FORTY-THREE

Antarctic Ice Sheet reconstruction using cosmic-ray-produced nuclides

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43.1 The problem: finding, mapping and dating Antarctic ice-marginal deposits

The Antarctic Ice Sheets are the largest extant ice masses on Earth, and understanding their history is relevant not only to past environmental changes but also to ongoing changes in global climate and sea level. The glacial-geological record in Antarctica provides a means of reconstructing this history, but the unique features of the Antarctic environment present several challenges that do not arise in more temperate latitudes. In addition to the basic fact that the Antarctic continent is nearly completely covered in ice, leaving few exposed surfaces on which glacial deposits might be preserved, much of the ice in Antarctica is frozen to its bed. It transports little sediment to the terrestrial ice margins that do exist, and may advance and retreat repeatedly without appreciably disturbing the landscape. Antarctic moraines and glacial drift are usually very thin, often consisting only of scattered cobbles on an otherwise bare bedrock surface. The combination of cold-based ice and extraordinarily slow rates of subaerial erosion during ice-free periods means that the deposits of both recent and long-past glacier advances and retreats may not only be found together, but be nearly indistinguishable. Finally, not only is it difficult to identify and correlate ice-marginal deposits, but there exist few ways to date them. Organic material that could be radiocarbon dated is rarely found outside of coastal areas, and waterlain sediment suitable for optical dating techniques is equally unusual.

43.2 A solution: exposure-age dating with cosmic-ray-produced nuclides

The chief recent advance in understanding the history of the Antarctic Ice Sheets, therefore, has been the development of a dating technique that is perfectly suited to the Antarctic landscape: exposure-age dating with cosmic-ray-produced nuclides. This relies on the measurement of rare nuclides such as ^{10}Be, ^{26}Al and ^{3}He, which are produced within mineral grains by cosmic-ray bombardment of rocks exposed at the Earth's surface. These nuclides are useful for dating ice-marginal deposits because nearly all cosmic rays stop within a few metres below the rock (or ice) surface, so any clast that is quarried by subglacial erosion at the bed of the ice sheet and brought to the ice margin arrives there with a negligible nuclide concentration. The surface production rate of these nuclides varies in a predictable way with altitude (Stone, 2000), and once this is determined, the nuclide concentration in an erratic cobble or boulder is related only to the duration of subsequent surface exposure, that is, the time since the ice margin lay at that position. Thus any erratic, lying on any previously glaciated surface, is a record of the past ice-sheet configuration. Inferring deglaciation ages from nuclide concentrations in erratics relies only on the two assumptions that the rock samples of interest have been emplaced with zero nuclide concentration, and that they have not been eroded, moved, or covered with a significant thickness of soil or snow since exposed by ice retreat. In principle, these assumptions could be true of bedrock surfaces eroded subglacially and exposed by deglaciation as well as erratic clasts. The important difference is that, in practice, there is generally no assurance that subglacial erosion was sufficient to remove any nuclide inventory that might date from a previous period of exposure (e.g. Briner & Swanson, 1988). Cosmic-ray-produced nuclide concentrations in bedrock surfaces can provide some information about glacial history (e.g., Stroeven *et al*., this volume, Chapter 90); however, they are hard to interpret. For Antarctic erratics, on the other hand, both assumptions are nearly always met. First, the extreme scarcity of exposed rock, and near absence of supraglacial debris, in most of the continent means that any glacially transported clast was almost certainly derived

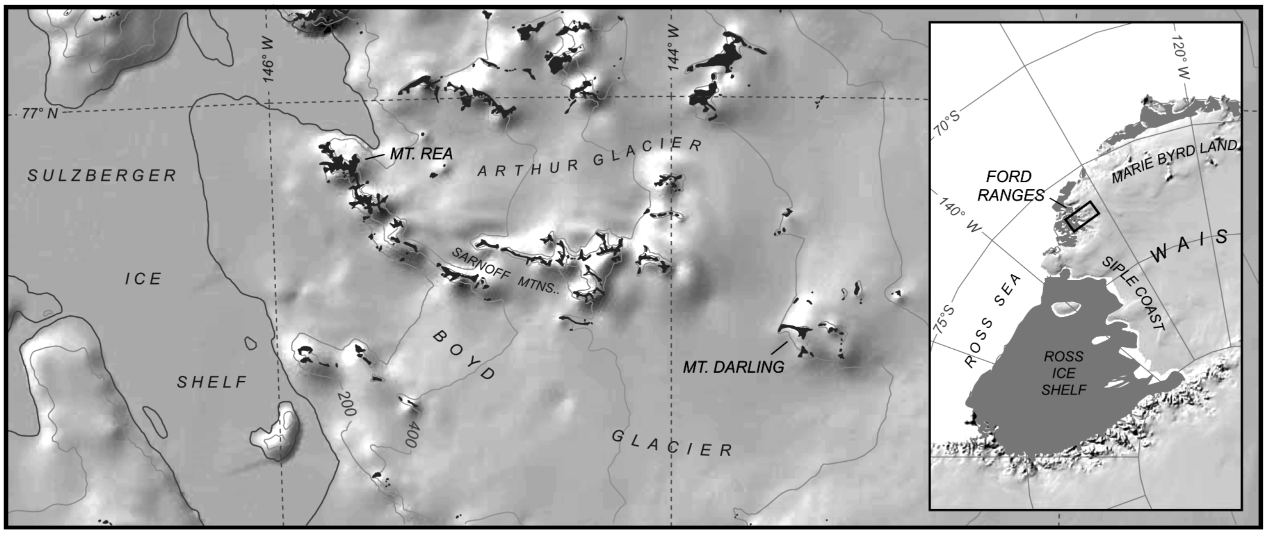

Figure 43.1 Map of part of the Ford Ranges of Marie Byrd Land, West Antarctica. Shaded-relief background from RAMP-DEM version 2; vector data from the Antarctic Digital Database.

from the glacier bed and thus will have negligible inheritance. In the case of erratics of lithologies that do not crop out at all above the ice surface, this assumption is always true. Second, once such a clast arrives at the ice margin, the typical occurrence of only thin and patchy glacial deposits, and the windy, arid climate of most nunataks, mean that it is unlikely to be covered by soil or snow, and the extremely slow rates of erosion ensure that it is preserved unmodified for very long periods of time.

43.3 An example from the Ford Ranges of West Antarctica

The Ford Ranges of West Antarctica consist of scattered nunataks that separate large outlet glaciers draining the interior of the West Antarctic Ice Sheet into the Sulzberger Ice Shelf (Figs 43.1 & 43.2). Ice-free surfaces in the Ford Ranges consist mostly of steep slopes of bare granite and phyllite bedrock or locally derived talus and blockfields. Striated surfaces at all elevations indicate past overriding by the ice sheet. Ice retreat is recorded only by a few patches of thin till and by erratic cobbles scattered on rock surfaces (Fig. 43.2). We collected such erratic cobbles from a range of elevations on several nunataks, measured ^{10}Be concentrations, and found that they yielded a precise record of continuous Holocene lowering of the ice-sheet surface and consequent exposure of the peaks (Stone *et al*., 2003; Fig. 43.2). Analyses of adjacent cobbles from a few sites agreed within analytical uncertainty, and cobbles very close to the ice margin had exposure ages of only a few hundred years, reinforcing the idea that these cobbles arrived at the ice margin with no inherited nuclide inventory. Sets of cobbles from single nunataks yielded smooth deglaciation histories, and adjacent nunataks produced similar results, indicating that the cobbles had not been significantly covered by snow or sediment, and had not moved since they were emplaced. A few nunataks, however, yielded more complicated results. At Mount Rea (Fig. 43.2) we found that samples at lower elevations, as well as the youngest sample near the summit, recorded the same Holocene deglaciation as on nearby nunataks. At higher elevations, we found many erratics that were physically indistinguishable from Holocene erratics, but had very much greater exposure ages. Some of these old erratics also had ^{26}Al/^{10}Be ratios below the surface production ratio of 6.1, indicating that they had been covered by ice for long periods (Cowdery, 2004; also see Stroeven *et al*., this volume, Chapter 90). It appears that these erratics were deposited during long-past episodes of ice retreat, and remained undisturbed by subsequent ice advances: their ^{10}Be concentrations integrate several periods of exposure in addition to the most recent one. These repeatedly exposed erratics persist through multiple glacial–interglacial cycles, not only because of the ineffectiveness of weathering processes that might degrade or destroy them during ice-free periods, but also because of the common occurrence of cold-based ice at higher elevations where overriding ice was thinner. Although some parts of Antarctica (the McMurdo Dry Valleys in particular, where surfaces have been exposed for millions rather than thousands of years, and weathering and periglacial disturbance are correspondingly more important) present additional complexities in interpreting cosmogenic-nuclide measurements, much of Antarctica is similar to this example from the Ford Ranges. The near absence of ice-free areas that might supply pre-exposed erratics, the minimal ice-marginal sediment accumulations, and the very slow rates of weathering provide the best possible environment for reconstructing ice-

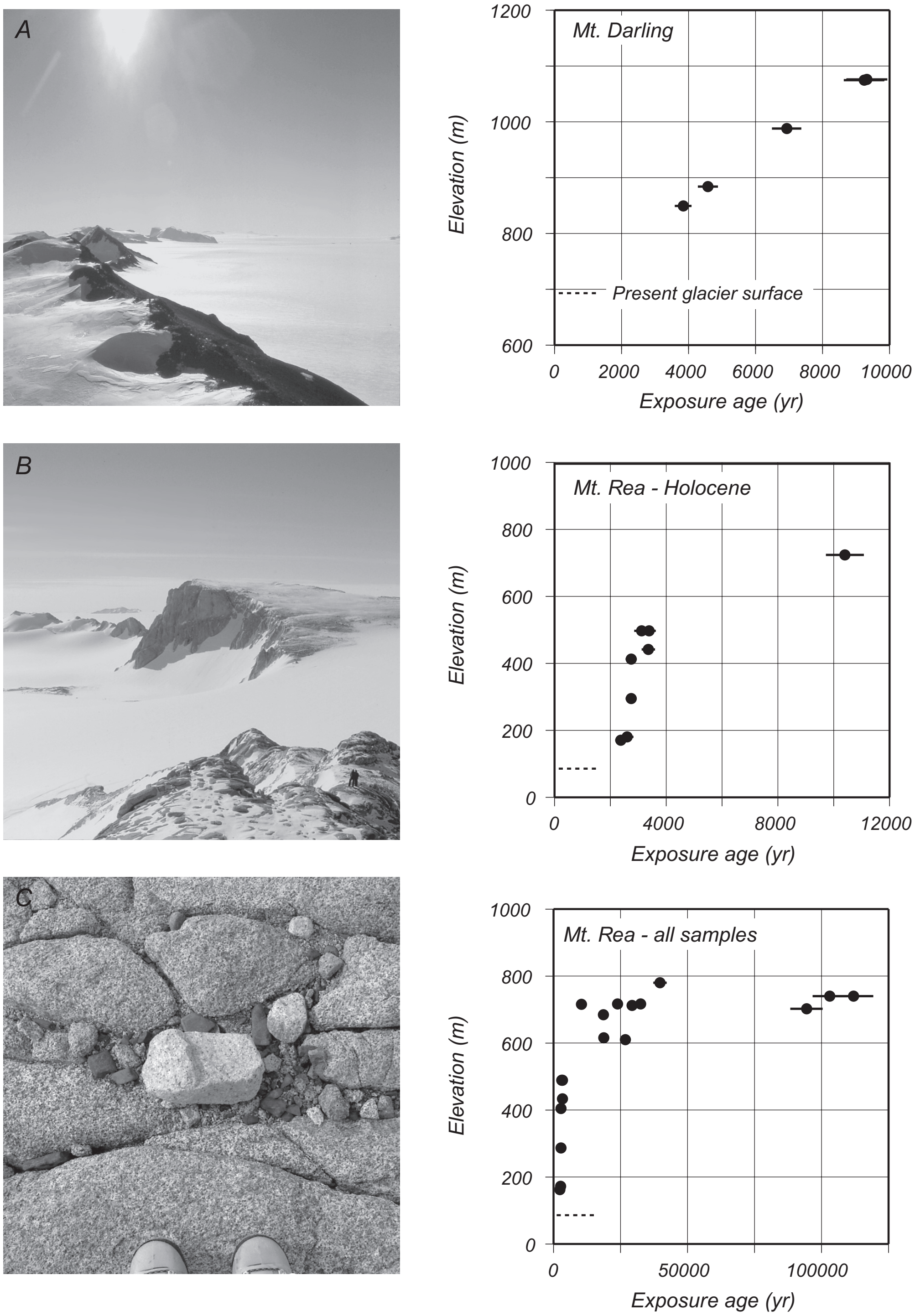

Figure 43.2 Exposure ages of glacial erratics from the Ford Ranges. Photographs: (A) View of the western Sarnoff Mountains and the Mount Rea massif from the east. (B) View of Mount Darling seen from the south. Ice flow is from right to left. (C) Typical granite erratic, resting on granodiorite, in the eastern Sarnoff Mountains. Panels to right: ^{10}Be exposure ages of erratic cobbles from Ford Ranges nunataks. These data were previously published in Stone *et al.* (2003) and Sugden *et al.* (2005).

sheet history by exposure-age dating. If the goal is to accurately reconstruct the most recent deglaciation, it is important to keep in mind that glacial erratics may survive many ice advances and retreats without being disturbed. On the other hand, these persistent erratics are a unique source of other useful information: evidence of the past subglacial temperature distribution, and a potential record of not one but many past ice advances and retreats.