Cosmogenic glacial dating, 20 years and counting

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Using cosmogenic isotopic analyses of less than two dozen samples, Mackintosh et al. (2007 [this volume, p. 551–554]) lift the veil of suspicion that has hung over the East Antarctic Ice Sheet. No longer should it be considered a major player in postglacial sea-level rise. Until just 20 years ago, when pioneering work in accelerator mass spectrometry (Elmore and Phillips, 1987), cosmogenic isotope systematics (Lal, 1988), and geologic applications (Craig and Poreda, 1986; Kurz, 1986) hit the presses, such conclusions were unreachable because many hypotheses regarding rates and dates of glacial processes were simply unfalsifiable. In two short decades, we have learned so much about when glaciers and ice sheets retreated that it's hard to imagine a world where glacial boulders were not targets for dating. Yet, children born when the first paper using cosmogenic nuclides to date such erratics was published (Phillips et al., 1990) are still not old enough to vote.

Mackintosh et al. took a simple and oft-used approach for characterizing the vertical extent of now-vanished ice. They used protruding mountains as chronometric dipsticks (e.g., Stone et al., 2003), analyzing the ^{10}Be and ^{26}Al content of submeter erratics left behind as the East Antarctic Ice Sheet lowered. For the most part, the model ages they calculate decrease with elevation, suggesting gradually thinning ice since the Last Glacial Maximum. The important finding is that many of the erratics are young and found only below a certain elevation, setting limits on ice thickness in the past and restricting the timing of ice sheet lowering to the latest Pleistocene and much of the early Holocene. These ages are young enough that they are inconsistent with the East Antarctic Ice Sheet contributing significantly to late Pleistocene sea-level rise. Similarly, the decrease in ice thickness that Mackintosh et al. infer is several times less than that implied by ice sheet models, and small enough that it effectively precludes ice extending to the shelf margin. Thus, they suggest that East Antarctic Ice Sheet volume changes are at most a minor factor in sea-level change after the Last Glacial Maximum.

It's not surprising that the authors avoided sampling bedrock underlying the erratics. In areas where ice has been frozen to the bed, concentrations of cosmogenic nuclides in bedrock often tell a garbled story (Bierman et al., 1999). The chronologic gibberish results from intermittent exposure of the rock to cosmic rays; between periods of surface or near-surface exposure, radioactive isotopes are no longer produced but rather decay under a passive cover of non-erosive ice. Those who want to date deglacial events refer to the fraction of cosmogenic nuclides left behind from prior periods of exposure as *inheritance* and do their best to avoid it (Davis et al., 1999). For others, this inheritance is a treasure trove of information about the stability of landscapes under ice and the distribution of erosion as a function of landscape position (Briner and Swanson, 1998; Colgan et al., 2002; Marquette et al., 2004). In any case, the cumulative isotope concentration tells the story of multiple but inseparable periods of exposure and burial.

Measuring a pair of isotopes with contrasting half-lives, most often ^{10}Be/^{26}Al, with ^{14}C now coming into vogue, can provide additional information about bedrock and erratic history (Bierman et al., 1999). Measurement of paired isotopes in glacial erratics has been done before (Davis et al., 1999; Marsella et al., 2000), but Mackintosh et al. use it as a powerful tool by which to reject data from two erratics that clearly had a history of prior exposure and substantial burial before they were abandoned by the retreating East Antarctic Ice Sheet. Four other erratics gave older but concordant ^{10}Be/^{26}Al ages; these were excluded from the analysis because their model ages did not conform to the age and elevation relationship that characterized younger samples. In glacial terrains, both north and south, paired isotope analyses of bedrock have become a powerful means for elucidating conditions at the bed of former ice sheets (Briner et al., 2006). For Mackintosh et al., field data on erratic shape serve the same purpose. Many analyzed erratics are striated, faceted, polished, and subrounded—all clues that the ice that transported them was once, at least in part, warm-based.

Figure 1. A fresh, young, angular erratic (left) perched on rounded, deeply weathered gneissic bedrock illustrates the complexity of cosmogenic dating in terrain where glacial ice has been frozen to the bed. This is the area above Pangnirtung Fiord on Baffin Island. The erratic has similar ^{10}Be and ^{26}Al model ages (Bierman et al., 2001), suggesting that melting ice exposed it ca. 10 ka. The weathered bedrock has a complex exposure history >700 k.y (Bierman et al., 1999, 2001).

Although there remain lingering uncertainties in these and other cosmogenic dates, there is no indication such uncertainties would change Mackintosh et al.'s fundamental conclusions. The dates Mackintosh et al. present, and many others measured on glacial erratics, show significant scatter (Putkonen and Swanson, 2003). Some of this reflects analytic uncertainty (particularly for ^{26}Al), but much of the noise is likely the result of small and variable amounts of inheritance and erosion as well as unknown and unknowable periods of burial and snow cover (Hallet and Putkonen, 1994; Schildgen et al., 2005). While the precision of glacial landform dating is likely to remain limited by geologic uncertainties, the accuracy of cosmogenic ages should continue to improve as the CRONUS (cosmic-ray produced nuclide systematics) initiative further constrains many of the "constants" needed for calculation, including production rate scaling over time and space.

It is worth considering the broadest implications of what Mackintosh et al. conclude. Most important is their suggestion that the East Antarctic Ice Sheet responds more to sea level than to direct climatic forcing, including changes in temperature and precipitation. The inter-hemispheric link Mackintosh et al. set out should leave us thinking. The authors imply that post-glacial East Antarctic Ice Sheet shrinkage is driven by rising sea

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Geology, June 2007; v. 35; no. 6; p. 479–480; doi: 10.1130/focus062007.1; 1 Figure.

levels that decouple ice from its bed and are the direct result of melting of northern hemisphere glaciers. Even though the mass balance of the East Antarctic Ice Sheet appears stable or perhaps even positive at the moment, if greenhouse-induced warming ravages the Greenland Ice Sheet, history could repeat itself. Northern hemisphere ablation, via the sea-level connection, would once again diminish Southern Hemisphere ice, pouring more water into already rising oceans—a powerful, positive feedback. If these linkages are correct, then the power of atom counting and the implications of Mackintosh et al.'s data may be far broader than their paper modestly suggests.

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