Evidence for an earliest Oligocene ice sheet on the Antarctic Peninsula

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ABSTRACT

There is growing consensus that development of a semipermanent ice sheet on Antarctica began at or near the Eocene-Oligocene (E-O) boundary. Beyond ice-rafted debris in oceanic settings, however, direct evidence for a substantial ice sheet at this time has been limited and thus far restricted to East Antarctica. It is unclear where glacier ice first accumulated and how extensive it was on the Antarctic continent in the earliest Oligocene. Sediments at the top of the Eocene marine shelf section on Seymour Island, Antarctic Peninsula, include glacial marine deposits and a lodgment till with clasts derived from a variety of rock units on the peninsula. Dinoflagellate biostratigraphy and strontium isotope stratigraphy indicate an age at or very close to the E-O boundary. Glacier ice extending to sea level in the northern peninsula at this time suggests the presence of a regionally extensive West Antarctica ice sheet, and thus an even more dramatic response to the forcing factors that facilitated high-latitude ice expansion in the earliest Oligocene.

Keywords: Oligocene, glaciation, Antarctica, till, stratigraphy.

INTRODUCTION

During the Eocene-Oligocene (E-O) transition, Earth's climate changed from warm and equable to cooler and glaciated. The earliest Oligocene (ca. 33.5 Ma) is marked by a rapid and significant positive shift in the oxygen isotope value of marine carbonates (Oi-1 event of Miller et al., 1991), and the appearance of ice-rafted debris in the Southern Ocean that corresponds to the first major expansion of Antarctic ice in the Cenozoic (Zachos et al., 1992). The magnitude of this shift and its comparative abruptness has led to a search for thresholds in the climate system that could produce such a response (Zachos et al., 1993; DeConto and Pollard, 2003). A significant question in this endeavor is the extent of the initial pulse of Antarctic glaciation. Direct sedimentologic evidence has been limited to cores from East Antarctica (e.g., Barrett, 1989; Hambrey et al., 1991; Cape Roberts Science Team, 2001), suggesting that initial ice expansion was restricted to that region. Deposits requiring an extensive marine-based ice sheet on the peninsula are not reported until the middle to late Oligocene (South Shetland Islands; Troedson and Smellie, 2002), lending support to the idea that East and West Antarctica may not share the same history of ice sheet growth (Dingle and Lavelle, 1998; Barrett, 1999). Uncertainty remains because there is not a complete record of the E-O boundary in West Antarctica.

Here we report the presence of glacial marine sediments and a diamicton of glacial origin exposed on Seymour Island, Antarctic Peninsula, that we delimit in age to at or very near the E-O boundary. This is the earliest direct evidence for the presence of glacier ice at sea level on the peninsula, and demonstrates that expansion of earliest Oligocene ice was not restricted to East Antarctica.

GEOLOGIC SETTING, FIELD RELATIONS, AND SEDIMENTOLOGY

Seymour Island is located off the northeastern tip of the Antarctic Peninsula (Fig. 1A). The Eocene La Meseta Formation, exposed on the northeastern third of the island, consists of fossiliferous, shallow-marine sandstones, mudstones, and shell banks that accumulated in a variety of inner shelf environments (Porębski, 1995; Sadler, 1988). The unit is unconformably overlain by Pliocene–Pleistocene till of the Weddell Sea Formation (Zinsmeister and DeVries, 1983; Gaździcki et al., 2004).

In an effort to find the youngest in situ Paleogene sediments on the island, we identified deposits that overlie the typical marine sands of the La Meseta Formation (Fig. 1B, unit a) but are beneath the Weddell Sea Formation (Fig. 1B, unit e) in an area on the northwest side of the island (64°14′S, 56°37′W). Here the uppermost La Meseta Formation consists of stratified, fossiliferous, occasionally cross-bedded, marine shelf sands. Lithologically similar, laterally equivalent sediments contain rare quartz pebbles. These sediments are overlain by ~2–3 m of dark brown-gray, compact, stratified, silty mudstone (Fig. 1B, unit b) containing a significant fraction of coarse sand grains, pebbles, and occasional outsized clasts several centimeters in diameter (Fig. 2B). This lithology does not appear in the underlying La Meseta Formation. The unit is truncated by a dense compact diamict (Fig. 1B, unit c) that ranges from <1 m to ~2 m thick (Fig. 2A); it is entirely unsorted and exhibits no evidence of stratification, grading, or other internal architecture. Cobbles and pebbles are polished and occasionally striated, faceted, and/or streamlined in shape (Figs. 3A, 3B). Fossil barnacles encrust the upper surfaces of cobbles at the top of the unit (Fig. 3C). The diamict is overlain by another pebbly mudstone, also with outsized clasts, and the entire section is disconformably truncated by the Weddell Sea Formation. Sediments are unconsolidated, but the diamict is weakly cemented with carbonate. These units are exposed for at least 100 m along the outcrop, but persistent poor weather precluded further exploration of their lateral extent.

Gravel clasts from the diamict consist of granite, metavolcanics, and quartz-phyllite schist. Thin sections reveal shell fragments in the matrix, but no complete individuals were found. Grain size distributions from diamict subsamples are similar and show no evidence for preferential size sorting (Fig. 2C). Pebbly mudstones above and below exhibit significant sorting within the fine fraction and varying proportions of sand between samples (Fig. 2C). Photomicrographs of diamict quartz sand reveal a combination of rounded and etched grains, some with freshly broken surfaces (Fig. 3D), and angular grains (Fig. 3E). Stepped breakage lamellae are evident on a number of grains (Fig. 3F).

GLACIAL ORIGIN OF DEPOSITS

Sedimentologic characteristics support a glacial marine or glacial interpretation for these deposits. Pebbly mudstones are characteristic of glacial marine deposits, consisting of mixtures of crudely stratified and sorted, background pelagic and/or current-driven deposits with variable contributions of ice-rafted debris (Anderson et al., 1991). Outsized clasts are dropstones typical of these deposits. The

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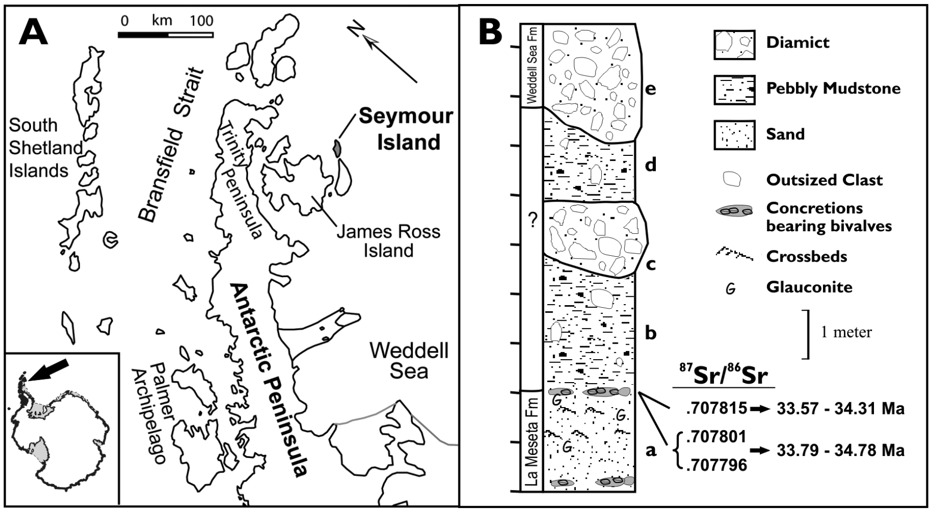

Figure 1. A: Location map. B: Relationships between La Meseta Formation marine sands (a), lower pebbly mudstone (b), diamict described here (c), upper pebbly mudstone (d), and Weddell Sea Formation diamict (e); ^{87}Sr/^{86}Sr values are from bivalve carbonate; age estimates reflect maximum range encompassed by internal 2σ error and corresponding uncertainty of calculated marine line (Howarth and McArthur, 1997; McArthur et al., 2001, lookup table v. 4).

compact nature of the intervening diamict and its truncational base suggest that this is a lodgment till, deposited directly beneath flowing ice. The lack of sorting is consistent with glacial transport and deposition, and the similarity of grain size distributions among samples demonstrates the textural homogeneity typical of individual glacial tills (Anderson et al., 1991). Although shell material is present in the till matrix, it is effectively comminuted, unlike what is expected with till-like glacial marine drift (Petersen, 1983). Quartz grain surface textures reveal a complex depositional history, including chemical weathering and transport by water, yet are often overprinted by conchoidal fractures consistent with more recent transport by ice. Angular grains with stepped and arcuate breakage lamellae (Figs. 3D–3F) are particularly diagnostic of glacial transport (e.g., Strand et al., 2003). Clast lithologies indicate a provenance on the Trinity Peninsula, ~100 km to the west, and hence are more consistent with glacial transport than local slope failure. Encrusting barnacles along the top of the unit indicate that the diamict was deposited in or rapidly returned to a marine environment. There is no evidence for subareal exposure anywhere in the section.

AGE CONSTRAINTS

The age of the Seymour Island diamict, and hence timing of glaciation, can be determined using several independent lines of evidence. First, ^{87}Sr/^{86}Sr ratios of bivalves from the highest shell-bearing marine bed in the underlying La Meseta Formation yield ages of 33.57–34.78 Ma on the marine curve (Fig. 1B; Howarth and McArthur, 1997; McArthur et al., 2001; GSA Data Repository[1]). These are the youngest documented ages from the La Meseta Formation and confirm that the unit extends to the E-O boundary (33.7 Ma; Gradstein et al., 2004). The transition to glacial marine deposition (unit b in Fig. 1) occurs immediately above this shell bed; there is no clear indication of an intervening disconformity.

Clast provenance and dinoflagellate assemblages provide additional age constraints and serve to distinguish the unit from the overlying similar, but much younger, glacial diamicts of the Pliocene–Pleistocene Weddell Sea Formation. Diamict clasts are representative of rocks of the Trinity Peninsula Group, Peninsula Volcanics, and Cretaceous sedimentary rocks of the Larsen Basin. All are Mesozoic, and distinct from the Miocene and younger volcanics (pallagonite and vesicular basalt) typical of the James Ross Island complex (Nelson, 1975). It is unlikely that ice derived from the Antarctic Peninsula would have bypassed sampling the younger rocks between there and Seymour Island (Fig. 1A), had they been present at the time. The glacial unit must predate the Miocene emplacement and associated uplift of volcanic strata in and around James Ross Island.

Calcareous and siliceous microfossils are not preserved in the glacial marine muds above or below the till, but organic-walled microplankton (dinoflagellates) are present, and can be tied into dinocyst biostratigraphy established for southern high latitudes (Brinkhuis et al., 2003). The assemblage immediately below the diamict contains the age-indicative dinocysts *Spinidinium macmurdoense*, *Vozzhennikovia rotunda*, *Alterbidinium* cf. *distinctum*, and *Enneadocysta partridgei* (Figs. 4B–4E). The last occurrence of both *A. distinctum* and *S. macmurdoense* in Southern Hemisphere high latitudes is defined with magnetostratigraphy as ca. 33.5 Ma (Williams et al., 2004), indicating a late Eocene age for this assemblage. The diamict contains a reworked fauna of Cretaceous and early Paleogene age, with a very few late Eocene in-

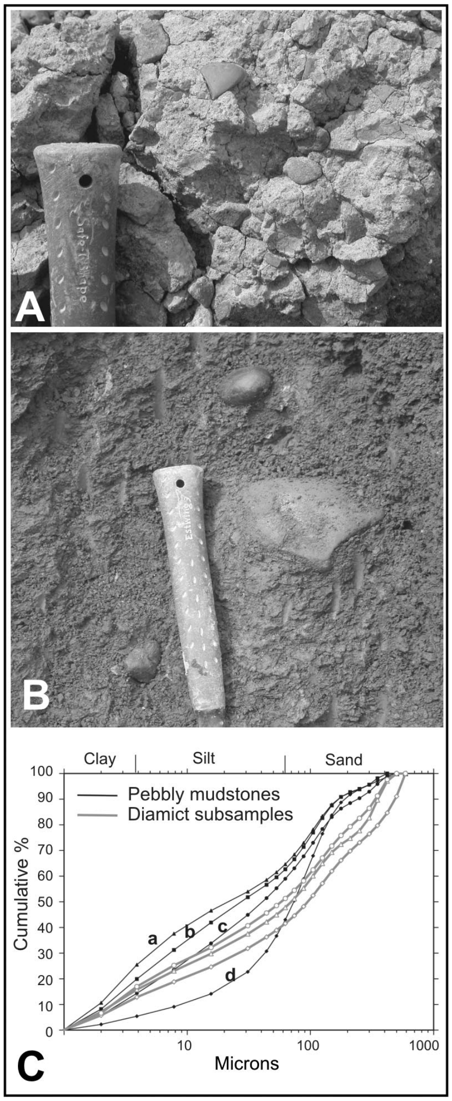

Figure 2. A: Diamict. B: Inferred dropstones in pebbly mudstone. Handle is 4 cm across at base. C: Cumulative grain size distributions for three subsamples of diamict (thick gray lines) and four samples of pebbly mudstone (black lines) from two horizons below (a, b) and two above (c, d) diamict.

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[1] GSA Data Repository item 2006075, sample preparation, prediction for offshore sections, and barnacle identification, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

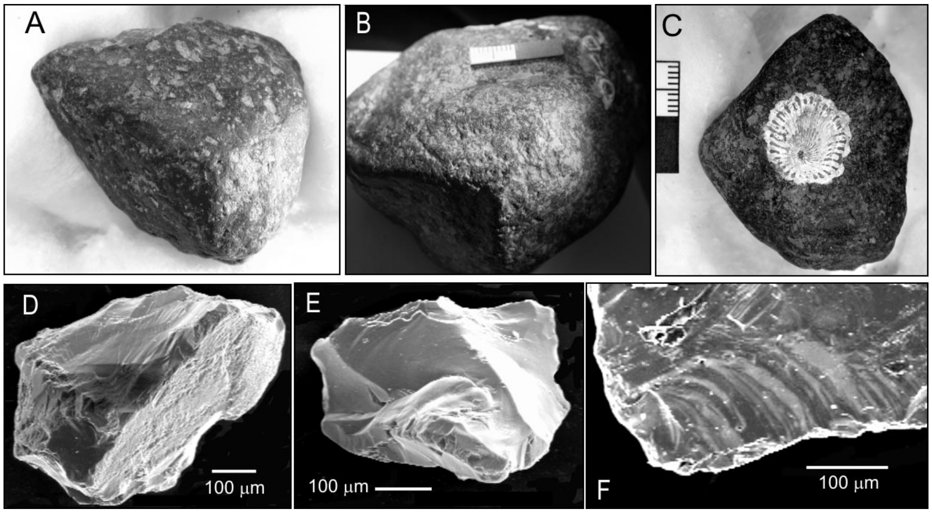

Figure 3. Surface features associated with diamict clasts. A: Facets. B: Suggestion of striations (upper left to lower right) on faceted pebble. C: Balanid barnacle encrusting pebble from top of diamict. D: Quartz grain showing preweathered etched surface on lower right superimposed by fresh conchoidal fractures. E: Angular quartz grain. F: Quartz grain exhibiting arcuate steps along fracture surface.

dividuals. Mudstones above the diamict contain the diagnostic Oligocene taxon *Chiropteridium lobospinosum* (Fig. 4A), the first occurrence of which is ca. 33.5 Ma (Williams et al., 2004). This, in combination with the low abundances of *E. partridgei* and *A. distinctum* characteristic of transitional Eocene-Oligocene deposits that disappear in the early and earliest Oligocene, respectively, indicates an earliest Oligocene age. Hence, the diamict is positioned at or very close to the E-O boundary. This is the first indication that the E-O boundary interval is preserved on Seymour Island, and provides the earliest direct evidence for marine-based Cenozoic glaciation on the Antarctic Peninsula.

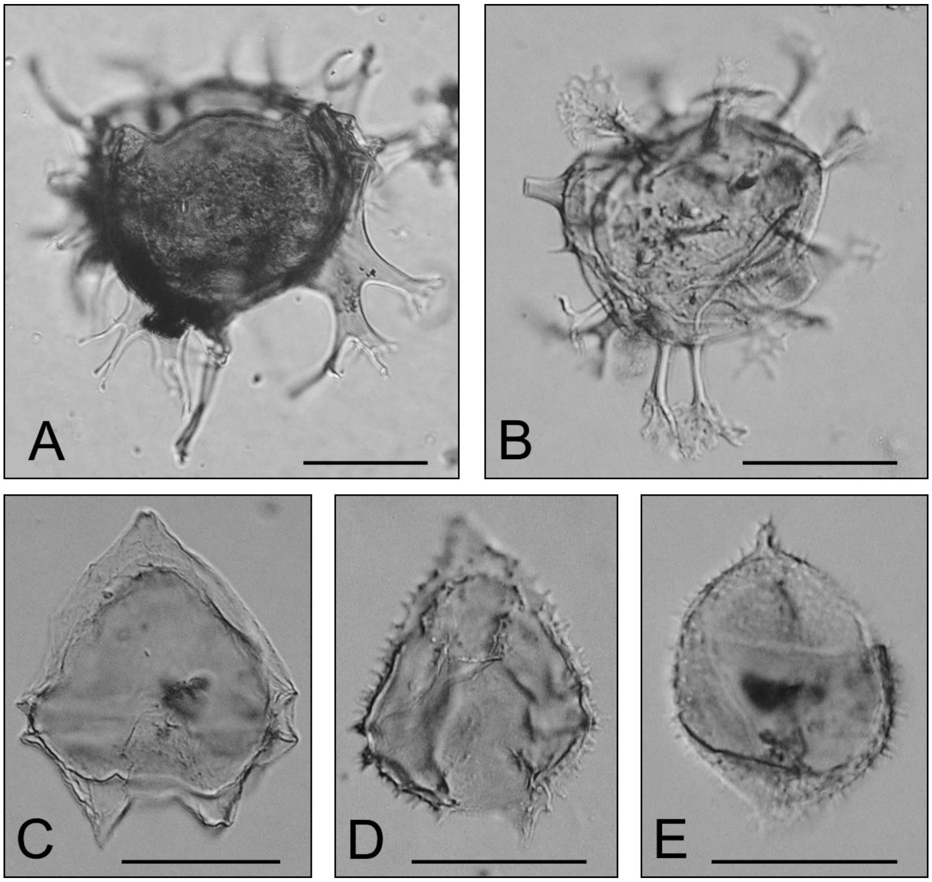

Figure 4. Age-indicative dinocysts. A: *Chiropteridium lobospinosum*. B: *Enneadocysta partridgei*. C: *Alterbidinium* sp. D: *Spinidinium macmurdoense*. E: *Vozzhennikovia rotunda*. Scale bars in each = 30 µm.

DISCUSSION

A primary concern with the age interpretation of this deposit is whether these sediments are in place, and whether they are distinct from the overlying Weddell Sea diamict. Slumping of the Weddell Sea Formation and mobilization of material during construction of a small airstrip for the Argentine Base Marambio have moved younger material downslope and mixed it with older sediments. We initially dismissed this diamict as resulting from one or a combination of these processes. However, excavation revealed that the pebbly mudstone with dropstones is present below the diamict and above, and is in turn truncated by the younger Weddell Sea glacial deposits. In addition, the preservation and nonrandom distribution of barnacles (on upper surfaces of clasts at the top of the diamict) requires that they are not reworked. The biostratigraphic succession of Eocene dinocysts below, reworked older taxa within, and basal Oligocene taxa above the diamict is also consistent with Paleogene deposition, and is unlikely if sediments had been remobilized. There are no younger dinoflagellates in either of the mudstone units or the diamict, which would be expected had this material accumulated at a later time and then been mixed into older sediments. Similarly, the absence of the Miocene and younger volcanics that crop out on James Ross Island, which would have been incorporated had they existed at the time ice overrode the area (and which are present in the overlying Weddell Sea Formation; Zinsmeister and DeVries, 1983; Gaździcki et al., 2004), demonstrates that this diamict is Paleogene in age. These factors require that this section is in place, and is older than and distinct from the Weddell Sea diamict above.

The lithologies of diamict cobbles reflect a broad source area on the Antarctic Peninsula, indicating that the ice responsible for this till was not simply a localized valley glacier, but an ice sheet extending over much of the peninsula. With ice cover to this degree, it is unlikely that a West Antarctica ice sheet was not present as well. This resolves the diachronism question, suggesting that initial expansion of ice on Antarctica encompassed the entire continent synchronously in the earliest Oligocene.

Consistent with the marine isotope record, the onset of ice growth on Seymour Island appears to have been rapid. Paleoclimate indicators in the La Meseta Formation, including palynology (Askin, 1997) and δ^{18}O values of marine bivalves (Dutton et al., 2002), show a trend toward cooler but still temperate conditions. Pebbles in the uppermost La Meseta Formation may have originated as ice-rafted debris (see Doktor et al., 1988), suggesting the possibility for limited ice in the area near the close of the Eocene, but they are not common. The onset of glacial conditions is reflected in the abrupt but apparently conformable transition from typical shelf sands to pebbly mudstone (e.g., Gilbert et al., 2003).

The initial volume of ice and the rate at which it expanded are critical for understanding the driving forces behind the Cenozoic transition from greenhouse to icehouse conditions in Antarctica. Expansion of earliest Oligocene ice to the northern reaches of the peninsula places additional constraints on the factors facilitating glaciation. The Seymour Island section preserves the only record of this transition exposed on land, provides a counterpart to deep-sea records and soon to be cored offshore shelf sections (Florindo et al., 2003), and poses a testable hypothesis for what should be seen in those cores (Data Repository; see footnote 1).

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