Reevaluation of the timing and extent of late Paleozoic glaciation in Gondwana: Role of the Transantarctic Mountains

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ABSTRACT

Evidence from Antarctica indicates that a 2000-km-long section of the Transantarctic Mountains—including Victoria Land, the Darwin Glacier region, and the central Transantarctic Mountains—was not located near the center of an enormous Carboniferous to Early Permian ice sheet, as depicted in many paleogeographic reconstructions. Weathering profiles and soft-sediment deformation immediately below the preglacial (pre-Permian) unconformity suggest an absence of ice cover during the Carboniferous; otherwise, multiple glacial cycles would have destroyed these features. The occurrence of glaciotectonite, massive and stratified diamictite, thrust sheets, sandstones containing dewatering structures, and lonestone-bearing shales in southern Victoria Land and the Darwin Glacier region indicate that Permian sedimentation occurred in ice-marginal, periglacial, and/or glaciomarine settings. No evidence was found that indicates the Transantarctic Mountains were near a glacial spreading center during the late Paleozoic. Although these findings do not negate Carboniferous glaciation in Antarctica, they do indicate that Gondwanan glaciation was less widespread, and, therefore, that glacially driven changes to other Earth systems (i.e., glacioeustatic fluctuations, climate) were much smaller than previously hypothesized.

Keywords: Gondwanan glaciation, Permian, Carboniferous, Antarctica, glacioeustasy.

INTRODUCTION

How large were the Gondwanan ice sheets? Was Antarctica completely covered by ice during the Carboniferous and Early Permian? Were the glaciers large enough to have caused the eustatic changes associated with cyclothem deposition and large enough to have substantially influenced Pangean climates? Answers to these questions are critical in determining links between glaciation and its influence on Earth systems during the late Paleozoic. For example, studies of Carboniferous cyclothems conclude that cyclic waxing and waning of Gondwanan glaciers caused high-frequency ($40–412 \times 10^3$ yr) sea-level fluctuations of between 60 and 200 m (e.g., Wanless and Shepard, 1936; Crowell, 1978, 1999; Veevers and Powell, 1987; Heckel, 1994). Such glacioeustatic changes required the waxing and waning of an ice sheet $35–115 \times 10^6$ km^3 (cf. Crowley and Baum, 1991). Some climate models also predict an ice volume as large as 150×10^6 km^3 (e.g., Hyde et al., 1999). For these reasons, Carboniferous and Early Permian paleogeographic reconstructions depict a massive ice sheet covering Antarctica and adjacent areas of Gondwana (Fig. 1; e.g., Veevers and Powell, 1987; Ziegler et al., 1997; Scotese, 1997; Scotese et al., 1999; Veevers, 2000, 2001).

The concept of massive Carboniferous and Early Permian ice sheets centered over Antarctica is deeply entrenched in the literature. Most reconstructions show Victoria Land, the Darwin Glacier region, and the central Transantarctic Mountains as occurring beneath the center of an ice sheet (Figs. 1 and 2; Barrett, 1991; e.g., Veevers and Powell, 1987; Ziegler et al., 1997; Scotese, 1997; Scotese et al., 1999; Veevers, 2000, 2001). Data we have collected from Antarctica challenge such interpretations and suggest that much of the Transantarctic Mountains was ice free during the Carboniferous and that this region was along ice margins during the Early Permian. This paper presents and synthesizes information from Victoria Land, the Darwin Glacier region, and the central Transantarctic Mountains to show that past reconstructions of Gondwanan glaciation in Antarctica are unrealistic.

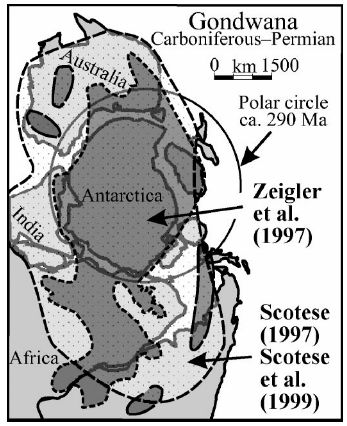

Figure 1. Carboniferous and Permian paleogeographic map of Gondwana (after Powell and Li, 1994), showing several hypothetical ice sheets.

BACKGROUND

Crowell (1978) and Veevers and Powell (1987) argued that glaciation began in Antarctica during the late Mississippian. Their evidence included the occurrence of glacial grooves cut into unconsolidated deposits (now forming Devonian sandstones) in the Pensacola Mountains and the occurrence of an extensive unconformity that separates possibly uppermost Pennsylvanian (Stephanian) and Permian glacial deposits above from Precambrian to Devonian rocks below. According to Veevers and Powell (1987) and Veevers (1994, 2000), Mississippian uplift in northern Victoria Land, uplift of the Gamburtsev Subglacial Mountains, and continental drift over the paleo–South Pole triggered a major episode of glaciation centered over Antarctica. Some workers speculate that maximum glaciation occurred during the late Mississippian to early Pennsylvanian (e.g., González-Bonorino and Eyles, 1995). Under this scenario, the Mississippian to late Pennsylvanian glacial record was completely destroyed by subglacial erosion during glacial maximum, resulting in formation of a continent-wide lacuna; deposition above this lacuna occurred during the late Pennsylvanian and early Permian, when glaciation waned (e.g., Barrett and Kyle, 1975; Veevers, 2000). Although the view of a middle Mississippian to Early Permian Antarctic-centered ice sheet is widespread (cf. Frakes and Francis, 1988; Crowley and Baum, 1991; Ziegler et al., 1997; Scotese, 1997; Scotese et al., 1999; Veevers, 2000, 2001), evidence for its formation, growth, maximum extent, and ultimate demise is unsubstantiated.

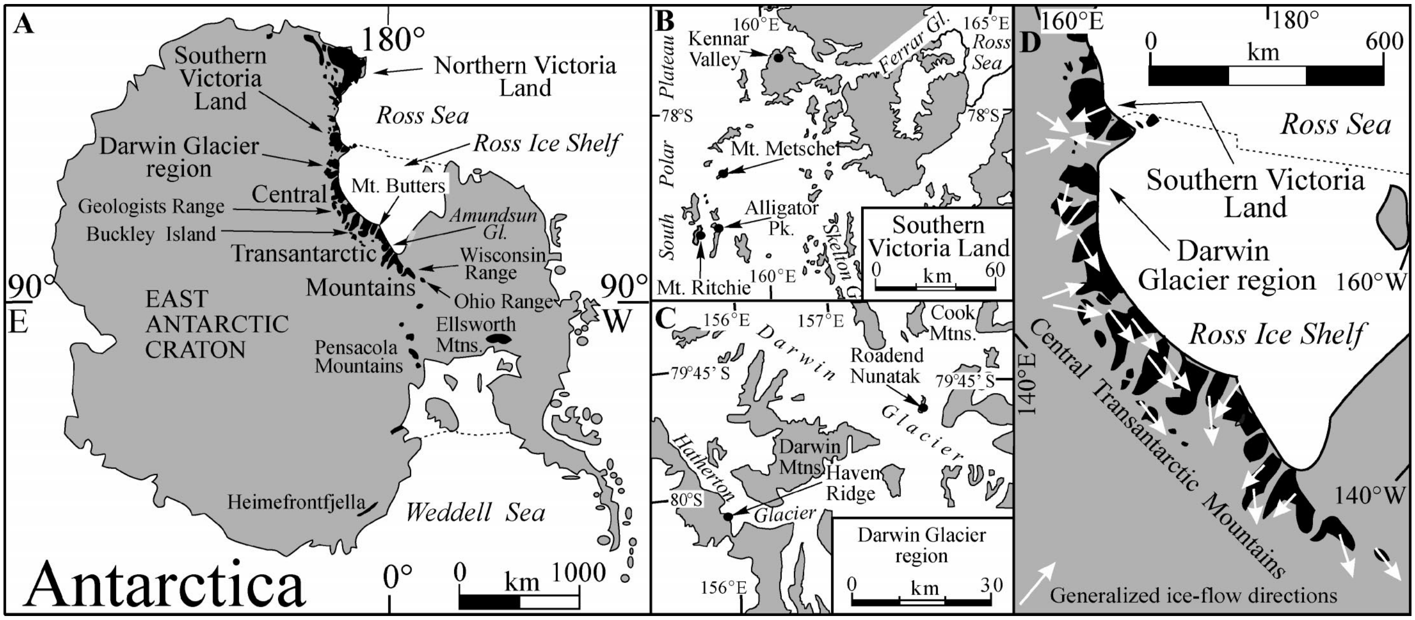

Figure 2. Maps of Antarctica. A: Locations mentioned in text. B: Southern Victoria Land. C: Darwin Glacier region. D: Generalized Permian ice-flow directions (data from Coates, 1985; Isbell et al., 1997, 2001; Lenaker, 2002; and this paper).

AGE AND EXTENT OF GLACIOGENIC DEPOSITS

Glaciogenic deposits are widespread in the Transantarctic Mountains and are as thick as 440 m (Isbell et al., 1997). However, deposits to 1200 m thick occur in the Pensacola and Ellsworth Mountains (Collinson et al., 1994). Only in a few places have the rocks in Antarctica been dated. Fossil microfloras within these strata indicate an Early Permian rather than a Carboniferous age. Glaciogenic strata in the Darwin Glacier region (Darwin Tillite), the Geologists Range (Pagoda Formation), and Heimefrontfjella contain fossil palynomorphs that correlate with Foster and Waterhouse's (1988) Western Australian Asselian–Tastubian (Early Permian) *Pseudoreticulatispora confluens* Oppel-zone (formerly upper Stage 2, Kyle, 1977; Kyle and Schopf, 1982; Lindström, 1995; Askin, 1998). A conchostracan fauna in basal glaciogenic rocks at Mount Butters indicates a late Pennsylvanian(?) to Early Permian age (Babcock et al., 2002).

CARBONIFEROUS GLACIATION?

Although upper Paleozoic glacial deposits clearly demonstrate the occurrence of Permian glaciers on Antarctica, previous authors have suggested that the underlying unconformity formed during more extensive Carboniferous phases of Gondwanan glaciation centered over Antarctica (e.g., Barrett and Kyle, 1975; Veevers, 2000). Although complete removal of the Carboniferous record before the final retreat of the ice sheet is a compelling hypothesis for explaining the formation of the lacuna, studies conducted on deposits of the Pleistocene Fennoscandian and Laurentide ice sheets partially invalidate this hypothesis (e.g., Boulton and Clark, 1990; Kleman and Hättestrand, 1999). In Canada and Scandinavia, extensive areas containing preglacial landscapes, older Quaternary glacial deposits, and subglacial sediments escaped erosion from overriding Pleistocene ice sheets. Data presented here do not support the hypothesis that the pre-Permian lacuna in the Transantarctic Mountains resulted from widespread Carboniferous glaciation, nor do the data support the concept of a massive, late Paleozoic, Antarctic-centered ice sheet.

Weathering Profiles

At Mount Butters in the central Transantarctic Mountains (Fig. 2A), weathered Ordovician granite grades upward into decimeter-thick breccia beds at the base of a 5.5-m-thick Lower Permian (possibly uppermost Pennsylvanian to Lower Permian) conchostracan and dropstone-bearing succession of shale, siltstone, sandstone, and stratified diamictite (Pagoda Formation; Coates, 1985; Isbell et al., 2001). These rocks were deposited as scree and in a lacustrine setting with rafted debris introduced by lake ice. An overlying massive diamictite truncates the basal strata and, to the west, directly overlies unweathered granite. At five other known localities in the Transantarctic Mountains (Wisconsin Range, Amundsen Glacier, Geologists Range, Roadend Nunatak, northern Victoria Land), Permian deposits directly overlie deeply weathered crystalline bedrock (Minshew, 1967; Coates, 1985; Collinson et al., 1986; this paper). Along the Amundsen Glacier and in northern Victoria Land, Lower Permian postglacial strata directly overlie weathered granite (Coates, 1985; Collinson et al., 1986).

Soft-Sediment and Glaciotectonic Deformation

At Haven Ridge in the Darwin Glacier region (Fig. 2C), the Permian Darwin Tillite unconformably overlies the Middle Devonian Hatherton Sandstone. There, the upper 7.5 m of sandstone contains abundant evidence that the Devonian strata underwent soft-sediment dewatering during the Permian. Evidence includes the occurrence of (1) massive sandstone, (2) dish and pillar structures, (3) dewatering pipes, and (4) millimeter- to centimeter-scale sand volcanoes (Fig. 3).

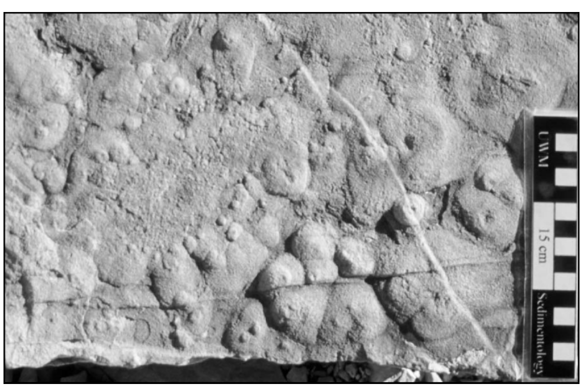

Figure 3. Sand volcanoes protruding from top of Devonian Hatherton Sandstone, at Haven Ridge in Darwin Glacier region.

Figure 4. Thrust sheets in Metschel Tillite exposed on Mount Ritchie in southern Victoria Land. Sheets are composed of internally folded Aztec Siltstone (Devonian) and Permian glaciogenic deposits. Thick thrust sheet in center of photograph is ~20 m thick.

Sand volcanoes on the upper sandstone surface protrude into overlying pebble- and boulder-bearing laminated shales of the Darwin Tillite. At the base of the shale, granite clasts are loaded into the top of the underlying Hatherton Sandstone.

In southern Victoria Land, meter-scale sandstone, siltstone, and shale at the top of the Middle to Upper Devonian Aztec Siltstone and diamictite and sandstone at the base of the Permian Metschel Tillite are deformed locally. Thrust sheets and recumbent folds to 20 m thick, composed of Devonian and basal Permian strata (at Mount Ritchie, Kennar Valley, and Alligator Peak; Fig. 2B) occur along the Aztec Siltstone–Metschel Tillite contact (Fig. 4). These sheets are similar to structures formed by compression in ice-marginal thrust moraines (Aber et al., 1989; Hart, 1990). Smaller-scale deformation along the unconformity at Mount Metschel consists of centimeter- to meter-scale folds and thrust faults in the upper 4.5 m of the Devonian strata. These strata grade upward into pervasively foliated and thrust-faulted homogenized diamictites at the base of the overlying Metschel Tillite. The Mount Metschel succession displays deformation characteristics identical to those in subglacial deforming bed deposits (Hart and Boulton, 1991; Benn and Evans, 1996; Van der Wateren, 2002).

Interpretation

The weathering profiles and soft-sediment deformation along the preglacial unconformity indicate that Carboniferous glaciation was not ubiquitous across Antarctica and raise the question whether pre-Permian glaciation ever occurred in Victoria Land, the Darwin Glacier region, or the central Transantarctic Mountains. Sites containing weathering profiles signify an absence of glacial cover and an extended period of exposure prior to Permian ice advance. Destruction of these profiles by subglacial erosion would have occurred if ice repeatedly overrode the areas during earlier stages of glaciation. The weathering profiles below the Lower Permian postglacial strata along the Amundsen Glacier and in northern Victoria Land indicate that even during Permian glaciation, complete ice cover of the Transantarctic Mountains was not attained.

Sand volcanoes, dewatering pipes, thrust sheets, folds, and deposits containing subglacially deformed beds develop in unconsolidated sediment near ice margins and in periglacial settings (cf. Hart, 1990; Van der Wateren, 2002). Permian deformation of unconsolidated sediments (now Devonian sandstones) suggests that southern Victoria Land and the Darwin Glacier region were not glaciated until the Permian. Although earlier glaciation cannot be ruled out, it is unlikely that unconsolidated sediments would have survived widespread Carboniferous glaciation, especially if these areas were beneath an ice-sheet spreading center that experienced numerous glacial advances and retreats, as previously presumed.

GLACIAL SPREADING CENTER?

Were the late Paleozoic glaciogenic strata deposited near a glacial spreading center, or were Victoria Land, the Darwin Glacier region, and/or the central Transantarctic Mountains located along ice margins? Much of the Permian glaciogenic strata in Antarctica are interpreted as terrestrial glacial deposits (Barrett and Kyle, 1975; Barrett, 1991; Collinson et al., 1994; Isbell et al., 1997). Previously, glaciomarine strata have only been identified in the Ohio Range, in the Ellsworth Mountains, and possibly in the Pensacola Mountains (Collinson et al., 1994). However, work by Lenaker (2002) on the Darwin Tillite indicates that widespread glaciomarine and/or glaciolacustrine conditions occurred during the Permian in the Darwin Glacier region. Stratified diamictites, dropstone-bearing laminated shales, and deformed diamictites and sandstones characterize rocks of the Darwin Tillite, suggesting that deposition occurred in many different settings, including (1) subglacial, (2) grounding line, (3) ice shelf, and (4) glacially influenced basinal settings. Lenaker (2002) also identified striated-boulder beds suggesting periodic advance of a grounded ice front into the area. In southern Victoria Land, stratified diamictites and dropstone-bearing shales overlie the thrust sheets and deforming-bed deposits described previously. Together, these features suggest initial ice-marginal conditions along an advancing ice front in southern Victoria Land followed by glaciomarine and/or glaciolacustrine conditions during glacial retreat.

Paleocurrent orientations and isopach maps indicate that late Paleozoic glaciogenic rocks in Antarctica were deposited in a series of linked elongate basins (Isbell et al., 1997). Paleocurrent orientations, taken from grooved and striated surfaces, pebble fabrics, thrust faults, and foliation within glacial deposits in southern Victoria Land, the Darwin Glacier region, and the central Transantarctic Mountains indicate that ice flowed transversely across the basin margins and then longitudinally down the basin axes (Fig. 2D; Isbell et al., 1997; this paper).

Convergent paleocurrents, glaciomarine facies, thrust sheets, and deformation tills are characteristic of ice-margin, periglacial, and glacially influenced marine or lacustrine settings. These features indicate that southern Victoria Land, the Darwin Glacier region, and the central Transantarctic Mountains were not under an ice-sheet spreading center during the late Paleozoic.

CONCLUSIONS

Data from Antarctica indicate that Victoria Land, the Darwin Glacier region, and the central Transantarctic Mountains were ice free during the Carboniferous, whereas during the Permian, deposition occurred in ice-marginal, periglacial, glaciomarine, glaciolacustrine, and glacially influenced marine or lacustrine settings. Lenaker's (2002) work in the Darwin Glacier region indicates that glaciomarine and/or glaciolacustrine conditions may have been more widespread than previously reported. These findings are contrary to previous models that placed much of the Transantarctic Mountains in terrestrial glacial settings under kilometers of ice near the center of an immense Gondwanan ice sheet. Although Carboniferous glaciation in Antarctica cannot be ruled out, it would have been less extensive than previous reconstructions show. Additionally, Antarctica's role in Gondwanan glaciation must have been even less than previously reported even during the Permian. These conclusions indicate that an Antarctic-centered ice sheet was too small to generate the high-frequency sea-level changes previously reported in the literature for development of Mississippian and Pennsylvanian cyclothems (60–200 m), and much smaller than ice sheets previously predicted by some climate models (e.g., Hyde et al., 1999).

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