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Evidence for a large surface ablation zone in central East Antarctica during the last Ice Age

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Abstract

Internal isochronous ice sheet layers, recorded by airborne ice-penetrating radar, were measured along an ice flowline across a large (>1 km high) subglacial hill in the foreground of the Transantarctic Mountains. The layers, dated through an existing stratigraphic link with the Vostok ice core, converge with the ice surface as ice flows over the hill without noticeable change to their separation with each other or the ice base. A two-dimensional ice flow model that calculates isochrons and particle flowpaths and accounts for ice flow over the hill under steady-state conditions requires net ablation (via sublimation) over the stoss face for the predicted isochrons to match the measured internal layers. Satellite remote sensing data show no sign of exposed ancient ice at this site, however. Given the lack of exposed glacial ice, surface balance conditions must have changed recently from the net ablation that is predicted at this site for the last 85,000 years to accumulation.

Introduction

The depth of a particle of ice below the surface of an ice sheet is dependent on ice flow over subglacial topography and the surface mass balance (or the accumulation of ice). Submergence occurs as a result of accumulation of snow, while emergence is possible because of ablation of ice, which in East Antarctica is dominated by wind-driven sublimation (Bintanja, 1999). Isochronous internal ice-sheet layers, measured by ice penetrating radar, can be used to assess the englacial flow paths of ice. Unless internal layers are disrupted by deformation due to enhanced (rapid) ice flow they can be traced over long distances across the ice sheet. Typically, internal layers get deeper toward the ice-sheet margin as surface accumulation increases, converge with each other in a vertical section over subglacial hills, and, conversely, diverge over subglacial valleys.

At a site in central East Antarctica in the foreground of the Transantarctic Mountains (~83°S, ~128°E), however, ice flows over a large subglacial hill with no observable change in the separation of the deepest internal layers (Figs. 1 and 2). Internal layers in the top 400 m (which are not resolved by the radar data) either converge vertically in this part of the ice sheet or must "outcrop" at the ice-sheet surface. In this paper, we use a two-dimensional numerical ice-flow model, which calculates isochronous surfaces and flow paths, to identify the long-term surface balance conditions compatible with the pattern of internal layering.

Internal ice-sheet layering

Introduction to internal layering

Internal layers in the Antarctic Ice Sheet, recorded by ice-penetrating radar, are understood to be formed by ice density variations in the upper 700–900 m of the ice sheet and acidic layers of ice caused by the aerosol product of volcanic events deposited formerly on the ice surface (Fujita et al., 1999). Under conditions of enhanced shear stress, layers of contrasting ice crystal orientation fabric may de-

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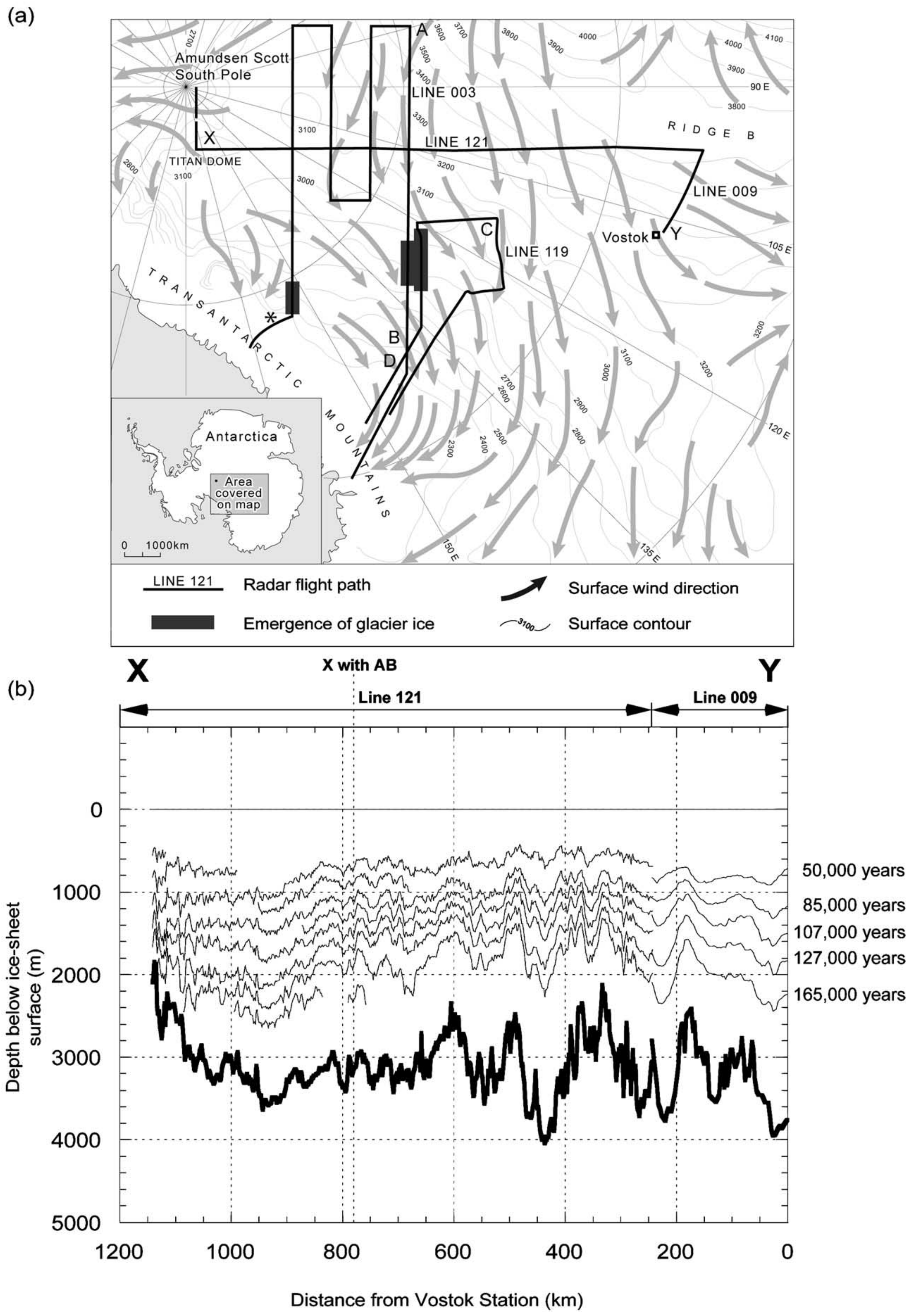

(a)
Amundsen Scott South Pole
X
TITAN DOME
A
LINE 003
LINE 121
RIDGE B
LINE 009
Vostok
Y
C
LINE 119
B
D
TRANSANTARCTIC
MOUNTAINS
90 E
105 E
120 E
135 E
150 E
Antarctica
Area covered on map
0 1000km
LINE 121 Radar flight path
Emergence of glacier ice
Surface wind direction
3100 Surface contour
(b)
X
X with AB
Y
Line 121
Line 009
50,000 years
85,000 years
107,000 years
127,000 years
165,000 years
Depth below ice-sheet surface (m)
0
1000
2000
3000
4000
5000
1200
1000
800
600
400
200
0
Distance from Vostok Station (km)

velop from acidic-based layers (Fujita et al., 1999; Siegert and Fujita, 2001). Internal layers are believed to be isochronous (Fujita et al., 1999; Vaughan et al., 1999). In East Antarctica, internal layering observed using 60-MHz radar has been used to construct stratigraphic links between Vostok Station, Dome C, and Titan Dome (near the South Pole) (Siegert et al., 1998; Siegert and Hodgkins, 2000). The depth–age relationship calculated for the Vostok ice core (Petit et al., 1999) allows internal layers traced from Vostok Station to be dated. Thus the depth–age relationship of ice can be established along radar lines connected to the Vostok Station.

A 60-MHz airborne radar transect (AB, Fig. 1) is aligned between the ice-sheet interior and the foreground of the Transantarctic Mountains and crosses the radar transect XY connecting Vostok and Titan Dome (Siegert and Hodgkins, 2000). Several continuous internal layers were measured along AB and along an additional radar line, CD, which runs parallel to AB (Fig. 1). The ages of the internal layers in AB were designated at the intersection with the dated layers in XY (Fig. 1b).

Pattern of internal layering across a large subglacial hill

Radar data along AB are shown in Fig. 2a. The ice thickness was measured continuously, providing an unbroken record of the subglacial morphology. From 0 to 600 km along AB the ice thickness varies between 2800 and 3500 m. After 600 km, however, ice thickness reduces from 3400 to 2000 m over a horizontal distance of about 120 km due to a large subglacial hill. Internal layers are relatively horizontal between 0 and 600 km. Across the stoss face of the subglacial hill, however, the internal layers lie at an angle, and they become closer to the ice-sheet surface as ice flows up the slope of the hill (Fig. 2).

Measured isochrons of all ages show very little variation in their separation from each other and from the ice-sheet base as ice flows across the hill (Fig. 2d). Isochrons older than 127,000 years can be resolved across the whole transect (Fig. 2d).

Isochrons younger than 107,000 years cannot be resolved across the whole transect. It is, therefore, not known whether they converge with each other or maintain their separation from the ice base (as the older layers do) and outcrop at the ice surface. Both possibilities have implications for the surface mass balance as ice flows across the subglacial hill. Convergence of internal layers requires a large spatial gradient in the accumulation rate of ice as ice begins to flow over the hill, while emergence of layers must be associated with the net loss of surface ice.

A second radar transect (CD) is aligned parallel to AB, approximately 50 km away (Figs. 1 and 3). In CD, internal layers appear to “emerge” across the stoss face of the hill. As ice flows across the lee side of this hill, however, an unconformity occurs between the internal layers (Fig. 3). This unconformity is evidence in support of the former “outcrop” of the isochron, which has been subsequently covered by snow and ice. The exposure must have been for a lengthy period, as there are several isochrons deposited on the former ice surface. However, the exposure is unlikely to have comprised ice of a wide range of ages, as only one isochron appears to make up the former ice surface, whereas a lengthy exposure of ice that has a wide range of ages would result in the truncation of internal layers above and below the unconformity.

Quantification of rates of ice accumulation

A two-dimensional model of horizontal ice flow and vertical compression is used to determine the mass balance of ice responsible for the pattern of internal layering observed along AB.

Ice-flow model

Isochrons are computed by solving the aging equation $\partial X/\partial t + \vec{u} \cdot \nabla X = 1$, where $\vec{u}$ is the velocity field (m yr^{-1}), t is time (yr) and X is the age (yrs old), assuming quasi-steady-state conditions. By this we mean a slightly more generalized criterion than $\partial X/\partial t = 0$; we assume that flow lines do not change with time, but that the rate of movement along the flow lines can change through time. This approximation is being studied by Hindmarsh and others (in preparation). The aging equation is solved by the second-order finite difference method discussed by Hindmarsh and Hutter (1988) and Hindmarsh (2001) in the mapped coordinate system discussed also in Hindmarsh and Hutter (1988). This solution requires knowledge of the horizontal ice velocity and flux at all places in the domain of solution. Balance

Fig. 1. (a) The location of radar transects AB and CD and the radar line XY used to build the dated stratigraphic link between Vostok Station and Titan Dome. AB is roughly normal to the ice surface contours, thus ice flow will be predominantly from A to B and from C to D across the radar transects. The location of the study area within the Antarctic continent is provided in the inset. Arrows denote the direction of katabatic surface wind (Parish and Bromwich, 1987; Parish, 1988), which cause the removal of snow and ablation of ice leading to the exposure of glacier ice (blue ice) at the ice-sheet surface. The locations of known blue ice zones, Lewis Cliff (84° 17′S, 161° 05′E) and MacAlpine Hills (84° 13′S, 160° 30′E), are denoted by a star at the end of line 003. (b) Sixty-megahertz airborne radar data are shown along XY, between Vostok Station and Titan Dome, in which layers are dated from their positions at the Vostok ice core site where a depth–age relationship has been calculated. The position where XY intersects with AB (Fig. 2) is indicated. The resolution of the internal layers is limited to the 250-ns pulse length of the radar equipment, which equates to about 40 m in the ice sheet. The tracing of internal layers across the ice sheet is open to a degree of error, as internal layers often merge and fade in and out across a transect. This problem is minimized here by including only those layers that could be traced continuously and confidently.

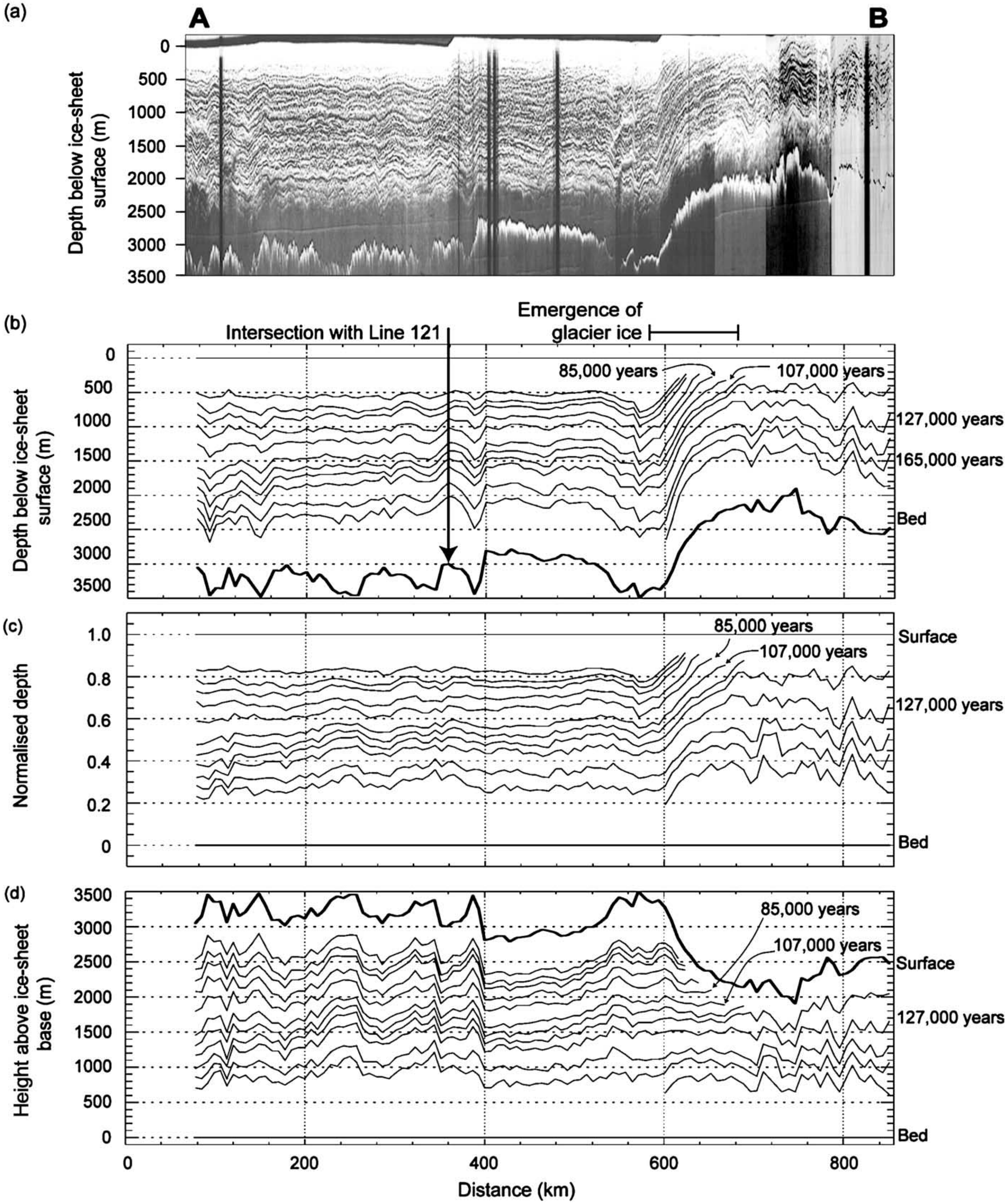


Fig. 2. (a) Sixty-megahertz airborne radar data along AB, from the South Pole region to the Transantarctic Mountains. (b) Processed radar data along AB. Internal layers are assigned ages at the place where they intersect with the dated isochrons along XY (Fig. 1). The position where AB intersects with XY is also shown. (c) Normalized profile of the radar data across AB. (d) Height of internal layers and the ice surface above the ice-sheet base along AB.

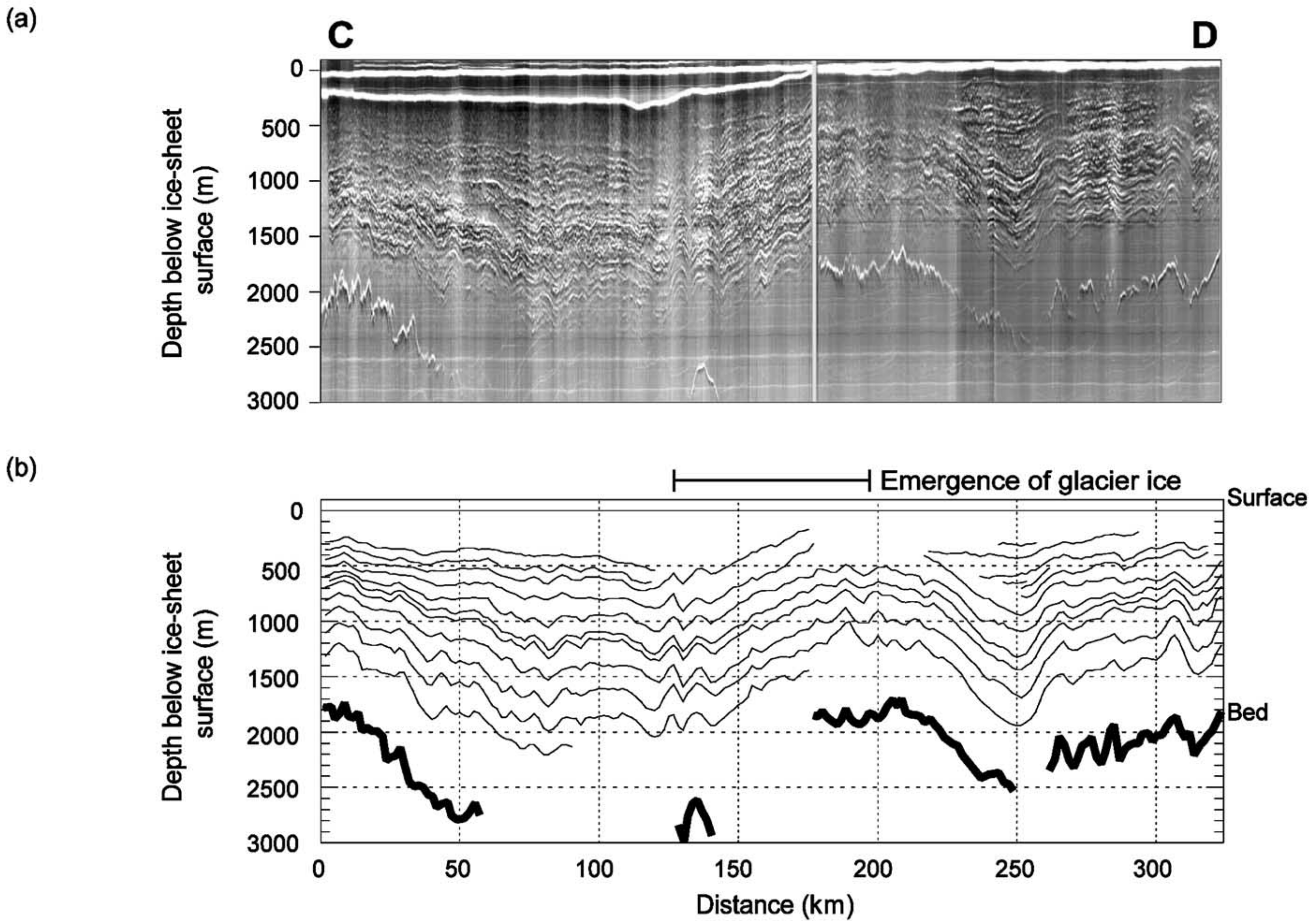


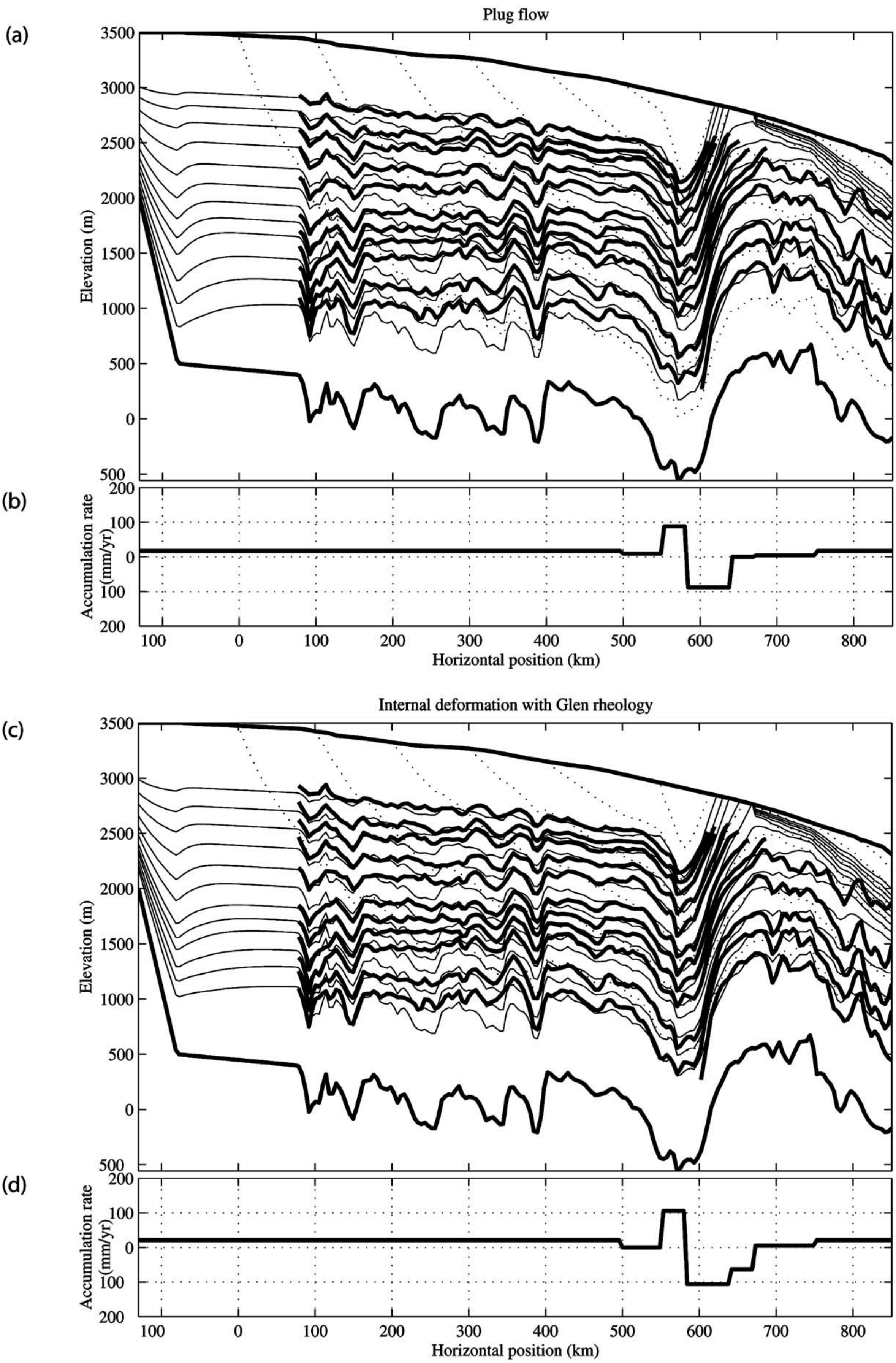
Fig. 3. (a) Sixty-megahertz airborne radar data along CD. (b) Processed radar data along CD. Note how internal layers emerge across the stoss face of the large subglacial hill and submerge over the lee side leading to an unconformity between former ice surface and recent accumulation of ice between 220 and 250 km along the transect. It should be noted that an unconformity, such as that shown in (b), would cause considerable problems for interpreting an ice core if one were ever drilled at this site.

fluxes were computed from an assumed accumulation rate distribution. These balance fluxes were used with the ice thickness data to obtain horizontal velocities. Some assumptions were also made about the manner in which horizontal ice velocity varies with depth, from which continuity considerations lead to knowledge of the vertical velocity field. Two types of horizontal ice flow are considered: (1) "plug" flow, where horizontal velocity is constant over the depth of the ice sheet and vertical velocity varies linearly with depth, and (2) simple shear with a shear stress increasing linearly with depth and ice deforming according to a Glen rheology (Glen, 1955) $\varepsilon = A\tau^3$, where ε is the strain rate, τ is the shear stress, and A is a rate factor. The horizontal and vertical velocities vary with depth according to Nye (1959). The value of A is not required in the model, as this is accounted for within the balance velocity calculation. The geometry of the flow line from the divide to the beginning of the radar transect is required, however, which is estimated from data available in Drewry (1983).

Ice-flow model results

Modeled isochrons were matched with measured internal layers along AB through adjustment to the pattern of surface mass balance. The results from two calculations, plug flow and Glen shear are presented in Fig. 4. The accumulation rate was hand-fitted for both cases, and the contours of the age field were also manually fitted to produce the best fit to the observed isochron structure. The accumulation rate distributions obtained show that our uncertainty of whether the flow is more akin to a plug flow or Glen-type shear is not really an issue in explaining the large-scale properties of the flow field. The accumulation rates were adjusted to fit the 85,000-year isochron and are shown in Fig. 4.

Upstream of the subglacial hill, accumulation was set at 1.5 cm yr^{-1}. Prior to ice flow over the hill, the rate of accumulation increases to $\sim$10 cm yr^{-1}. This highly increased rate was found to be necessary to force the layers to dip downstream. As ice flows up the stoss side of the hill,


(a)
Plug flow
Elevation (m)
(b)
Accumulation rate (mm/yr)
Horizontal position (km)
(c)
Internal deformation with Glen rheology
Elevation (m)
(d)
Accumulation rate (mm/yr)
Horizontal position (km)

however, the model requires the mass balance along a 100-km section to be negative (by as much as 10 cm yr^{-1}). The model calculates the pattern of internal layering in the upper 400 m of the ice sheet, which is the region where the radar does not resolve internal layers. Assuming "plug" flow, the model predicts that isochrons younger than ~60,000 years outcrop at the ice surface, whereas for Glen-type flow ice aged between 0 and 85,000 years is predicted at the ice surface (Figs. 2 and 4). The age of emergent ice was found to be very sensitive to the assumed mass-balance distribution. Across the lee side of the hill net accumulation (~2 cm yr^{-1}) is predicted, and the submergence of formerly exposed ice occurs. The model demonstrates (1) an increase in accumulation at the foot of the subglacial hill and (2) a sharp spatial change in surface mass balance conditions above the base of the subglacial hill. These changes in surface balance are most probably driven by changes in ice sheet surface slope (e.g., Gow and Rowland, 1965; Whillans, 1975) caused by alteration in the ice-sheet surface slope that results from ice flow over the hill (e.g., Vaughan et al., 1999). At this site, therefore, subglacial topography has a strong control on the ice-sheet surface balance.

Special attention was paid to matching the area upstream of the ablation zone. It was found that with a uniform accumulation rate the model layers upwarped and then dipped relative to the observed layers. To enforce a fit, the accumulation rate had to be lowered (to fit the upwarped areas) and then increased significantly (to fit the area with increased downstream dip). Once this was done, a reasonable fit was obtained, implying that transience in the relative accumulation rate was not particularly important in this area. Downstream of the ablation zone, however, differential thinning occurs in the ice column; i.e., isochrons at different levels diverge and converge differently. Here it was difficult to model the observed layering accurately. The most likely explanation of this poor fit is the transient behavior in the spatial distribution of *relative* accumulation rates in this region of the ice sheet. The modeling thus suggests that the region downstream of the ablation zone is subject to long-term variations in the spatial mass balance distribution.

Discussion

Paleo mass balance

The model predicts net surface ablation of the order of 10 cm yr^{-1} to allow the internal layer pattern to occur. We examined available high-resolution satellite imagery of the East Antarctic Ice Sheet along transect AB for evidence of exposed ice at the surface. Neither surface-penetrating RADARSAT imagery or visible-band MODIS imagery show any signs of exposed glacier ice in the region, however. As there is no evidence in support of the exposure of ancient ice, the current surface balance at this location is inferred to be positive. The most likely explanation for the mismatch between model results and the expected modern mass balance is that full glacial mass balance at this site was negative, while Holocene accumulation rates were positive. Hence, surface mass balance conditions must have changed markedly during recent times compared with the long-term (glacial) average. At the center of the Antarctic ice sheet, glacial accumulation rates are known to have been substantially lower than those at present (e.g., at Vostok Station, ice accumulation at the LGM was 1.2 cm yr^{-1}, compared with 2.2 cm yr^{-1} today). Our modeling shows, however, that toward the margin of the ice sheet, across a large (100 km long) region in the foreground of the Transantarctic Mountains, net loss of ice occurred for a significant proportion of the last glaciation.

Paleoclimate records

The internal layer pattern over AB demonstrates that shallow ice coring from the crest of the subglacial hill down to just a few hundred meters would retrieve ice from the last interglacial. As the ice strata are well preserved and aligned nonparallel to the ice surface, coring to cross cut the ice strata would produce a "traditional" ice core record. Further, as the positions and ages of the strata are known, an "angled" ice core could also be used to sample individual isochrons. Hence, shallow ice coring at this site could build a record of Antarctic climate change from the last interglacial unprecedented in resolution.

Conclusions

By analyzing ice-penetrating radar data, a location in East Antarctica has been discovered where internal layers appear to converge to the ice surface as ice flows over a large (>1 km high) subglacial hill in the foreground of the Transantarctic Mountains, without any noticeable change to the separation between the layers or the vertical distance between the layers and the ice base (Fig. 2). Tracing isochronous layers from this site to the Vostok ice core allows them to be dated and shows that ice 107,000 years old

Fig. 4. Modeled isochrons (thin solid lines), measured isochrons (thick solid lines), and ice-particle flowpaths (dashed lines) for (a) plug flow (the mass balance used in the plug flow experiment is shown in (b)) and (c) Glen-type flow (the mass balance used in the Glen flow experiment is provided in (d)). As the model predicts ice flow from the ice divide to an ice margin, the first 100 km or so of the transect is adapted to resemble the transect along the line of ice flow to Dome A (Drewry, 1983; Lythe et al., 2000). It should be noted, however, that there are very few data in this part of the ice sheet with which to constrain this adaptation.

occurs only 300 m from the surface. A two-dimensional ice flow model was used to determine the surface mass balance conditions across the hill by matching modeled isochrons with internal layers through adjustment to accumulation rate of ice. Net ablation is predicted in this area, which would cause ancient (up to 85,000 years old) ice to outcrop. The model demonstrates that ablation, due presumably to the sublimation of ice, occurs as a consequence of ice flow across the stoss face of the hill. Satellite data show that there is currently no sign of ancient ice at the ice-sheet surface. Surface balance conditions must have changed recently (during the Holocene), therefore, from net ablation to accumulation.

Paleo ice accumulation rates are not well established for the East Antarctic Ice Sheet. This study shows that a 100-km-wide region of surface ablation existed for the major part of the last 85,000 years and indicates that surface ablation may have been more prevalent in Antarctica during glacial periods than at present. This study also shows that ice as old as 107,000 years exists close to the ice surface. This location is, therefore, a prime site for extracting an ice core record from the last interglacial.

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References

Bintanja, R., 1999. On the glaciological, meteorological, and climatological significance of Antarctic blue ice areas. Reviews of Geophysics 37, 337–359.

Cresswell, R.G., 1988. Meteorite concentrations in Antarctica: Sites of katabatic wind ablation? Geophysical Research Letters 15, 342–245.

Drewry, D. J., 1983. Antarctica: Glaciological and Geophysical Folio. Scott Polar Research Institute, University of Cambridge.

Fujita, S., Maeno, H., Uratsuka, S., Furukawa, T., Mae, S., Fujii, Y., Watanabe, O., 1999. Nature of radio-echo layering in the Antarctic ice sheet detected by a two-frequency experiment. Journal of Geophysical Research 104 (B6), 13013–13124.

Glen, J.W., 1955. The creep of polycrystalline ice. Proceedings of the Royal Society of London A228, 519–538.

Gow, A.J., Rowland, R., 1965. On the relationship of snow accumulation to surface topography at Byrd Station, Antarctica. Journal of Glaciology 5, 843–847.

Hindmarsh, R.C.A., 2001. Notes on basic glaciological computational methods and algorithms, in: Greve, R., Ehrentraut, Y., Wang, Straughan, B. (Eds.), Continuum Mechanics in Geophysics and the Environment, Springer-Verlag, Berlin/New York.

Hindmarsh, R.C.A., Hutter, K., 1988. Numerical fixed domain mapping solution Of free-surface flows coupled with an evolving interior field. Int J Numer Anal Met 12 (4), 437–459.

Lythe, M.B., Vaughan, D.G., the BEDMAP consortium, 2000. BEDMAP — Bed topography of the Antarctic. 1:10,000,000 map. BAS (Misc.) International Journal for Numerical and Analytical Methods in Geomechanics. 9. Cambridge.

Parish, T.R., 1988. Surface winds over the Antarctic continent: A review. Reviews of Geophysics 26, 169–180.

Parish, T.R., Bromwich, D.H., 1987. The surface windfield over the Antarctic ice sheets. Nature 328, 51–54.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.M., Basile, I., Benders, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., Stievenard, M., 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399, 429–436.

Reeh, N., Oerter, H., Letreguilly, A., Miller, H., Hubberten, H.W., 1991. A new, detailed ice age oxygen 18 record from the ice sheet margin in Central West Greenland. Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section) 90, 373–383.

Siegert, M.J., Fujita, S., 2001. Internal ice-sheet radar layer profiles and their relation to reflection mechanisms between Dome C and the Trans Antarctic Mountains. Journal of Glaciology 47, 205–212.

Siegert, M.J., Hodgkins, R., 2000. A stratigraphic link across 1100 km of the Antarctic Ice Sheet between the Vostok ice core site and Titan Dome (near South Pole). Geophysical Research Letters 27, 2133–2136.

Siegert, M.J., Hodgkins, R., Dowdeswell, J.A., 1998. A chronology for the Dome C deep ice-core site through radio-echo layer correlation with the Vostok ice core, Antarctica. Geophysical Research Letters 25, 1019–1022.

Vaughan, D.G., Corr, H.F.J., Doake, C.S.M., Waddington, E.D., 1999. Distortion of isochronous layers in ice revealed by ground-penetrating radar. Nature 298, 323–326.

Watanabe, O., 1997. Antarctica: East Queen Maud Land - Enderby Land Glaciological Folio. National Institute of Polar Research, Japan.

Whillans, I.M., 1975. Effect of inversion winds on topographic detail and mass balance on inland ice sheets. Journal of Glaciology 14 (70), 85–90.

Winther, J.-G., Jespersen, M.N., Liston, G.E., 2001. Blue-ice areas in Antarctica derived from NOAA AVHRR satellite data. Journal of Glaciology 47, 325–334.