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NOTE

A Terrestrial Analogy for Martian "Accublation Zones" Revealed by Airborne Ice-Penetrating Radar from the East Antarctic Ice Sheet

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The surface of the northern martian ice cap is known to contain alternating white–dark scarp–trough features, and one method of their formation involves spatially coherent patterns of ice accumulation and ablation via sublimation. In this so-called "accublation" model, the internal ice sheet layers submerge into the ice sheet across the accumulation zone and emerge to the ice surface across the ablation region. Here we report on an Antarctic analogy to the martian accublation model, which demonstrates that surface mass balance conditions actually affect internal ice-sheet structure as predicted by D. A. Fisher (2000, *Icarus* 144, 289–294). This analogy shows how it is possible for ancient ice to become exposed at the surface of an ice sheet, allowing the paleoclimate record stored within the ice to be measured without the need for deep ice coring. © 2002 Elsevier Science (USA)

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 by acidic layers of ice caused by the aerosol product of volcanic events deposited formerly on the ice surface (Fujita *et al*. 1999). Internal layers are also thought to be isochronous. Generally, internal radar layers converge in vertical section over subglacial hills and diverge across subglacial troughs. However, in at least one site in central East Antarctica, internal radar layers have a different relationship to the subglacial topography (see Fig. 1). At this location, glacier ice from over 500 m below the ice surface is exposed at the surface (blue ice) as ice flows across the stoss face of a subglacial hill. Ablation in this blue ice zone, required to remove 500 m of ice, must derive from katabatic-wind-driven sublimation (Cresswell 1988) as surface temperatures never approach the melting point of ice. Over the lee side of the hill, net accumulation of ice causes a stratigraphic unconformity between the former ice surface and the recent ice above (see Fig. 1).

The Antarctic subsurface ice-sheet structure revealed from the internal radar layers (see Fig. 1) represents an Earth analogy for the flow trajectory of ice across scarp–trough surface features on the northern ice cap of Mars. In the same way that Antarctic ice emerges across the blue ice zone, and then submerges beneath an unconformity downstream (see Fig. 1), numerical modelling has shown that martian ice may outcrop as a consequence of sublimation over 20-km-wide "dark zones" and then be covered downstream by accumulation across 60-km-wide "white zones" (see Fig. 2) (Fisher 1993, 2000).

Although the physical dimensions of the blue ice zone and the accublation zones are comparable, the main difference between them involves the rates of ice flow and ice accumulation/ablation. In Antarctica, ice accumulation rates and ice flow are on the order of centimeters per year and meters per year, respectively. This means than the age of ice exposed at the surface of the Antarctic ice sheet will be on the order of tens of thousands of years. The extremely low accumulation rates on Mars (anticipated to be less than 1 mm per year) mean that subsurface ice is much older than ice at comparable depths in Antarctica (it is possible that the age of the martian "blue ice" is on the order of millions of years).

The discovery of an accublation zone on Earth demonstrates that the model for similar processes on Mars is feasible. There are two major implications of our Earth analogy of emergent ice on Mars. First, climate records can be sampled from the surface of the martian ice cap, and indeed Antarctica, without the need for deep ice coring. Second, meteorites and dust will collect on the ice surface on Mars in the same way as they do over Antarctic blue ice zones but over a much longer timescale, which, together with the relatively higher flux of dust can explain why the surfaces of the sublimation zones on the northern martian ice cap are far dirtier than they are on Earth.

The next step in the research is to model accurately the flow of ice across the Antarctic emergence zones by matching calculated isochrons to the internal radar layers. When this model is perfected it could be applied to the northern ice cap of Mars. However, this application would require measurements of ice thickness and internal layers. This is only possible through the use of ice-penetrating radar. Over the next few years, the Mars Express project aims to undertake such a study, which, if our analogy is appropriate, could result in the identification of sites on the martian ice surface for paleoclimate data collection.

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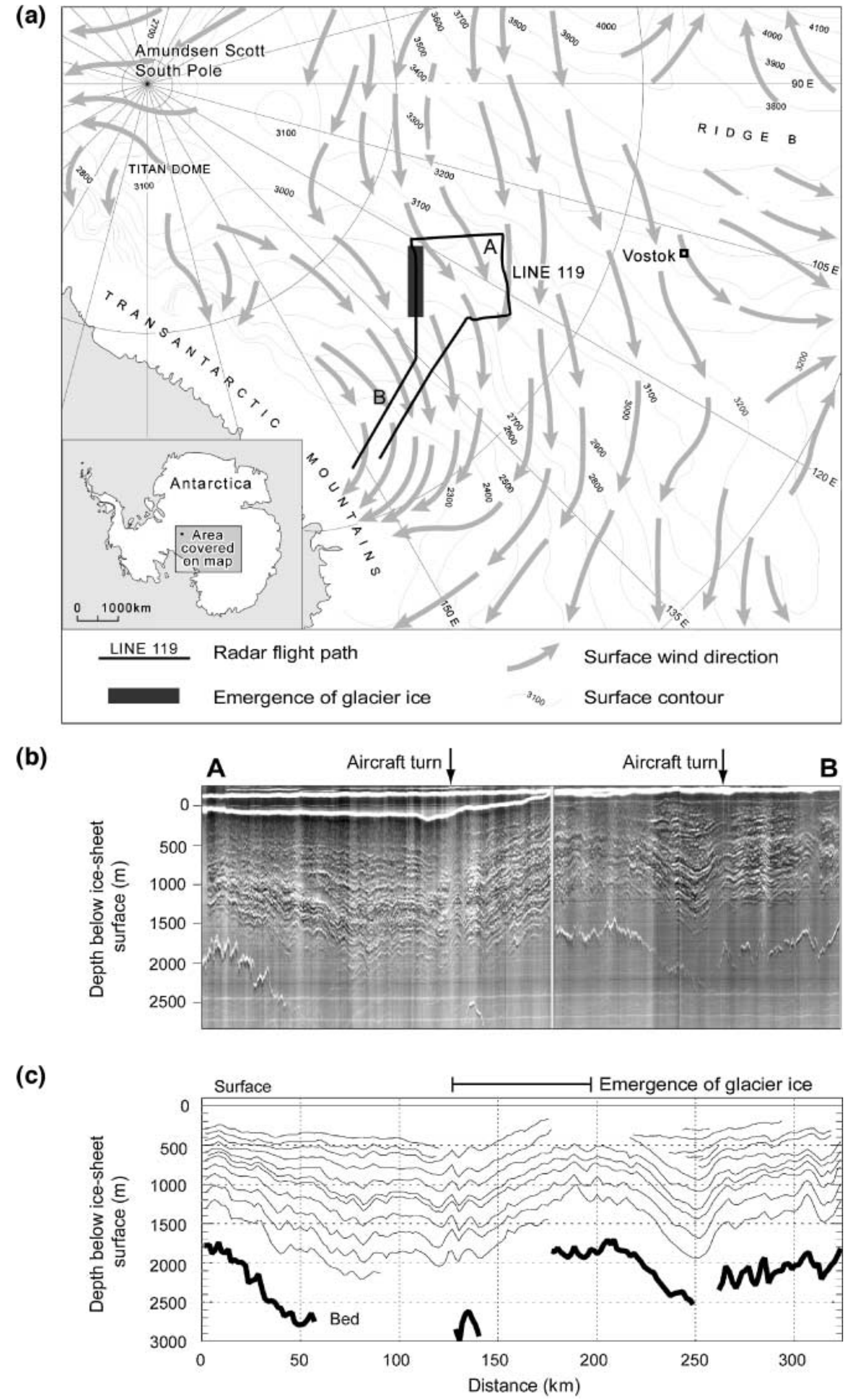

FIG. 1. Airborne radar evidence for ancient ice outcropping at the surface of the Antarctic ice sheet. (a) The location of radar transect AB. Arrows denote the direction of katabatic surface winds (Parish and Bromwich 1987, Parish 1988), which cause the removal of snow and ablation of ice leading to the exposure of glacier ice at the ice-sheet surface. (b) 60 MHz airborne radar data along AB. The top line in the radar section is caused by the direct wave, from transmitter to receiver. This is followed by a second, caused by the reflection from the surface of the ice sheet. The separation of these lines corresponds inversely with the altitude of the aircraft above the ice surface. The vertical white bar in the middle of the section represents a short break in record most likely caused by a problem with the radar equipment. (c) Processed radar data along AB. 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 the former ice surface and recently accumulated ice between 220 and 250 km along the transect. The temporal discontinuity in the depth–age relationship formed by the unconformity is an inherent feature of "accublation" regimes on the northern martian ice cap (Fisher 1993, 2000). The "bed" (base of the ice sheet) appears discontinuous on the record simply because the radar equipment failed to record the base reflector on three occasions.

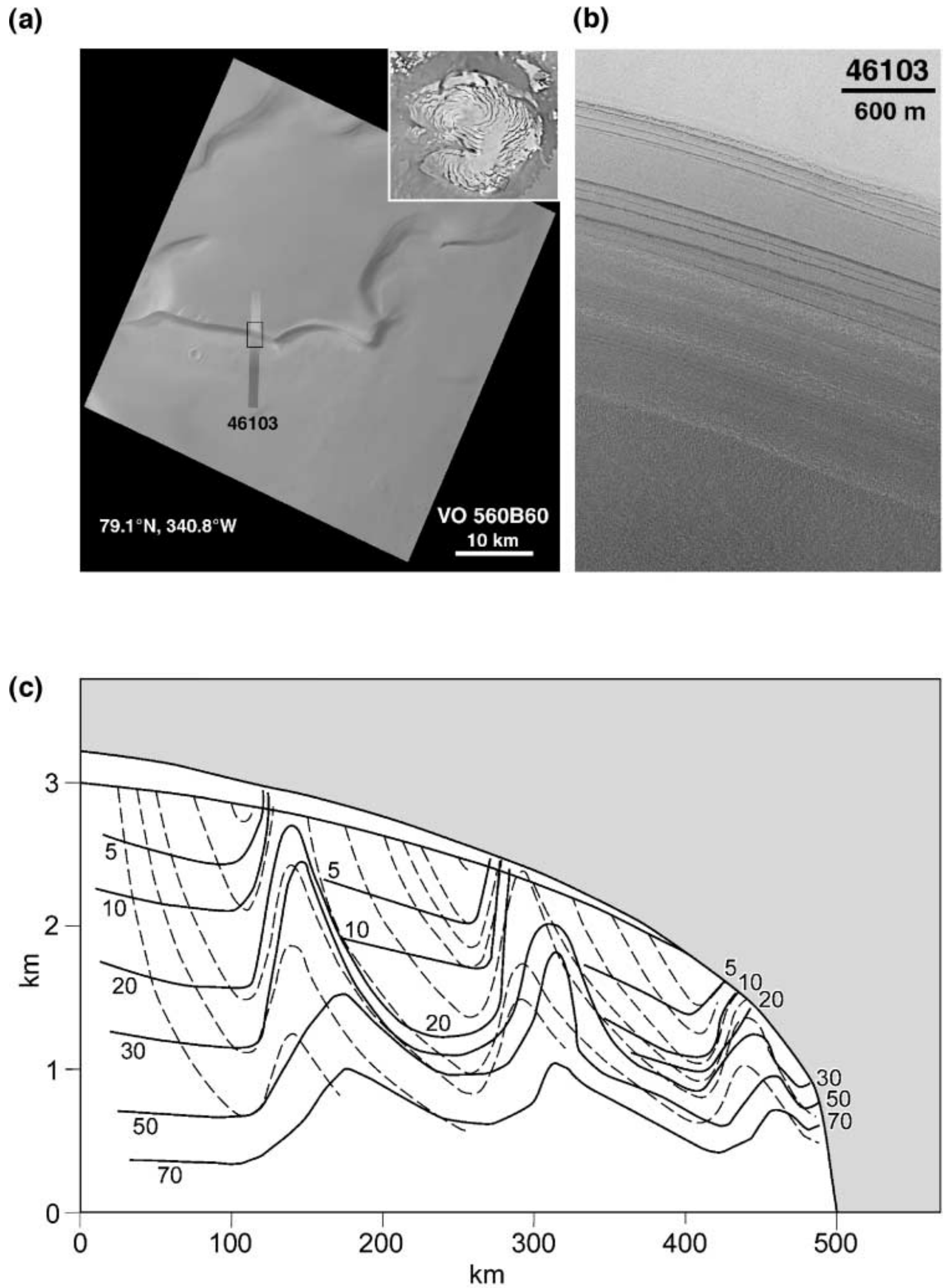

FIG. 2. Evidence from the Mars Orbital Camera (MOC) for ancient ice exposures on the surface of the northern martian ice cap, and from numerical modelling for "accublation" zones. (a) Viking Orbiter 2 (VO2) image of the northern martian ice cap. The box denotes the position of MOC data, while the inset shows the whole ice cap and the location of the VO2 image. (b) MOC image of the North Polar Layered Deposits. It should be noted that this example of surface banding is near to the ice sheet margin. It is, therefore, unlikely that a "white" accumulation zone will appear downstream of this site. These data are, however, representative of surface banding within the ice sheet interior, where alternating white and dark strips have been observed. (c) Numerical model results of the flow of ice through a cross section of the northern martian ice cap (Fisher 2000). The dashed lines refer to ice particle flow paths and the continuous lines are the isochrons, which are comparable to the internal radar layers observed in Antarctica (Fig. 1). In this model, ice outcrops in three places due to surface sublimation of ice. If this model is correct, the sublimation zones would correspond with layered surface deposits. Downstream from the regions of exposed ice, the ice submerges beneath a stratigraphic unconformity due to the deposition of fresh ice over the former ice surface. The VO2 and MOC data appear courtesy of Malin Space Science Systems/NASA (http://mars.jpl.nasa.gov/mgs/msss/camera/images/10_19_98_polar_release/10_19_98_npld_rel/index.html).

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