan Dome and Vostok Station. In doing so, three major ice divides (Dome C, Ridge B and Titan Dome) in Antarctica are linked directly for the first time.

Correlating internal radar layers across the ice sheet

Titan Dome is linked to the Vostok Station by radar flightlines as follows (Fig. 1). One airborne radar flightline between Ridge B (200 km from Vostok Station) and South Pole was examined to identify a radar link between these sites (line 121). The radar line at Ridge B is crossed by a further radar line (line 009) which is aligned along the line of ice flow from Ridge B to Vostok Station and, therefore, the ice core site. We also link an unnamed ice dome, referred to here as 'Dome X', located 100 km from South Pole, to the Vostok ice core by radar data along lines 133 and 009 (Fig. 1).

Because the radar data are in the same format, the method used to trace internal layers in this paper is detailed

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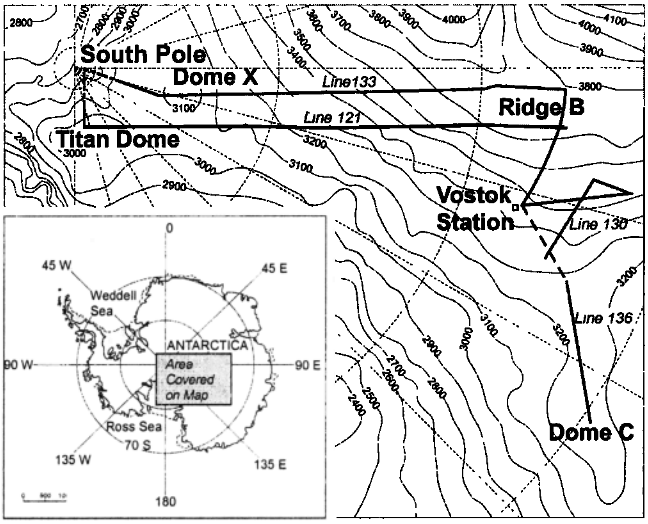

Figure 1. Airborne radar flightlines between Dome C, Vostok and South Pole. The area covered by the investigation is indicated in the inset. Line 136 is dashed near to Vostok Station due to a lack of 60 MHz Z-scope data [*Siegert et al.*, 1998], and lines 121 and 133 are dashed near to South Pole due to the break up of internal layers.

in *Siegert et al.* [1998]. Specifically, individual layers are traced across 2 km sections of the ice sheet through separate analysis of A-scope (single pulse radar data) and Z-scope (time-continuous pseudo-cross sections of the ice sheet) (Fig. 3).

Three internal layers were traced continuously along the radar flightlines. However, it should be noted that layers were difficult to trace across about 5% of the transect due to the apparent break-up of radar layering between Titan Dome and South Pole Station. Radar-layer buckling in Z-scope mode is an artefact that can be resolved using migration procedures. However, in the analogue data presented here, migration techniques cannot be used. The occurrence of radar 'buckling' may be associated with a change in the flow of ice, from the slow-moving ice sheet interior where layers are continuous, to the faster flowing ice drainage features where the layers deform [*Bell et al.*, 1998]. Importantly, at South Pole, there is a significant enhanced ice flow system that is located where layers have been observed to buckle [*Bamber et al.*, 2000]. However, the bedrock elevation between Titan Dome and South Pole, and therefore the ice thickness, can be measured accurately from our radar data (Fig. 2).

Internal radar reflections are not caused by a single layer of ice, but rather a number of closely spaced layers which may contain dielectric properties different to the 'background' value of the surrounding ice. The resolution of our results is limited to the 250 ns pulse length of the radar equipment, which equates to about 40 m in the ice sheet [e.g. *Siegert et al.*, 1998]. Our results must therefore be viewed in the context of these limitations.

Linking Titan Ice Dome and the Vostok ice core site

The depths of internal layers, and from these the normalised depths (i.e. the depth of an internal layer as a

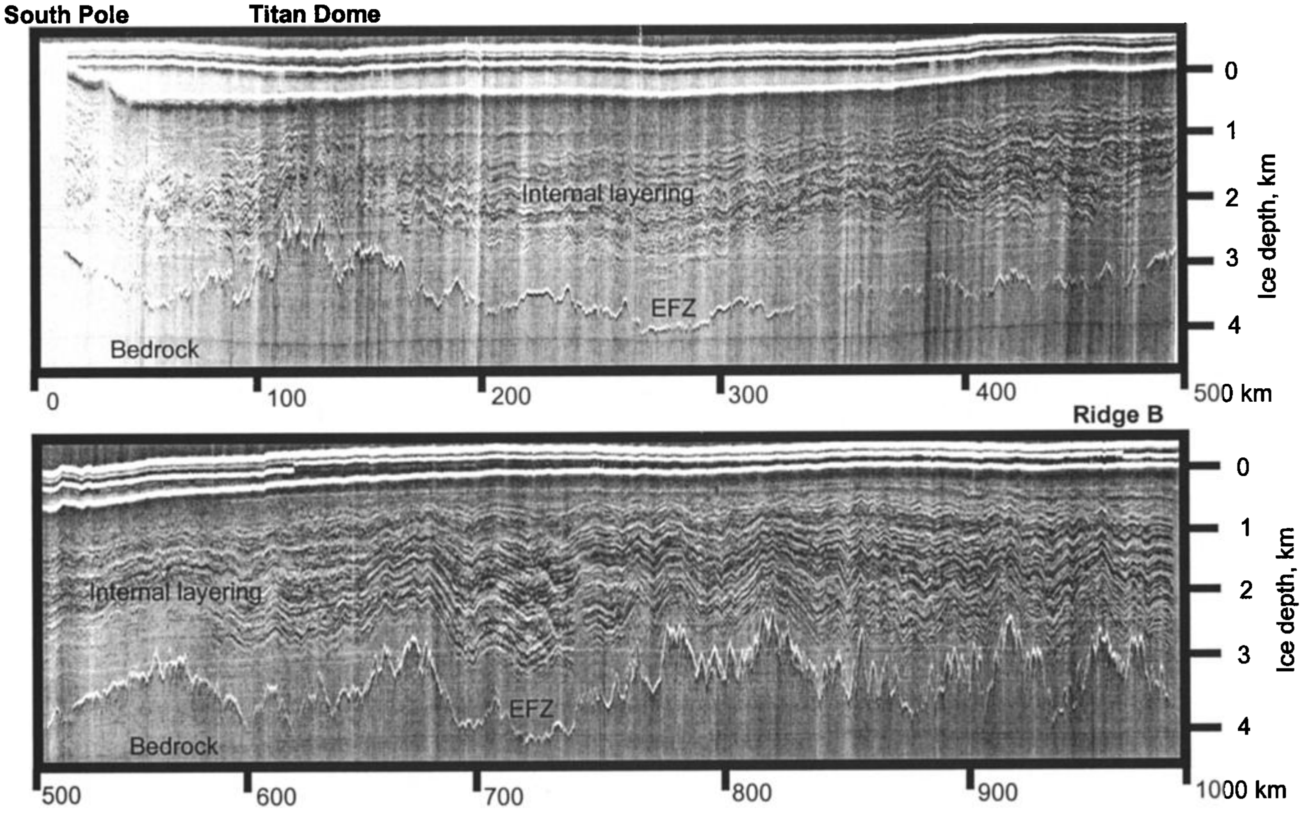

Figure 2. 60 MHz Radar data from line 121 between South Pole and Ridge B. Note how the internal layers are traceable across the ice sheet even in this heavily vertically-exaggerated image.

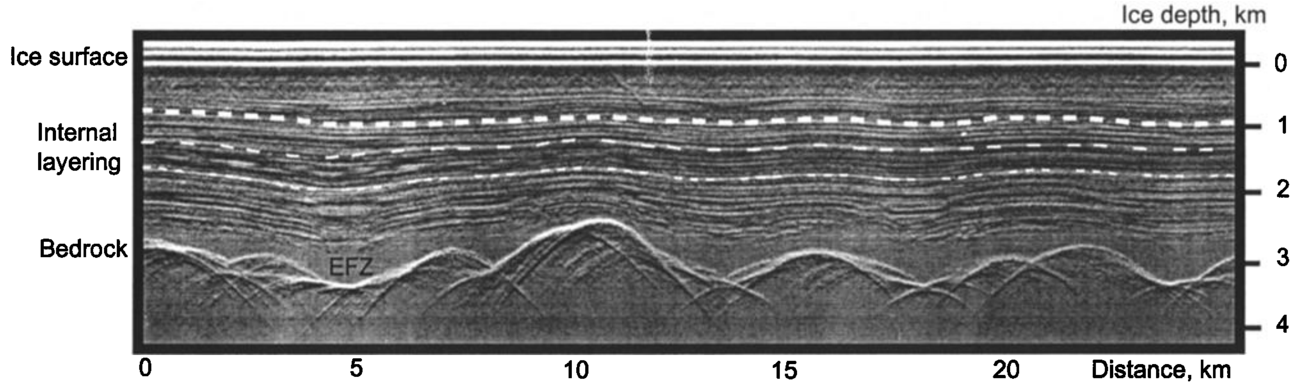

Figure 3. An example of 60 MHz radar, taken from flightline 121 between Ridge B and South Pole, Continuous radar layering is easily identified and, therefore, traceable across this section. Radar data on this scale were used to trace internal layering across the flightlines in Fig. 1.

fraction of the total ice thickness), were measured from the radar data (Fig. 2). The depths layers are affected by the flow of ice, the thickness of echo free zones (EFZs, referred to below) and the rates of ice accumulation across the continent. The absolute depth of internal layers can be clearly seen to increase generally beneath progressively deeper ice as one moves from Ridge B to Titan Dome and Dome X (Figs 4 and 5). The relative accumulation rates at ice divides can be estimated from dated isochrons because the effect of strain thinning via horizontal ice-sheet flow should be negligible. However, in order to date isochrons, they need to be linked to an ice core.

EFZs represent several hundred meters of the total ice thickness and are thought by *Fujita et al.* [1999] to be caused by enhanced shearing of ice that destroys the internal layering. Exact identification of the thickness of

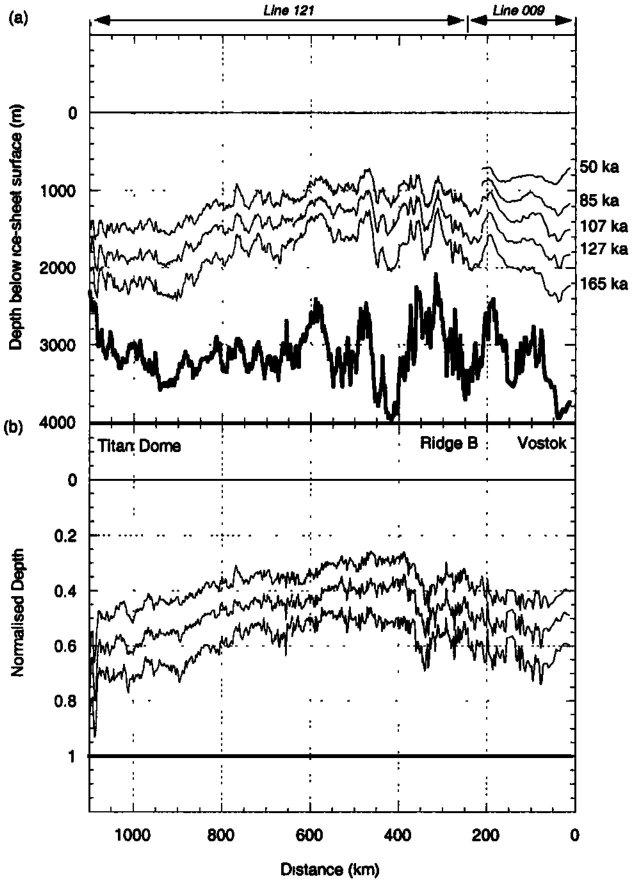

Figure 4. (a) Internal layering and (b) normalised depth of internal layers, digitised from 60 MHz radar records, between Titan Dome and Vostok Station. The bold line denotes the ice-sheet base.

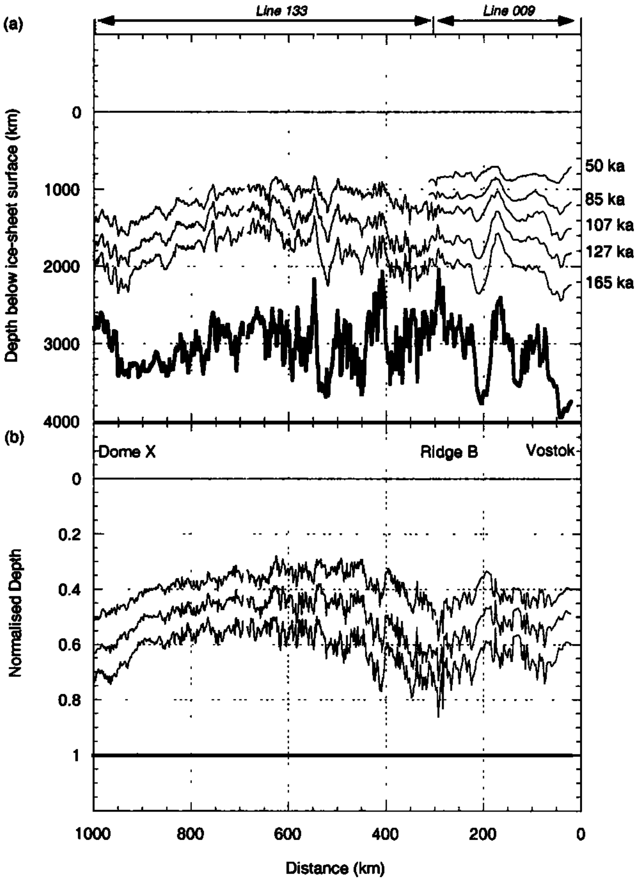

Figure 5. (a) Internal layering and (b) normalised depth of internal layers, digitised from 60 MHz radar records, between Dome X and Vostok Station (Fig.1). The bold line denotes the ice-sheet base.

EFZs in our 60 MHz radar data is problematic because the appearance of an echo-free zone could be caused by reflections below the detection limit of the radar equipment. Thus, in our radar data, the thickness of the EFZ may be an over estimate. However, the way in which the thickness of our EFZs relate to the subglacial relief is very similar to that of the calibrated EFZs observed at Dome Fuji [*Fujita et al.*, 1998]. In topographic lows the EFZ is relatively thick whereas over topographic highs the zone has a minimum thickness. There is greater folding of internal layers over subglacial bedrock where EFZs are absent (e.g. at ice divides). The presence of an EFZ causes a relative decrease in the normalised depth of internal layers. At the Titan Dome ice divide there is no EFZ and the internal layers found at a normalised depth of between 0.4 and 0.6 at Vostok Station are instead located between normalised depths of 0.5 and 0.8 (Fig. 4).

Estimates of the depth-age profile at Titan Dome and, by inference, around South Pole

By matching isochrons to the established depth-age relationship at Vostok [*Petit et al.*, 1999], our results indicate that the thickness of ice younger than 100 ka at Titan Dome is 600 m greater than at Ridge B, and 400 m more than at Vostok (Fig. 5). Further, the existing radar link between Vostok and Dome C [*Siegert et al.*, 1998] shows that there is 300 m more ice younger than 100 ka at Dome C than at Vostok. Our radar link between three ice divides allows us to infer that the average rate of accumulation over the last 100,000 years at Titan Dome is 75% greater than that at Ridge B, and 30% more than at Dome C. The ice accumulation rate at South Pole has recently been measured to be around 70 mm yr^{-1} (averaged over the last 900 years) [*van der Veen et al.*, 1999], whilst at Vostok Station the rate is only 27 mm yr^{-1} [*Kapitsa et al.*, 1996]. Our results suggest, therefore, that the present rates of ice accumulation in Antarctica may differ substantially to those in pre-Holocene time.

In contrast, the thickness of ice between isochrons at 100 and 165 ka is 650 m at Titan Dome; 350 m less than at Vostok and 550 m less than at Dome C. Therefore, the depth-age gradient between 100 and 165 ka must less steep at Titan Dome than at Vostok or Dome C. Given that the ice thickness at Titan Dome is around 2200 m, there must be very little ice older than 165 ka at Titan Dome. This has implications for the age of ice downstream at the nearby South Pole Station ice core site [*Price et al.*, in press]. Assuming that the normalised depths of radar layers continue to increase between Titan Dome and South Pole as they do between Titan Dome and Ridge B (and likewise for the South Pole - Dome X - Ridge B data), we would expect the depth of the 165 ka isochron to be located close to the ice base (or EFZ) at South Pole. This means that an ice core taken from the South Pole Station should yield a very high resolution ice core for the last glacial-interglacial cycle [*Price et al.*, in press].

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