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Past rates of accumulation in central West Antarctica

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[1] The spatial variation in ice accumulation is critical to the form and stability of ice sheets. In West Antarctica, knowledge of present ice accumulation rates is restricted to sparse measurements and interpolations across data free regions, while information on former ice accumulation is restricted to a small number of ice cores and numerical modeling results. Here, isochronous internal ice sheet layers, recorded by airborne radio-echo sounding and dated at their stratigraphic position at the Byrd ice core site, are used to reconstruct the spatial pattern of accumulation across the main West Antarctic ice divide for the past 16,000 years. Mean accumulation calculated for the last 3100 years matches well to present-day accumulation rates, which is compatible with previous observations on Siple Dome. Accumulation between 6400 and 16,000 years ago is calculated to be around half that at present, in accordance with recent ice sheet modeling results. *INDEX TERMS:* 1223 Geodesy and Gravity: Ocean/Earth/atmosphere interactions (3339); 1827 Hydrology: Glaciology (1863); 9310 Information Related to Geographic Region: Antarctica; 9604 Information Related to Geologic Time: Cenozoic; 3349 Meteorology and Atmospheric Dynamics: Polar meteorology. **Citation:** Siegert, M. J., and A. J. Payne (2004), Past rates of accumulation in central West Antarctica, *Geophys. Res. Lett.*, *31*, L12403, doi:10.1029/2004GL020290.

1. Introduction

[2] *Whillans* [1976] showed that internal layers near Byrd Station in West Antarctica, recorded by radio-echo sounding (RES), reveal the ice sheet to have been stable for the past 30,000 years. He concluded that the englacial structures were compatible with the current accumulation and flow regime of the ice sheet. This conclusion has been debated over the last 30 years. Whereas the $\delta^{18}O$ signal from the Byrd ice core has been interpreted as recording an elevation increase of ~500 m at the Last Glacial Maximum (LGM) [*Grootes and Stuiver*, 1986], analysis of the core's air content suggests that the site was 200 m lower at this time [*Raynaud and Whillans*, 1982]. Ice sheet modeling is similarly equivocal on this issue. While some models have shown how the ice sheet could thicken at the LGM even though the accumulation rate halved [e.g., *Huybrechts*, 2002], others have claimed that a modern-type accumulation rate is required to replicate the LGM ice sheet [*Ackert et al.*, 1999]. In this paper we test the hypothesis that "the central West Antarctic Ice Sheet (WAIS) has not experienced change to its elevation or accumulation regime". If this hypothesis is correct, a 1-D ice thinning model used to calculate past rates of ice accumulation from RES layering should show the accumulation rates to be unchanged through time and comparable to modern measurements.

2. RES Layering and Ice Accumulation Rates

[3] Isochronous internal RES layers are traced across the centre of the WAIS dome (AB in Figures 1 and 2). AB is crossed by the 2001 International Trans Antarctic Scientific Expedition (ITASE) ground traverse radar line [*Welch and Jacobel*, 2003], which intersects with the Byrd ice core site. A depth-age relationship was established at the crossing point of AB and the ITASE line, by tracing internal layers to the Byrd ice core where they can be dated [*Hammer et al.*, 1994; *Blunier and Brook*, 2001; R. Jacobel, personal communication, 2004]. This depth-age relationship was used to assign the following ages to five internal layers along AB: 800, 3100, 5600, 6400, and 16,000 years (Figure 2a).

[4] Across the centre of an ice sheet, the position of an internal layer within the ice column is a function of three processes: ice accumulation, ice thinning/thickening and ice flow around subglacial obstacles. Assuming that internal layers are isochronous [*Vaughan et al.*, 1999a], and that the ice sheet is (and has been) in steady state, a 1-D vertical ice compression model can be used to calculate past ice accumulation rates at the ice divide. The approach used here assumes that the strain rate of the ice is constant with depth to a level h above the base, below which the strain rate decreases linearly to zero at the ice sheet base [*Dansgaard and Johnsen*, 1969]. The mean rate of ice accumulation responsible for the burial of an internal layer is given by:

$$c_{0-t} = \frac{2H-h}{2t} \ln\left(\frac{2H-h}{2y-h}\right) \quad , \qquad h \leq y \leq H, \tag{1}$$

where c_{0-t} is the average accumulation of ice from the present day ($t = 0$) to time t (positive as time before present), H is the total ice thickness, and y is the distance above the bed of an internal layer. This model requires a value for h, the thickness of the basal shear layer, which has previously been estimated at 400 m in Greenland [*Fahnestock et al.*, 2001], although it is acknowledged that the real value is actually not known. Despite this problem, the model is thought to be accurate in the upper ~80% of the ice column [*Philberth and Federer*, 1971], which makes its use here appropriate because the dated internal layers used in the calculations are mostly within the upper half of the ice column.

3. Accumulation Across the West Antarctic Ice Dome

[5] The accumulation rates calculated from all internal layers show a general decrease from north to south with

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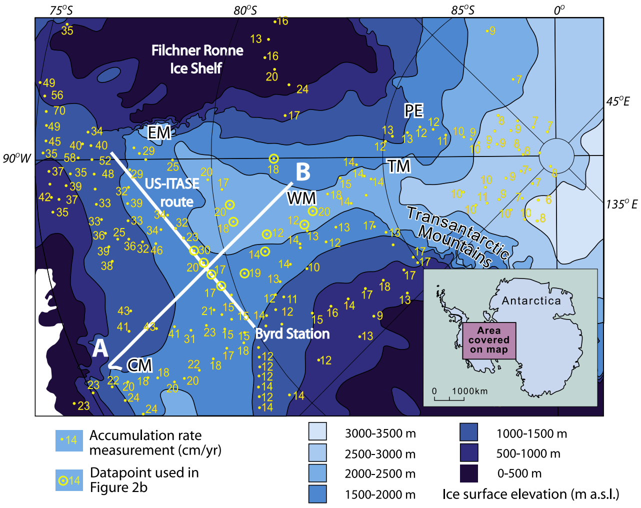

Figure 1. Location of RES transect AB and the 2001 ITASE traverse [*Welch and Jacobel*, 2003], superimposed on the ice surface elevation of West Antarctica [*Drewry*, 1983]. Digitized version of the raw radio-echo sounding record along AB is presented in Figure 2a. The locations and rates of in situ ice accumulation measurements are provided [adapted from *Bull*, 1971]. Abbreviations to mountain ranges are as follows: WM (Whitmore Mountains); CM (Crary Mountains); TM (Thiel Mountains); EM (Ellsworth Mountains); PE (Pechora Escarpment).

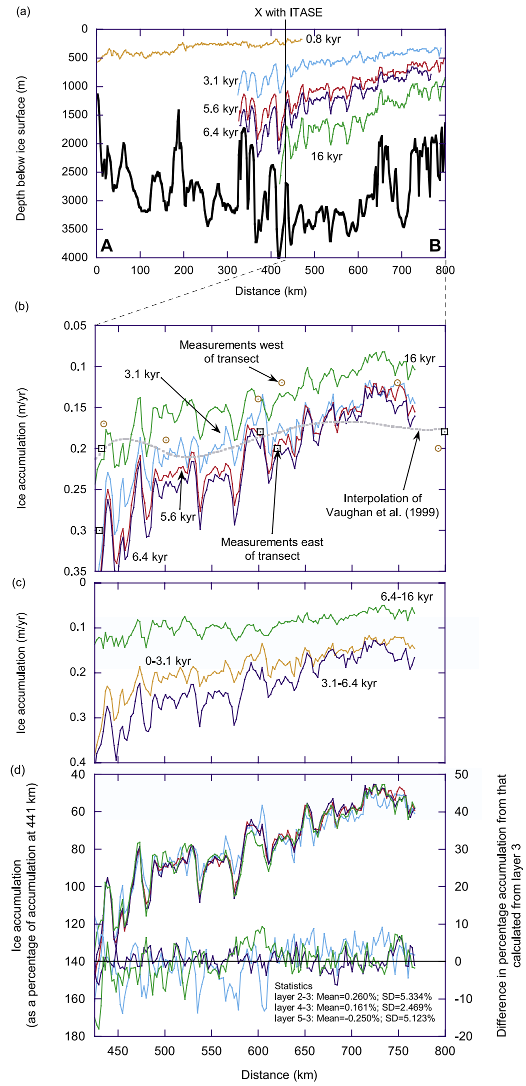

Figure 2. (a) Digitized RES records along AB. The raw data were recorded by the Scott Polar Research Institute in 1977, using a 60 MHz radio-echo sounder with a pulse width of 250 ns. The position of AB is illustrated in Figure 1. Five prominent internal layers are extracted from AB, and used to calculate ice accumulation rates. Layers are numbered from the top (1) to the bottom (5), and their respective colors are maintained in (b) and (d) but not in (c). Layers were dated through stratigraphic connection with the Byrd ice core (as annotated). The bed is denoted in black. (b) Ice accumulation rates between 425 and 800 km calculated for each dated RES layer. Also shown are direct surface measurements (shown in the figure as data points) that have been acquired within ~100 km of the transect (Figure 1) and an interpolation of surface measurements [after *Vaughan et al.*, 1999b]. (c) Ice accumulation rates calculated for the following periods: 0–3100, 3100–6400, and 6400–16,000 years (noted on the diagram in units of kyr). (d) Relative accumulation rates calculated for each internal layer as a percentage of accumulation at 441 km (upper group of lines). Differences in relative accumulation from that calculated for Layer #3 are provided in the lower group of lines. Statistics relating to the deviation of accumulation from that for Layer #3 are also given.

increasing distance from the coast (Figure 2b). Beneath the ice divide, from 425 to 800 km, ice accumulation calculated for the last 3100 years decreases from over 20 cm yr^{-1} to about 12 cm yr^{-1} (Figure 2b). Measurements of net surface accumulation taken within roughly 100 km of the RES transect (Figure 1), and an interpolated map of ice accumulation based on these measurements [*Vaughan et al.*, 1999b], compare well with the accumulation rate calculations for the past 3100 years between 500 and 700 km (Figure 2b). Either side of this 200 km long section, the comparison is less good, however. This mismatch is most probably a result of the considerable spatial variability in the data used to construct the accumulation record in *Vaughan et al.* [1999b]. Importantly, the results compare more closely either side of this section with new unpublished microwave derived estimates of ice accumulation (R. Arthern, unpublished data, 2004).

[6] Ice accumulation rates calculated from older internal layers are noticeably different to the present-day accumulation rates. The mean accumulation for both the past 5600 and 6400 years is slightly higher than for the past 3100 years (Figure 2b). Between 3100 and 6400 years ago, accumulation rates are, on average, ~3.0 cm yr^{-1} greater than today (Figure 2c). Conversely, accumulation rates between 6400 and 16,000 years ago are around 50% of modern rates (Figure 2c).

[7] Relative accumulation rates (i.e., the percentage accumulation calculated for an individual layer along AB relative to the value at position 441 km, Figure 2d) demonstrate both that the accumulation rate decreases spatially by ~50% from north to south across the ice dome, and that this spatial distribution is constant over time (for the last 16,000 years). Mean deviation from the relative

accumulation established from Layer #3 (the middle layer), and averaged between 425 and 800 km, is less than 0.3% in all cases (Figure 2d).

[8] It must be noted that the accumulation results are dependent on the ages assigned to internal layers. Internal layers along AB have a resolution of around ±40 m, which means the absolute error of internal layer dates increases with depth beneath the ice surface. Age errors for each of the five internal layers in AB, calculated at the intersection between AB and the ITASE transect, are as follows (percentage errors are in parentheses): Layer #1, 800 ± 156 years (±20%); Layer #2, 3100 ± 160 years (±5.2%); Layer #3, 5600 ± 175 years (±3.1%); Layer #4, 6400 ± 181 years (±2.8%); Layer #5, 16,000 ± 324 years (±2.0%). Although accumulation results presented in this paper should be viewed with these errors in mind, the main conclusions of the paper are unaffected (the percentage errors in age will equate with percentage errors in accumulation rates).

4. Testing the Hypothesis and Its Implications for Glacial History

[9] The hypothesis that "the central WAIS has not experienced change to its elevation or accumulation regime" appears consistent with calculations for the past 3100 years but not for earlier. Lower rates of ice accumulation between 6400 and 16,000 years are consistent with an elevation change of several hundred meters across the ice dome (based on empirical measurements by *Fortuin and Oerlemans* [1990], and as modeled by *Huybrechts* [2002]).

[10] The theory behind equation (1) involves an assumption that the ice thickness does not change in time. Consequently our use of inferred accumulation changes, calculated by equation (1), to propose past ice surface elevation changes may not be strictly appropriate. If the ice column thinned at a constant depth-related rate between 16,000 and 6400 years, then our calculations will be correct. If, however, the ice column did not thin uniformly with respect to depth (i.e., the bottom thinned disproportionately more than the top), then our calculations of past accumulation rates will be overestimates (i.e., maximum possible values).

[11] The spatial consistency of past relative accumulation rates is compatible with the idea that the ice sheet has not experienced major changes in either the position of its ice dome or regional atmospheric circulation. We should, however, consider what the possible alternative explanations for this consistency are. One is that the changes to internal layer structure caused by ice accumulation variation over time and space are countered by changes to the ice sheet flow regime, so leaving the layering unchanged. Although this is difficult to assess quantitatively, we regard this explanation as unlikely, given that small changes to the flow regime will affect the model's prediction of relative accumulation consistency (we can demonstrate this effect down a flowline where the flow regime is affected by divergence). A second explanation is that the model's calculation of consistent relative accumulation is simply incorrect (i.e., a more sophisticated model is required to model ice-sheet conditions in West Antarctica). The model's most significant assumption is that the shear layer, h, is constant across the ice sheet. In fact, it may change in space and time. Spatial variation in the shear layer will not make significant difference to the results; although the relative accumulation rates will change, their consistency over time will not. Temporal variation in the shear layer, h, will affect this consistency. We would expect such change to reduce the level of consistency, however, rather than maintain it. Further, if the observed accumulation rate patterns were due to errors in h one would expect the results to show some relation to ice thickness. We note that there is no relation between the calculated accumulation rates and local ice thickness.

5. Summary and Discussion

[12] Internal RES layering across the ice dome in central West Antarctica, dated at the intersection with the Byrd ice core, is used as input to a simple layer thinning model. Results reveal maximum estimates for the time-dependent change in accumulation in the past 16,000 years, which represent an important contribution to accumulation rate information currently lacking across the central West Antarctic ice divide. Accumulation for the past 3100 years is very similar to that at present. However, accumulation is slightly greater between 3100 and 6400 years, and about 50% of modern values between 6400 and 16,000 years.

[13] Steady rates of ice accumulation for the past 3100 years are consistent with analysis of RES layering from the Siple Dome, which reveal the ice dome and accumulation rates to have remained stable for the past 2000–5000 years [*Nereson et al.*, 1999] and be comparable to modern values [*Hamilton*, 2002].

[14] Low rates of ice accumulation between 16,000 and 6400 years may be associated with a rise in ice sheet surface elevation. The Vostok ice core record reveals a background temperature reduction in Antarctica of about 1.8°C between 16,000 and 6400 years [*Petit et al.*, 1999]. Such a temperature change is unlikely to cause sufficient reduction to water-vapor pressures (and, thus, accumulation rates) and, so, another process is required. *Stone et al.* [2003] calculated that the ice sheet across Marie Byrd Land (located to the north of the main ice dome in West Antarctica) has thinned by as much as 700 m over the past 10,000 years. This result compares well with recent numerical ice sheet modeling [*Huybrechts*, 2002], in which the main ice divide in West Antarctica was several hundred meters higher at ~7000 years ago compared with today. In such case, ice accumulation rates are likely to be lowered through (1) a reduction in air temperature which leads to significant decline in the water vapor pressure [e.g., *Lorius et al.*, 1985], and (2) the resulting topographic barrier, which may inhibit the propagation of storm tracks. The reconstruction of *Huybrechts* [2002], in which former low ice accumulation rates are linked to an enhanced elevation, finds support in our results. As the spatial variation in relative accumulation constant through time it then follows that atmospheric circulation patterns, dictating the paths of storm tracks across the ice sheet, must have changed in a manner which preserves this consistency.

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References

Ackert, R. P., D. J. Barclay, H. W. Borns et al. (1999), Measurements of past ice sheet elevations in interior West Antarctica, *Science*, *286*, 276–280.

Blunier, T., and E. J. Brook (2001), Synchronization of the Byrd, Greenland (GISP2/GRIP) records, http://www.ngdc.noaa.gov/paleo/pubs/blunier2001/blunier2001.html, World Data Cent. for Paleoclimatol., Boulder, Colo.

Bull, C. (1971), Snow accumulation in Antarctica, in *Research in the Antarctic*, edited by L. O. Quam, pp. 367–421, Am. Assoc. for the Advance. of Sci., Washington, D. C.

Dansgaard, W., and S. J. Johnsen (1969), A flow model and a time-scale for the ice core from Camp Century, Greenland, *J. Glaciol.*, *53*, 215–223.

Drewry, D. J. (Ed.) (1983), *Antarctica: Glaciological and Geophysical Folio*, Scott Pol. Res. Inst. Univ. of Cambridge, Cambridge, U. K.

Fahnestock, M., W. Abdalati, S. Luo, and S. Gogineni (2001), Internal layer tracing and age-depth-accumulation relationships for the northern Greenland ice sheet, *J. Geophys. Res.*, *106*, 33,789–33,798.

Fortuin, J. P. F., and J. Oerlemans (1990), Parameterization of the annual surface temperature and mass balance of Antarctica, *Ann. Glaciol.*, *14*, 78–84.

Grootes, P. M., and M. Stuiver (1986), Ross ice shelf oxygen isotopes and West Antarctic ice sheet history, *Quat. Res.*, *40*, 70–80.

Hamilton, G. S. (2002), Mass balance and accumulation rate across Siple Dome, West Antarctica, *Ann. Glaciol.*, *35*, 102–106.

Hammer, C. U., H. B. Clausen, and C. C. Langway (1994), Electrical conductivity method (ECM) stratigraphic dating of the Byrd Station ice core, Antarctica, *Ann. Glaciol.*, *20*, 115–120.

Huybrechts, P. (2002), Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles, *Quat. Sci. Rev.*, *21*, 1–3, 203–231.

Lorius, C., J. Jouzel, C. Ritz et al. (1985), A 150,000-year climate record from Antarctic ice, *Nature*, *316*, 591–596.

Nereson, N. A., C. F. Raymond, R. W. Jacobel, and E. D. Waddington (1999), The accumulation pattern across Siple Dome, West Antarctica, inferred from radar-detected internal layers, *J. Glaciol.*, *46*, 75–87.

Petit, J. R., et al. (1999), Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, *399*, 429–436.

Philberth, K., and B. Federer (1971), On the temperature profile and the age profile in the central part of cold ice sheets, *J. Glaciol.*, *10*, 3–14.

Raynaud, D., and I. M. Whillans (1982), Air content of the Byrd core and past changes in the West Antarctic ice sheet, *Ann. Glaciol.*, *3*, 269–273.

Stone, J. O., G. A. Balco, D. E. Sugden et al. (2003), Holocene deglaciation of Marie Byrd Land, West Antarctica, *Science*, *299*, 99–102.

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

Vaughan, D. G., J. L. Bamber, M. Giovinetto et al. (1999b), Reassessment of net surface mass balance in Antarctica, *J. Clim.*, *12*, 933–946.

Welch, B. C., and R. W. Jacobel (2003), Analysis of deep-penetrating radar surveys of West Antarctica, US-ITASE 2001, *Geophys. Res. Lett.*, *30*(8), 1444, doi:10.1029/2003GL017210.

Whillans, I. M. (1976), Radio-echo layers and the recent stability of the West Antarctic ice sheet, *Nature*, *264*, 152–155.

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