

Possible redeposition of volcanic ashes in the Dry Valleys by glacier transport

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Summary Debate continues whether Antarctica has been in a stable deep freeze since the Miocene or experienced major fluctuations in climate and glacier extent though the Pliocene. A key question here is whether ashes are *in situ* and postdate their underlying deposits. There are at least three reasons suggesting that some of these ashes are reworked. First, we found blocks of glacially-transported ash in Beacon Valley. After disintegrating, these erratics leave localized deposits of relatively pure volcanic ash that is much older than the surfaces they overlie. Second, most surface-age estimates older than 2 Ma in the Dry Valleys are based on the eruption (Ar-Ar) ages of these reputed *in situ* tephra. In contrast, the majority of cosmogenic exposure ages are younger. Third, geomorphic and weathering processes are active today in Dry Valleys, indicating a younger landscape than Miocene age implied by the ancient tephra eruption ages.

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Introduction

Controversy continues over the geological history of the Dry Valleys. The “Stabilist” school argues the Dry Valleys have been locked in a cold, hyper-arid climate similar to present for at least 14 Myr (Denton et al., 1993; Marchant and Denton, 1996; Marchant et al., 1993a; Marchant et al., 2002; Sugden and Denton, 2004). On the other side, the “Dynamicist” school argues that the Dry Valleys experienced repeated fluctuations in climate accompanied by significant geomorphic changes until ca. 2.5 Ma when the East Antarctic Ice Sheet assumed its present extent and glaciological characteristics (Barrett et al., 1992; Hambrey and McKelvey, 2000a; Harwood and Webb, 1998; McKelvey, 1991; Webb et al., 1984; Wilson, 1995). Resolving this controversy is important because the dynamics of the Antarctic climate and ice sheets have global-scale impacts. The Dry Valleys are a key site because they are one of the few ice-free places in Antarctica where ice-sheet and climate history can be studied. The linchpin of the Stabilist model is the dating of volcanic ashes in the Dry Valleys (Marchant et al., 1996; Marchant et al., 1993b). The eruptive ages of these ashes—some as old as the middle Miocene—have been interpreted as also being their depositional ages and then used to constrain landscape surface ages (Lewis et al., 2006; Marchant et al., 1993a; Marchant et al., 1996; Marchant et al., 2002). The key question is whether some or all of these ashes have been reworked from older deposits.

New Observations

Erratic blocks of volcanic ash

In Beacon Valley, we observed two blocks of volcanic ash in sublimation till on the surface of the purported Miocene-aged glacial ice (Marchant et al., 2002; Sugden et al., 1995). One of these blocks measured about 1 x 1 m and consisted of greenish yellow tephra ranging in particle size from very fine to coarse sand (Figure 1). The other erratic tephra block was finer grained, mainly clay to very fine sand in texture. It measured about 2 x 2 m and was partly exposed in the flank of a polygon trough in an area of thick sublimation till. This block was beige to white in color and had a massive, unstratified structure. Where naturally exposed, this tephra block was releasing a fine white powder that was blowing in the wind. The presence of these erratic blocks of volcanic ash suggests that similar ash erratics could be the source for some of the deposits of Tertiary-aged volcanic ash found in ice-wedge cracks and on the surface of till sheets in the Dry Valleys (Marchant et al., 1996; Marchant et al., 2002; Marchant et al., 1993b). Thick, englacial tephra deposits are well-known from Antarctica and are known to be transported great distances within glacial ice (Dunbar et al., in review; Dunbar et al., 1998a; b; Smellie, 1999; Wilch et al., 1999).

Ancient ashes on a younger landscape?

Most surface-age estimates that are >2 Ma in the Dry Valleys are based on the ⁴⁰Ar/³⁹Ar ages of ashes interpreted to represent *in situ* deposits of tephra (Figure 2). The rarity of comparably old cosmogenic ages casts doubt on the assumption that the eruption ages of these ashes record the time when they were deposited in their present stratigraphic positions.



Figure 1. An erratic block of volcanic ash in sublimation till in Beacon Valley. Ash particle sizes range from very fine to coarse sand. Cross-bedding and deformation and truncation of bedding are interpreted as resulting from some combination of syn-eruptive reworking followed by deformation during post-eruptive glacial transport. The eruption age of this ash is currently unknown, though the ice it rests on is thought to be Miocene in age (Sugden et al., 1995).

A range of geomorphic processes are currently active in the Dry Valleys in seeming contradiction to the ancient age of the landscape. The presence of “boulder wakes”—flow features where scree is moving downhill around protruding bedrock outcrops (Morgan and Putkonen, 2005)—clearly indicates that scree slopes are still active. Even in Beacon Valley, one of the highest and coldest of the Dry Valleys, streams of meltwater are building small alluvial fans. Sand wedges are resurfacing the landscape of the Dry Valleys (Sletten et al., 2003) and a diversity of pedogenic processes are underway (Bockheim, 1990). Soil erosion rates in the Dry Valleys are slow but are in the range found in other arid regions (Putkonen, pers. comm.). The erosion rates of boulder surfaces in the Dry Valleys vary from 0.05 to 1.00 m/Myr (Staiger et al., 2006), which is slow but still significant at geological timescales. The geomorphology of this polar landscape is not anywhere as active as Svalbard or arctic Alaska, but it is by no means static. These age/rate data are qualitative in nature because it is difficult to date all parts of a landscape; nonetheless, they are difficult to reconcile with the Stabilist hypothesis of geomorphic stasis since the mid-Miocene.

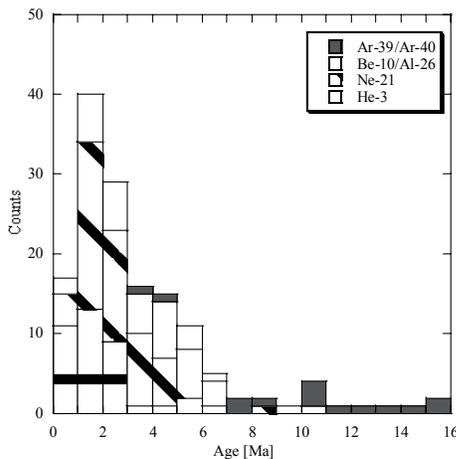


Figure 2. Published exposure ages determined by ^{10}Be , ^{26}Al , ^{21}Ne , and ^3He (Brook et al. 1995; Ivy-Ochs et al. 1995; Bruno et al. 1997; Hall et al. 1997; Schäfer et al. 1999; Summerfield et al. 1999; Schäfer et al. 2000) compared to $^{39}\text{Ar}/^{40}\text{Ar}$ ages from ash deposits. Exposure ages of till boulders and other sedimentary deposits range from 0.5 to 5 Ma, while the ash deposits date from 3-15 Ma. Most old rock ages of 6-11 Ma are from bedrock or Till at high altitudes on Mount Fleming and Table Mountain, where denudation rates are very low. Why are the ash deposits so much older? One possibility is that glaciers carried erratic blocks of ancient ash deposits into the Dry Valleys during late Miocene and Pliocene glaciations.

The importance of resolving the stabilist-dynamicist debate

To predict the roles of the Antarctic ice sheets in future climate change, we must understand their behavior in the past. The landscape history of the Dry Valleys is important because geological deposits there comprise the richest, subaerial, terrestrial record in Antarctica. It follows that we urgently need to resolve the Stabilist-Dynamicist debate.

The Stabilist school presents a consistent system of arguments supporting the view that the Dry Valleys slipped into a hyper-arid deep freeze during the middle Miocene and have remained there ever since (Sugden and Denton, 2004). In this view, much of the landscape is relict from the Paleogene when it formed under the combined actions of fluvial action (Denton et al., 1984; Sugden et al., 1999). It follows that the Dry Valley landscape is in effect geomorphically paralyzed today and has been for millions of years. Another important part of the Stabilist interpretation is the inference that local, alpine glaciers as well as western-sourced, axial glaciers like the Taylor and Wright Upper Glaciers have been cold-based and occupied retracted positions since the Miocene (Hall et al., 1993; Hall et al., 1997; Marchant et al., 1993a). This inference is based on correlating the Peleus till, the most recent deposit left by warm-based ice in Wright Valley (Prentice, 1985; Prentice et al., 1987), with the Sessrumnir till in the upper valley (Denton et al., 1993). The Sessrumnir till is believed to be >15 Myr old based on the $^{40}\text{Ar}/^{39}\text{Ar}$ age of an overlying volcanic ash (Marchant et al., 1993a). From this correlation, the late Miocene and Pliocene are interpreted as having been continuously as cold and dry as today resulting in inactive slope processes and alpine glaciers that fluctuated very little.

The Dynamicist view, in contrast, is that Antarctic climate system including ice and ocean underwent significant fluctuations since ice-sheet formation around the Eocene-Oligocene boundary (~34 Ma), up until the late Pliocene. During warmer intervals, outlet glaciers of the EAIS as well as glaciers within the Dry Valleys were partially warm-based, with significant subglacial sediment erosion, transport, and deposition (Prentice et al., 1985; 1987). Meltwater would have been plentiful. Support for this hypothesis comes from marine-sediments in Taylor Valley and the Antarctic region (Barrett et al., 1992; Bohaty and Harwood, 1998; Harwood et al., 2005; Scherer et al., 1998; Webb and Harwood, 1991) and some onshore stratigraphy (Hambrey and Mckelvey, 2000b). The correlation of the Peleus and Sessrumnir tills remains problematic as noted by Prentice et al. (2003) and Prentice and Krusic (2005). On this point hangs the question of when warm-based ice last flowed through the Dry Valleys, and what contribution local alpine glaciers made to this glaciation. If the Peleus till is appreciably younger than the 15 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age of the ash overlying the Sessrumnir till, then a wide variety of geomorphic events (and climatic fluctuations) could have occurred in Wright Valley during the late Miocene and the Pliocene. Prentice et al. (1998) pointed out widespread bedrock morphologic features indicating that the Dry Valleys were largely carved by glacial erosion. Van der Wateren et al. (1999) note that cosmogenically measured surface age declines with altitude, suggesting recent surface denudation that is incompatible with the geomorphic stasis suggested by the Stabilists. Further support for the Dynamicist view comes from deep-sea oxygen isotope records that are ascribed to marked changes in the EAIS during the late Neogene (Billups and Schrag, 2003; Lear et al., 2000; Lisiecki and Raymo, 2005; Prentice and Matthews, 1991). Recent finding from the ANDRILL project reveal substantial glacial-interglacial variability during the Late Neogene including periods with cold polar climate and periods with warmer climate with polythermal ice (Naish et al., 2007; Witze, 2007)

Prospectus

The pioneering studies of ash deposits in the Dry valleys represented great strides in dating Antarctic surfaces; however, science often advances by challenging established paradigms, in this case by challenging a chronostratigraphic foundation of the Stabilist model. Given that Ar-Ar dating methods are robust, there is little reason to question that validity of the eruptive ages of the Dry Valley ashes published in the literature. What is debatable are their depositional ages. We believe there are reasonable mechanisms for reworking tephra with ancient eruptive ages into much younger deposits. How do you test this idea? Briefly, we think that a re-examination of stratigraphic relationships at several key ash deposits in the Dry Valleys, in conjunction with new methods of radiometrically dating the emplacement of non-volcanic contaminant mineral grains in ash deposits and with cosmogenic dating of surrounding surfaces, can conclusively test the hypothesis that some of the old ashes were redeposited more recently. If we are wrong, the Stabilist model will be stronger for having survived this challenge. If we are right and key ashes in the Dry Valleys were redeposited long after they were erupted, then a paradigm shift may be in order for the Dry Valley geomorphology and Antarctic climate history.

Summary

Resolving the Stabilist-Dynamicist debate depends on checking the deposition ages of volcanic ashes at several key sites in the Dry Valleys. Field observations of glacially transported clasts of volcanic ash and accumulating data on landscape-surface ages suggest that the eruption ages of some of the key ashes may not equate to their deposition ages in the Dry Valleys. If true, this has significant implications for our understanding of the climatic and glaciologic history of the Antarctica.

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