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Radar stratigraphy connecting Lake Vostok and Dome C, East Antarctica, constrains the EPICA/DMC ice core time scale

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Abstract

New airborne radar sounding surveys at 60 MHz are used to trace internal layering between the Vostok and EPICA Dome C ice core sites. Eleven layers, spanning two glacial cycles from the last glacial maximum back to the MIS 7c interglacial, are used to correlate the two ice core chronologies. Independent of palaeoclimate signals, radar sounding enables correlation of the timescales, with a radar depth uncertainty equivalent to hundreds of years, which is small relative to the ice core dating uncertainties of thousands of years. Along the radar transects, horizons belonging to the last glacial cycle are impacted by aeolian stratigraphic reworking that increases radar technique uncertainty for this interval. However, older layers are used to propagate the higher resolution Vostok ages to the lower resolution Dome C ice core using the Suwa and Bender (2008) Vostok O_2/N_2 chronology to give a recalibration of the Parrenin et al. (2007) EPICA EDC3 timescale between 1597 m and 2216 m depth (126 ka to 247 ka age interval).

1 Introduction

Ice cores retrieved from East Antarctica provide the longest record of direct greenhouse gas concentrations and are key to understand late Quaternary climate forcings. EPICA Dome C (EDC) (75° 28′ S 106° 48′ E, (Bender et al., 1994)) and Vostok (75° 06′ S 123° 21′ E, (Landais et al., 2006)) provide dated records down to 3300 m and 3189 m depths, corresponding to 411 ka and 801 ka, respectively (Parrenin et al., 2007; Bender and Suwa, 2008). Modelling uncertainties at such depths become significant: the EDC3 chronology has a 6 ka confidence interval for ice older than 100 ka. The O_2/N_2 dating method applied at Vostok gives an improved accuracy of 2 ka throughout (Kawamura, 2009). The combined age uncertainties limit temporal and spatial resolution of climate change. We argue that modern radio-echo sounding (RES) surveys of the ice sheet provide an accurate way of validating ice cores age-depth relationship and extending these chronologies to spatially extensive areas of the ice sheet where no cores exist. Internal RES layering can be related to (a) density changes, (b) ice chemistry variation or (c) ice fabrics (Dowdeswell and Evans, 2004). For the depths considered, ice chemistry variation (b) is thought to be the dominant source of reflecting horizons. These horizons result from the deposition of discrete acidic aerosols as laterally extensive sheets on the ice surface and are preserved by later accumulation (Siegert et al., 1998a). The RES layering represents an independent method for ice core correlation as it is related to discrete volcanic events and not solely climatic events. Use of continuous RES interpretation as an alternative method for ice core correlation is advantageous over other techniques: (1) for contributing negligible errors to layer ages with respect to core dating uncertainties, (2) for providing a fast correlation method, (3) for providing an independent signal for palaeoclimate correlation and (4) for imaging spatially large areas to map englacial flow (Siegert, 1999).

2 Data and methods

We use RES lines acquired over several seasons by the University of Texas Institute of Geophysics (UTIG) aerogeophysical program (Fig. 1). The radar system operates with a centre frequency of 60 MHz, (Blankenship et al., 2001). Pre-2008 radar data (Vostok site coverage) were collected using a 250 ns pulse width; signals were digitised at 16 ns intervals and stacked to along track records every 10–12 m along track (Carter et al., 2009). Post-2008 data (Dome C site coverage) were acquired using a 1 µs chirp width and 6400 Hz pulse repetition frequency, with ≈ 100 ns pulse width after range compression (Peters et al., 2005); signals were digitised at 20 ns intervals and stacked yielding records every ≈ 22 m along-track (Young et al., 2011). Data interpretation was performed by tracking continuous horizons in ice, following peaks or troughs in processed amplitude, using an industry standard layer interpretation package (Schlumberger's GeoFrame).

Horizon depths relative to the surface are computed assuming a constant electromagnetic velocity of 169 m μs^{-1} and 300 m μs^{-1} in ice and air, respectively (Carter et al., 2009). Complex internal layer geometry in the area of buried megadune structures requires manual interpretation to track layers.

3 Correlating Dome C and Vostok

3.1 Horizon correlation

Eleven horizons (see Fig. 2) spanning a 209 ka period, from the last glacial to the penultimate interglacial, were successfully picked between the Vostok and EPICA Dome C ice core sites, providing a direct stratigraphic correlation between the two sites. Ten to twelve radar lines were used for each horizon correlation; intersecting lines with crossover points ensure that the same horizon is being tracked throughout. Two alternative routes lead to Dome C ice core sites from Vostok providing a means of double-checking the correlation.

An initial correlation was given by Siegert et al. (1998b), but involved a 150 km data gap close to Vostok, over which horizontal layer geometry was assumed. More recent data suggests that this approximation is not valid, due to the sloping bedrock and ice surface geometry of the area (Tabacco et al., 2006). Similarly, we find that layers are deeper at Vostok than in the Siegert et al. (1998b) study, for the same depth interval, which is more consistent with the local topography.

The eleven horizons were chosen on the basis of brightness and continuity, some dimmer horizons showing strong interference patterns were rejected. For all successful horizons, depths were measured at both ends of the correlation, where the radar lines passed closest to the ice core site location, using diffraction hyperbolae off station buildings in the radar data as a reference location (see Fig. 3 for radar lines). Horizontal continuity was assumed over the minor data gaps between the ice core sites and the radar lines of closest approach, corresponding to 1.2 km and 0.4 km at

Vostok and Dome C, respectively. Depths are measured from the surface, to which we apply firn corrections (z_f) of 14.71 m and 9.40 ± 0.94 m at Vostok and Dome C, respectively; these corrections were computed using the Eq. (1), following (Dowdeswell and Evans, 2004) and published vertical density profiles for each site (Dowdeswell and Evans, 2004; Barnes et al., 2002, respectively) (firn corrections confirmed at Dome C by two independent studies: radar reflection study, 9.48 ± 2.7 m, E. Le Meur, personal communication, 2012; and seismic refraction study, 9.23 ± 2.7 m, R. Gasset, 1982).

$$z_\mathrm{f} = \frac{K}{n'_\mathrm{i}} \int (\rho_\mathrm{i} - \rho(z))\mathrm{d}z \qquad (1)$$

- K coefficient adopted by Robin et al. (1969), $0.85\,\mathrm{m}^3\,\mathrm{Mg}^{-1}$.
- n'_i refractive index of solid ice, 1.78.
- ρ_i density of solid ice, $917\,\mathrm{Mg\,m}^{-3}$.
- $\rho(z)$ density at a depth z, $\mathrm{Mg\,m}^{-3}$.

Vertical resolution of RES layer interpretations is obtained from the measured radar pulse width (Millar, 1982); it represents 30 m at Vostok and 8 m at Dome C, respectively. The picking accuracy is estimated to be ±1/10th of the pulse width, except for layers traversing megadune disturbances where it decreases to ±1 pulse width. This is the case of the five shallowest layers (excluding the top-most) that span the last glacial period from 113 ka to 41 ka (see Table 1).

3.2 Age-depth stratigraphy

Horizons are dated at Dome C and Vostok sites using published age-depth chronologies (Parrenin et al., 2007; Suwa and Bender, 2008). We linearly interpolate bagged ice core depths to fit our picked radar depths, and the same is done with the corresponding ice-sample age data to date the layers.

The age uncertainty associated with dating the RES layers is computed independently at each horizon; radar depth uncertainties combine radar depth picking accuracy, core location uncertainty, and a firn correction uncertainty. RES depth uncertainty intervals are then projected to age uncertainty intervals, which vary with depth due to strain thinning and glacial/interglacial accumulation rate variations. All uncertainties can be found in Table 1. Published ice core dating errors are also reported at each horizon for comparison.

3.3 Discussion

A distinction must be made between layers belonging to the last glacial period and layers from the penultimate glacial period. The last glacial cycle is characterized by pervasive aeolian reworking of the ice sheet surface and translates to zones of buried megadunes through subsequent accumulation. These have been described as actively present at the surface of the East Antarctic Ice Sheet (Arcone et al., 2012a,b). Megadune facies are clearly visible in the post-2008 RES data sets collected with a modern “coherent” radar sounder (Peters et al., 2005, 2007). In these profiles, erosional surfaces are easily identifiable and some diagonal cross-bedding is visible in areas (see Fig. 4). Because of widespread aeolian reworking, radar-dating uncertainties (Table 1) in this region of the ice sheet are larger than traditional ice core dating uncertainties at shallow layer depths corresponding to the last glacial cycle.

Layers pertaining to the penultimate glacial cycle (from the MIS5e interglacial at 126 ka to the start of the MIS 7c interglacial at 247 ka) are mostly unperturbed and, upon comparing radar and ice core age uncertainties, a large difference in the scale of these uncertainties is very clear. The radar survey gives uncertainties on the order of tens to hundreds of years, while core errors are a minimum of 2 ka. Although age uncertainties for the radar layers increase with depth, they remain much smaller than ice core modelling uncertainties. The deepest layer picked at Vostok reaches 2779 m (Table 1), correlating with 7/10th of the full EPICA/DMC core length retrieved; however, the age error extrapolated from Vostok remains below 1 ka including for layer depths at Dome C in close proximity to the echo-free-zone.

Considering our extrapolated estimate of age-depth resolution at Dome C, we would expect a horizon to show a geochemical age difference between Dome C and Vostok no greater than the order of the radar resolution i.e. less than 700 yr. Differences obtained here are of the order of ka. Reasons for this discrepancy, if we do not consider layers from the last glacial cycle, are that (1) layers are not as laterally continuous as assumed and volcanic deposits from different layers merge, (2) interpretation errors are underestimated where radar vertical resolution is not sufficient to identify breaks in the stratigraphy or where layer roughness induces a jump to a contiguous shallower/deeper layer, giving an erroneous correlation, and (3) errors in ice core dating of ± ka are too large and the age differences observed between the two sites are a result of the lower dating resolution of the EDC3 timescale. The magnitude of our radar uncertainties lead us to believe that errors in ice core dating (3) is the most likely cause of the age differences. This implies that integration of an ice core site with relatively small age uncertainties in a network of radar surveys and ice core sites would allow refinement of age-depth estimates for other ice core stratigraphies.

For layers in the penultimate glacial cycle, we note that six out of the seven horizons considered are deeper at Vostok than at Dome C. We hypothesize that this can be explained by the presence of Lake Vostok (Kapitsa et al., 1996). Subglacial water eliminates strain thinning of the layers. In addition, melting of the bottom layers accommodates surface accumulation, thereby reducing compaction thinning in the Vostok area. (Petit et al., 1999) uses this argument for derivation of the GT4 Vostok timescale. The MIS6a glacial period is 324 m (≈ 50 %) thicker at Vostok than Dome C. (Siegert et al., 1998b) show the reverse of what we observe but we argue that the 150 km gap between the older RES data and Vostok, over which the authors assumed layers remained horizontal is the reason behind the discrepancy.

Our results show that radar layer tracing over larger areas of the central East Antarctic Ice Sheet would allow propagation of ice core stratigraphies to anywhere layers can be reliably traced. This tracing would strongly benefit inverse model studies of age-depth over any area. In addition, modern coherent radar measurements over cored sites would allow direct inter-core stratigraphic correlations and provide a verification of the quality of layer interpretations. Identification of future deep "old ice" coring sites is strongly reliant on such radar studies.

4 The EDC3 timescale

4.1 Recalibration

Using the (Suwa and Bender, 2008) Vostok timescale and our RES correlation, we are able to carry ages from Vostok Station to the Dome C ice core. We only do so for the seven layers of the penultimate glaciation that are unaffected by megadune reworking. Each layer at Dome C is in turn assigned the corresponding age obtained at Vostok. For depths between 1590 m and 2320 m at Dome C, radar uncertainties are negligible with respect to ice core dating errors in the computation of our associated age uncertainty and we give the combined rms error. Table 2 gives our recalibrated EDC3 timescale (termed hereafter EDC3-radar). A simple linear interpolation is used to reconstruct EDC3 between horizon pairs and should be taken as an initial result as no thinning function or accumulation model has been used in the reconstruction.

The EDC3-radar timescale is plotted with the EDC3 Parrenin et al. (2007) δO^{18} timescale for comparison (Fig. 5): differences are within the Parrenin et al. (2007) error range but significantly different if the EDC3-radar timescale uncertainty bounds are considered.

4.2 Discussion

The EDC3-radar chronology is older than the Parrenin EDC3 chronology for the intervals 120–140 ka and post 220 ka, while it is younger than the ice core-based EDC3 between 140 ka and 220 ka. The 140–220 ka interval corresponds to the penultimate glacial period, while the other two intervals correspond, respectively to the last and penultimate interglacials. The disagreements between the two trends could reflect (1) incorrect assumptions used for the EDC3 ice core chronology reconstruction or (2) incorrect interpolation of the “EDC3-radar timescale”. Various parameters used in the modeling of Parrenin et al. (i.e., initial accumulation rate temporal variation as well as the vertical thinning function) are poorly known and determined by inverse methods (Parrenin et al., 2007). They further indicate that the resulting ages do not match age markers perfectly. Accumulation rate reconstructions could easily be responsible for the change in sign of the discrepancies. We must also keep in mind that this study uses deep horizons; with the deepest layer (layer 13) reaching 7/10th of the total ice thickness, where high rates of shear thinning are experienced in the ice sheet. Interpolation of the new EDC3 timescale would benefit from the use of a thinning model. We believe the disagreement between the two timescales reflects a combination of errors (1) and (2).

Our results do agree with comparative dust flux variations in the two ice cores. Delmonte et al. (2004a) detailed dust fluxes in the Vostok and Dome C cores and found a strong coherence between the respective dust profiles; both show highest dust concentrations at glacials while low concentrations reflect interstadial or interglacial conditions. They were able to correlate the two cores through the matching of 10 outstanding dust events, which show the same stratigraphic relationship as this radar study. Their correlation shows a common dust marker to be shallower at Vostok between the surface and a depth of 1120 m, and an inverse relationship between 1120 m and 2200 m. Our eleven layers match this stratigraphic relationship extraordinarily well. The fact that dust markers in the ice would show the same stratigraphic relationship confirms the strong link between our radar reflectors and discrete dust/acidic depositional events, and supports the stratigraphic correlation obtained in this study (see Fig. 2).

5 Conclusions

Thirteen strong and continuous radio-echo layers were identified in UTIG airborne surveys from 2000 to 2011 and eleven of these layers were tracked between the EPICA Dome C and Vostok ice core sites. The correlation provides the first continuous direct chrono-stratigraphic link between the two ice core timescales. The location of this study along the Byrd-Totten ice divide over deep bedrock basins makes this area a very important one in our search for old ice. We map layer geometries over the last two glacial cycles, which can strongly benefit ice core modeling as well as studies of spatial patterns of accumulation over time using inverse layer modeling (Leysinger Vieli et al., 2011). The strong advantage of the technique used is that it does not require traditional modeling and inter-core marker comparisons with the uncertainties involved. Through the last glacial cycle, where ice core chemistry is very reliable, radar dating techniques are compromised by buried megadune fields, whilst the penultimate glacial cycle, where larger uncertainties prevail in the ice core chemistry and timescales, RES dating uncertainties are of the order of several hundred years, quite small in comparison to current ice core dating uncertainties.

By linking Vostok and Dome C ice cores, age uncertainties in the EDC3 timescale are reduced from ±3–6 ka to ±2 ka, a major chronology improvement for precise climate change and forcing studies (Kawamura, 2009). Our results indicate that an improved EDC3 chronology will be required to understand spatial and temporal climate variation at Dome C and, in turn, more accurate age-depth model there will be useful as a final validation of our techniques. We emphasize the importance of extending these techniques over wider areas of Antarctica as well as carefully connecting interpreted radar surveys (and new surveys) to existing ice cores; this will be especially important where a known age depth stratigraphy will be needed to constrain modeling in search of deeper "old ice".

Supplementary material related to this article is available online at: http://www.the-cryosphere-discuss.net/7/321/2013/tcd-7-321-2013-supplement.zip.

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Table 1. Age and depth data for all radar layers at EPICA Dome C and Vostok ice core sites.

Ice core sites	Dome C			Vostok			VK - DMC
Horizons	*Z+4.06 (m)	Age (ka)	Rms (ka)	Z (m)	Age (ka)	Rms (ka)	Age (ka)
wsb0	700	38		597	41		3
Radar err (±) *(Pub core err (±))*	±1	0.110 (1)	1.0	±3	0.247 (1)	1.0	
wsb01	784	45			UC		/
Radar err (±) *(Pub core err (±))*	±8	1.093 (1.5)	1.9				
wsb1	1077	72		947	66		-6
Radar err (±) *(Pub core err (±))*	±8	1.215 (1.5)	1.9	±30	1.836 (1)	2.1	
wsb2	1174	81		1366	97		16
Radar err (±) *(Pub core err (±))*	±8	1.065 (1.5)	1.8	±30	2.609 (1)	2.8	
wsb22	1340	96		1498	108		12
Radar err (±) *(Pub core err (±))*	±8	1.166 (1.5)	1.9	±30	2.486 (2)	3.2	
wsb24	1423	105		1555	113		8
Radar err (±) *(Pub core err (±))*	±8	1.314 (3)	3.3	±30	2.583 (2)	3.3	
wlk03a	1597	122		1735	126		4
Radar err (±) *(Pub core err (±))*	±1	0.095 (3)	3.0	±3	0.185 (2)	2.0	
wsb3	1685	128		1842	132		4
Radar err (±) *(Pub core err (±))*	±1	0.091 (3)	3.0	±3	0.166 (2)	2.0	
wsb4	1889	159		2091	156		-3
Radar err (±) *(Pub core err (±))*	±1	0.246 (6)	6.0	±3	0.463 (2)	2.1	
wsb41	1980	178			UC		/
Radar err (±) *(Pub core err (±))*	±1	0.267 (6)	6.0				
wsb7	2092	201		2459	197		-4
Radar err (±) *(Pub core err (±))*	±1	0.215 (6)	6.0	±3	0.388 (2)	2.0	
wsb8	2216	224		2686	230		6
Radar err (±) *(Pub core err (±))*	±1	0.348 (6)	6.0	±3	0.617 (2)	2.1	
wsb9	2317	247		2779	247		0
Radar err (±) *(Pub core err (±))*	±1	0.271 (6)	6.0	±3	0.580 (2)	2.1	

* An additional 4.06 m are added to Dome C radar depths for direct comparison with published ice core measurements. In dark grey, top six layers disturbed by megadune areas; in light grey, more consistent layers. Age is computed for each ice core site separately, using the EDC3 (Parrenin et al., 2007) and the Vostok (Suwa and Bender, 2008) chronologies. Rms error combines radar and ice core uncertainties at each site. UC = Unconformity break in the layer.

Table 2. Recalibrated EDC3-radar timescale.

Layers	Depth (m)	EDC3-radar Age (ka)	*Age error (± ka)
wsb0	700	41	1.0
wsb01	784	UC	/
wsb1	1077	66	2.4
wsb2	1174	97	3.0
wsb22	1340	108	3.4
wsb24	1423	113	3.5
wlk03a	1597	126	2.0
wsb3	1685	132	2.0
wsb4	1889	156	2.1
wsb41	1980	UC	/
wsb7	2092	197	2.0
wsb8	2216	230	2.1
wsb9	2317	247	2.1

[*] Here age error represents the rms of Dome C radar uncertainty, and Vostok radar and ice core dating combined error. UC stands for Unconformable Surface, which limited radar propagation all the way to Vostok site. Our top six layers span the ultimate glacial cycle; our bottom seven layers span the penultimate glacial.
UC = Unconformity break in the layer.

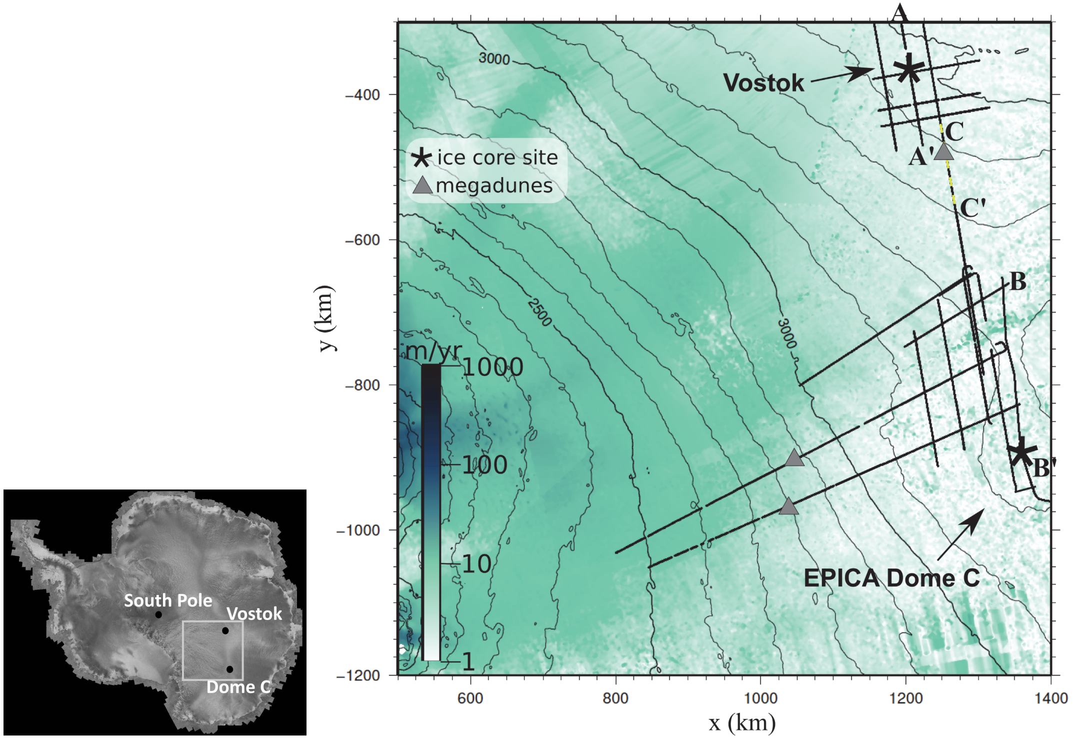

Fig. 1. Map of the East Antarctic Plateau focused on the study area. The inset locates the ice cores in a map of Antarctica; a white rectangle locates the blown-up study area. Radar transects used are shown, overlaid on MODIS ice surface velocity mosaic (Rignot et al., 2011); black contours are ice surface elevation in meters (Bamber et al., 2009).

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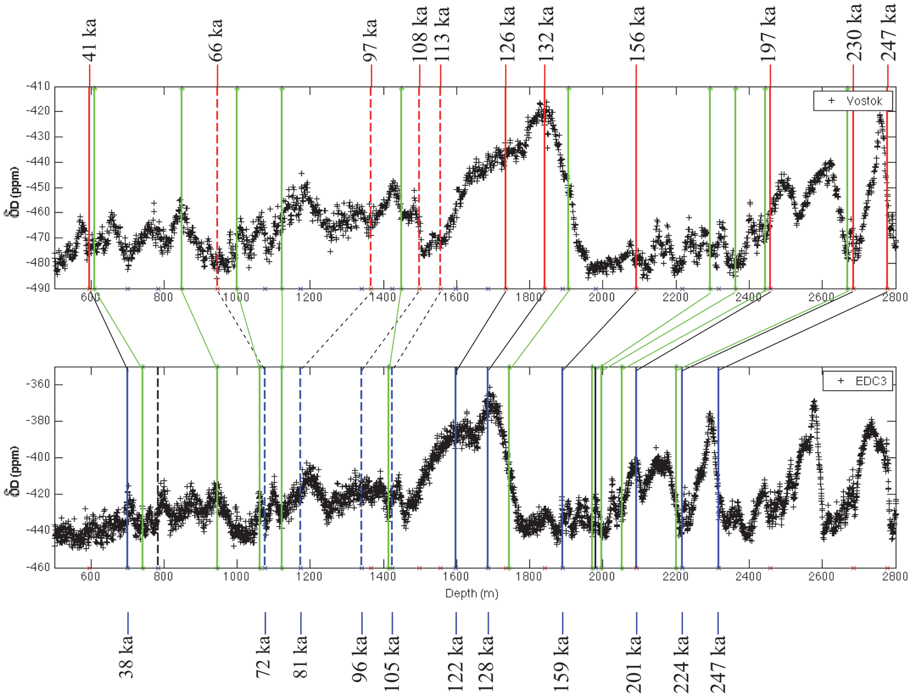

Fig. 2. Vostok and EPICA Dome C δD chronologies. On top, Petit et al. (2001) Vostok δD based on the Suwa and Bender (2008) O_2/N_2 timescale; below, Jouzel et al. (2007) EPICA Dome C δD based on the Parrenin et al. (2007) $\delta^{18}O$ timescale. Vertical blue and red lines denote the eleven radar layers: dashed lines denote the last glacial radar layers affected by megadune areas and therefore not used in the recalibration of EDC3; black lines are radar layers that could not be carried all the way to Vostok ice core site. In green, Delmonte et al. (2004) dust layers. Dust and radar layers only cross in the megadune-disrupted depths. Layer ages for both ice core sites are given for each of the eleven layers.

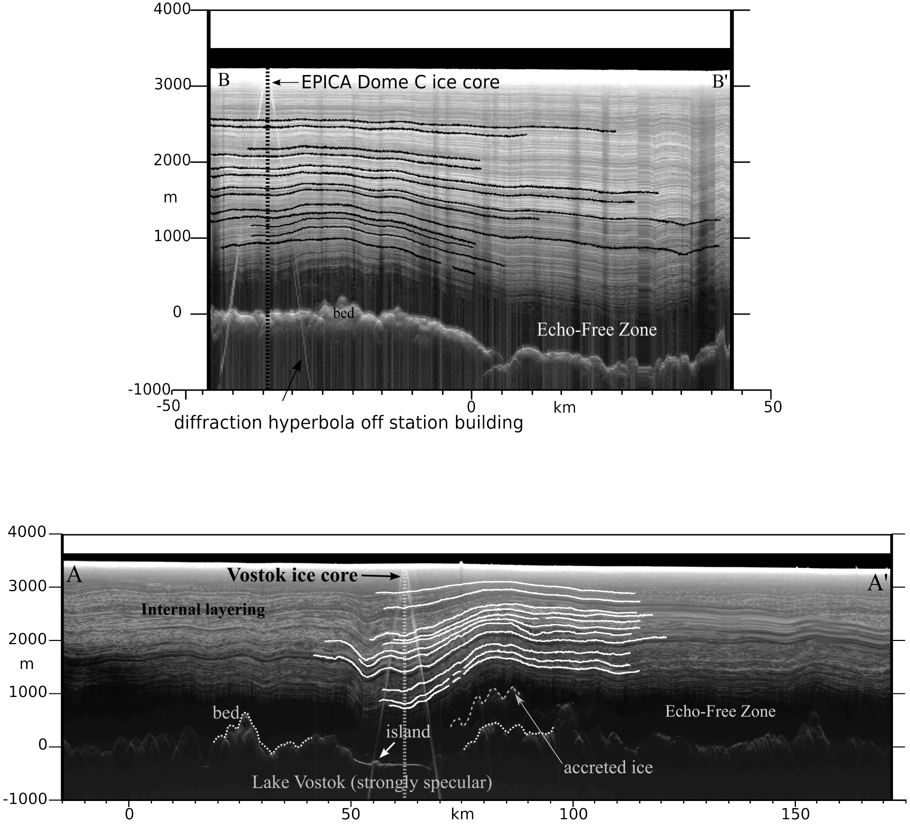

Fig. 3. Internal layering along UTIG RES transects, over Vostok (A-A′) and EPICA Dome C (B-B′) ice core sites. Ice core locations are indicated. Note the bright bedrock and Lake Vostok reflections, as well as the thick accreted ice layer, well resolved in the Vostok section. Internal layering is clearly visible and continuous throughout.

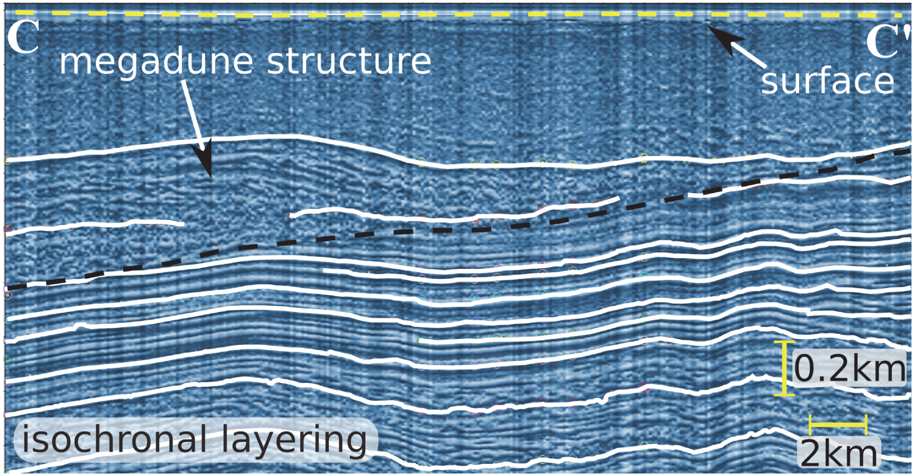

Fig. 4. Incoherent RES transect showing transition between isochronal well-behaved layering to re-worked megadune structures eastwards. Reworking is identifiable from the strong interference texture of the layering. Section is vertically stretched. The 2nd to the 6th layer, belonging to the last glacial period, are highly perturbed in this zone. Location of this transect is indicated in Fig. 1.

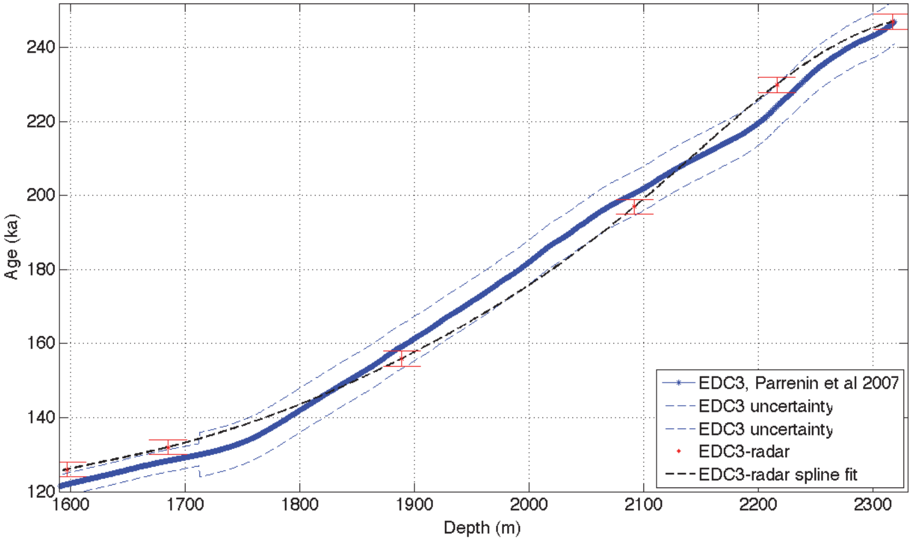

Fig. 5. EPICA Dome C timescale comparison for the penultimate glacial cycle. In blue, EDC3 Parrenin et al. (2007) Dome C δ^{18}O timescale, uncertainty bounds are dashed; in red our EDC3-radar recalibration using Vostok ages and radar direct core correlation, rms uncertainty bounds are shown. A simple cubic-spline interpolation is used to trace EDC3-radar.

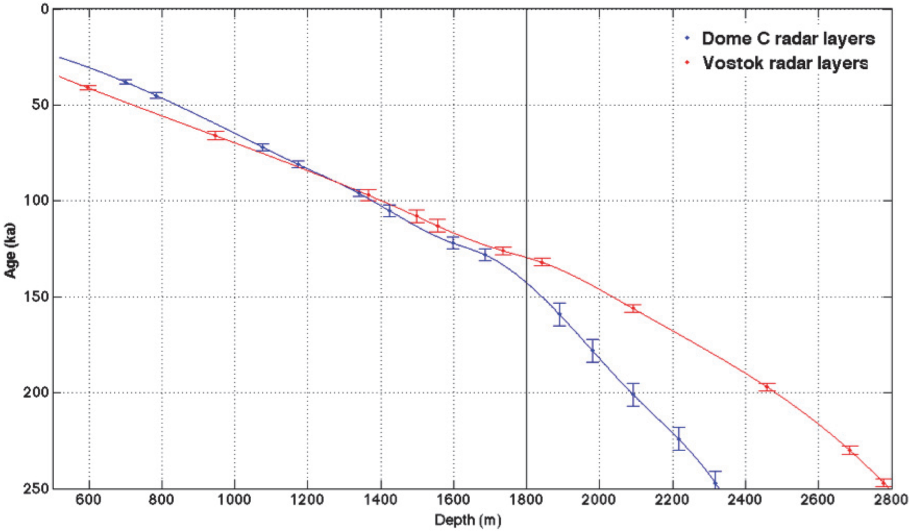

Fig. 6. Age-depth relationship at Dome C and Vostok ice core sites based on RES layering. In blue, Dome C age-depth relationship; in red, Vostok age-depth stratigraphy. Uncertainties are bracketed, and increase with depth. A vertical black line separates the ultimate and penultimate glacial cycles.