Permian-Triassic boundary in the central Transantarctic Mountains, Antarctica

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ABSTRACT

The Permian-Triassic boundary occurs within a relatively complete terrestrial sequence in the Shackleton Glacier area of the central Transantarctic Mountains. The boundary is within a 7- to 10-m-thick interval between the Permian *Glossopteris* flora and the Lower Triassic *Lystrosaurus* fauna. This interval, representing on the order of 200 k.y., records some of the events that occurred in the transition from the Permian to Triassic. In the best-documented section at Graphite Peak in the Beardmore Glacier region, *Protohaploxypinus microcorpus* zone palynomorphs, which we assign to the latest Permian, record the declining *Glossopteris* flora and occur near the top of the Buckley coal measures, just below a previously reported major negative $\delta^{13}C$ excursion. In the Shackleton Glacier area, the Permian *Glossopteris* flora, including fossil wood, roots, and leaves, occurs within the lower part of the Fremouw Formation. The Antarctic *Lystrosaurus* assemblage of Early Triassic age has several species in common with the South African fauna that lived 20° to 35° closer to the equator. The migration of vertebrates from southern Africa into Antarctica in the Early Triassic supports hypotheses of runaway greenhouse warming possibly related to CO_2 emissions from Siberian flood basalts and large methane gas releases. Changes in flora bracketing the first of the major negative $\delta^{13}C$ anomalies near the boundary in Antarctica and in East Greenland support the hypothesis that a global event, perhaps through mutations caused by enhanced ultraviolet radiation, may have played a role in the destruction of floras.

Keywords: Antarctica, boundary, *Glossopteris, Lystrosaurus*, Permian, Triassic.

INTRODUCTION

Possible catastrophic events and mass extinction of biota at the end of the Paleozoic Era and the location of the Permian-Triassic boundary have been of great interest to geologists for many years (e.g., Schindewolf, 1954; Logan and Hills, 1973; Erwin, 1993, White, 2002; Benton, and Twitchett, 2003). Clearly different kinds of worlds existed before and after the Permian-Triassic boundary (252 ± 1 Ma; Bowring and Erwin, 1998; Mundil et al., 2004). Most typical types of Paleozoic life did not survive the boundary. Erwin (1994) estimated that over 90% of marine species and ~70% of terrestrial vertebrate species became extinct near the boundary. Major hypotheses proposed for the end-Paleozoic extinctions include: (1) draining of the continental shelves during exceptionally low sea level (Newell, 1973); (2) radiation from extraterrestrial sources (Schindewolf, 1954; Visscher et al., 2004); (3) bolide impact (Retallack et al., 1998; Kaiho et al., 2001); (4) anoxia in stratified oceans (Wignall and Hallam, 1992; Isozaki, 1997; Wignall and Twitchett, 2002; Grice et al., 2005), (5) atmospheric changes caused by release of gases from the eruption of Siberian basalts (Reichow et al., 2002; Renne et al., 1995), (6) large methane gas releases (Erwin, 1993; Berner, 2002; Ryskin, 2003), and (7) hypoxia owing to low oxygen levels in the atmosphere and global warming (Retallack et al., 2003, and the discussion by Engoren, 2004; Berner, 2005; Huey and Ward, 2005).

Permian-Triassic boundary sections in the central Transantarctic Mountains (Figs. 1–3) represent the only known paleopolar sequence with abundant Late Permian floral and Early Triassic tetrapod faunal data. Evidence of sudden warming at the Permian-Triassic boundary in the central Transantarctic Mountains suggests that combinations of the above hypotheses could have contributed to runaway greenhouse warming and to the mass extinctions (Berner, 2002; Benton and Twitchett, 2003). Antarctic sections do not hold all the answers to end-Permian extinctions, but they contribute to a growing body of data, which may eventually help in finding the solutions.

Deposited in a rapidly subsiding terrestrial foreland basin setting, the central Transantarctic Mountains boundary sequences are thick enough to document separate events that characterize

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GSA Bulletin; May/June 2006; v. 118; no. 5/6; p. 747–763; doi: 10.1130/B25739.1; 13 figures; 2 tables; Data Repository item 2006080.

the Permian to Triassic transition. These include a floral change beginning 1–2 m below the top of the coal measures, the final extinction of the glossopterid flora and end of coal deposition, change from carbonaceous strata with large root structures to noncarbonaceous strata with small root structures, and the appearance of tetrapod faunas within 7–10 m above the uppermost coal or glossopterid flora. The Permian-Triassic boundary lies somewhere within the sequence between the last coal or glossopterid fossils and the lowest tetrapod fossils. Using Lower Triassic rates of rock accumulation in the foreland basin, we estimate that the transitional sequence represents on the order of 200 k.y. and constrains the maximum duration of extinction events. This figure is similar to estimates determined by different methods from other places in other depositional settings (i.e., Bowring and Erwin, 1998; Rampino et al., 2000; Ward et al., 2000; Twitchett et al., 2001).

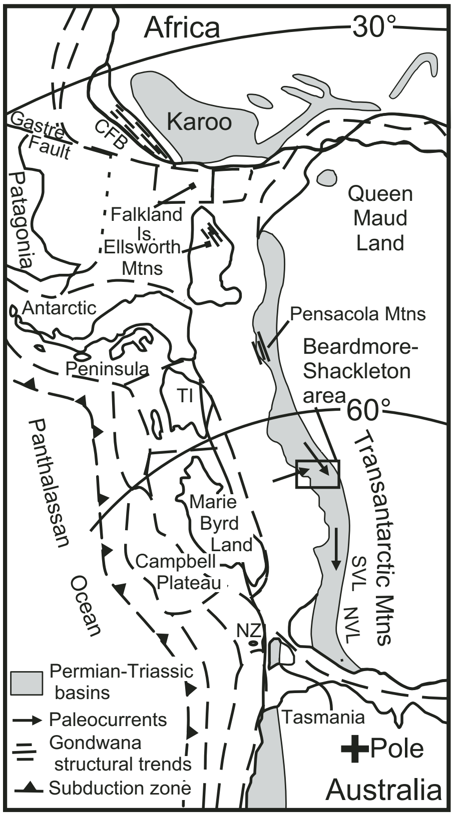

Figure 1. Map of the Panthalassan Ocean margin of Gondwana showing paleolatitudes as determined from paleomagnetic data (Powell and Li, 1994). Average paleocurrent directions for Upper Permian–Lower Triassic strata are from Collinson et al. (1994). CFB—Cape fold belt; TI—Thurston Island plate; NZ—New Zealand plate; SVL—southern Victoria Land; NVL—northern Victoria Land.

In the terrestrial paleopolar realm, including Antarctica and Australia, Upper Permian carbonaceous and coal-bearing fluvial deposits are overlain by Lower Triassic fluvial deposits with no coal and little organic content. Fossil wood, roots, leaves, and palynomorphs of the *Glossopteris* flora, which are characteristic of the Gondwana Permian, also disappeared in the boundary transition. In the Shackleton Glacier area just below the boundary, fossil logs, in situ tree stumps, and large root casts are evidence of a forested landscape. The basal Triassic flora, represented by small root casts and sparse plant remains, marks the change to more scrubby herbaceous vegetation. Coal and significant fossil wood did not reappear in Antarctica and other paleopolar localities until the Middle Triassic.

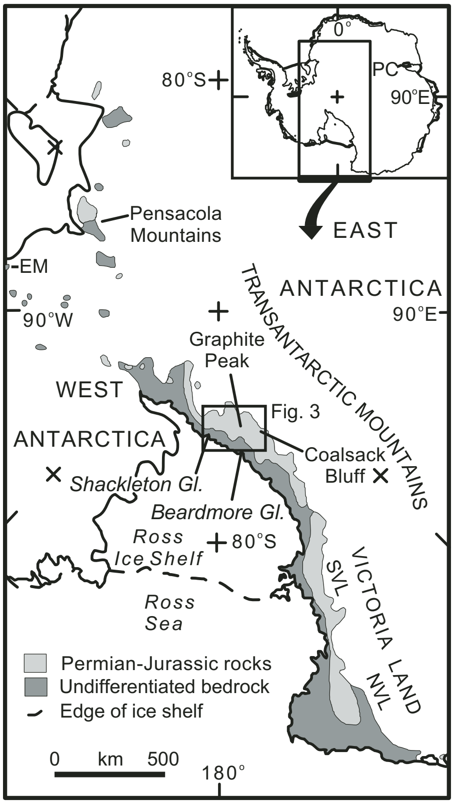

Figure 2. Locality map of Antarctica and the central Transantarctic Mountains. EM—Ellsworth Mountains, PC—Prince Charles Mountains (upper right corner), NVL—northern Victoria Land, SVL—southern Victoria Land.

We suggest that the two-step ecosystem change just below and at the top of the coal measures in Antarctica, coupled with the isotope data, correlates with the two-step floral collapse documented just below the boundary in a marine section in East Greenland (Twitchett et al., 2001; Looy et al., 2001). The Greenland boundary sequence is relatively thick compared to most marine sections and includes a mixture of terrestrial palynomorphs and marine fossils. The end-Permian changes in terrestrial floras appear to have been global but not instantaneous.

The extinction of Permian vertebrate faunas is not recorded in Antarctica, because to date no exclusively Permian vertebrates have been found. The only known representatives of the uppermost Permian vertebrate *Dicynodon* zone are three species of *Lystrosaurus*. Of these, the large dicynodont reptile *L. maccaigi* is thus far restricted to the uppermost Permian in South Africa (Botha and Smith, 2004). A single specimen of *L. maccaigi*, a skull, occurs at the base of the vertebrate-bearing sequence in one section in Antarctica (Cosgriff et al., 1982). Its occurrence in the same bed as Triassic amphibian fragments and just beneath a typical Early Triassic fauna indicates that the range of *L. maccaigi* extends at least into the basal Triassic.

Evidence of large methane gas releases have been documented in Antarctica by Krull and Retallack (2000), who reported major negative $\delta^{13}C$ shifts in their stratigraphic section near the boundary at Graphite Peak (Figs. 2 and 3). These negative carbon isotope shifts are characteristic of Permian-Triassic boundary sections in many places (Erwin, 1993), including the marine global stratotype for the Permian-Triassic boundary at Meishan, China (Jin et al., 2000) and terrestrial sections in Australia (Morante et al., 1994; Morante, 1996).

Data suggesting meteorite impact in samples from Graphite Peak cited by Retallack et al. (1998), Poreda and Becker (2003), and Basu et al. (2003) have been mostly discounted (e.g., Buseck, 2002; Koeberi et al., 2004; Langenhorst et al., 2005).

In this study, we present and reassess data collected in the central Transantarctic Mountains during five field seasons over a period of 26 yr. We did not collect our data with the possibility of a Permian-Triassic boundary in mind, because we assumed the presence of a major unconformity separating Permian and Triassic rocks. We now recognize that complete sections may exist in some localities in the central Transantarctic

Mountains. Future field work concentrating on chemostratigraphy, dating of volcanic tuffs just below the boundary, and collecting of additional samples for palynomorphs, offers promise of learning more about the transition from the Permian to Triassic in a paleopolar region.

GEOLOGIC SETTING

Late Permian and Triassic rocks in the central Transantarctic Mountains were deposited in a retroarc foreland basin (Dalziel and Elliot, 1982; Collinson, 1990, 1991; Isbell, 1991; Collinson et al., 1994). This basin was one of several foreland basins along the Panthalassa Ocean margin of Gondwana, extending from eastern Australia to Antarctica, southern Africa, and South America (Fig. 1; Veevers et al., 1994a). In Antarctica, evidence of an orogenic belt is preserved in folded Permian rocks in the Ellsworth and Pensacola Mountains (Fig. 1; Ford, 1972; Craddock et al., 1992; Collinson et al., 1992). The Permian-Triassic magmatic arc stretched from New Zealand through West Antarctica and the Antarctic Peninsula (Fig. 1). Direct evidence that this magmatic arc was active during the Permian in West Antarctica has been confirmed through U-Pb and Rb-Sr isotope studies (Mukasa, 1995; Pankhurst et al., 1995; Mukasa and Dalziel, 2000; Pankhurst, 2002).

Figure 4 shows a generalized Permian to Triassic sequence in the central Transantarctic Mountains. The oldest beds in this sequence are diamictites left by glaciers, which covered parts of Gondwana during the late Carboniferous and Early Permian (e.g., Crowell, 1999; Isbell et al., 2003). Glacial deposits are overlain by black shale, which was deposited in an extensive post-glacial inland sea that stretched from Antarctica into South Africa and southern Brazil and had probable marine connections to the Panthalassa Ocean (Miller and Collinson, 1994a). The sequence grades upward from lacustrine into deltaic and then fluvial deposits, which dominate the Upper Permian and entire Triassic. Provenance changed in the Late Permian from sandstone dominated by quartz and feldspar from the cratonic basement in East Antarctica to calc-alkaline volcanics from the magmatic arc in West Antarctica (Isbell, 1990, 1991; Collinson et al., 1994). The change in sandstone composition is at the same level as a reversal in paleocurrents. Volcanic tuffs occur within the Lower Permian sequence in the Ellsworth Mountains (Collinson et al., 1992), in the Lower Triassic

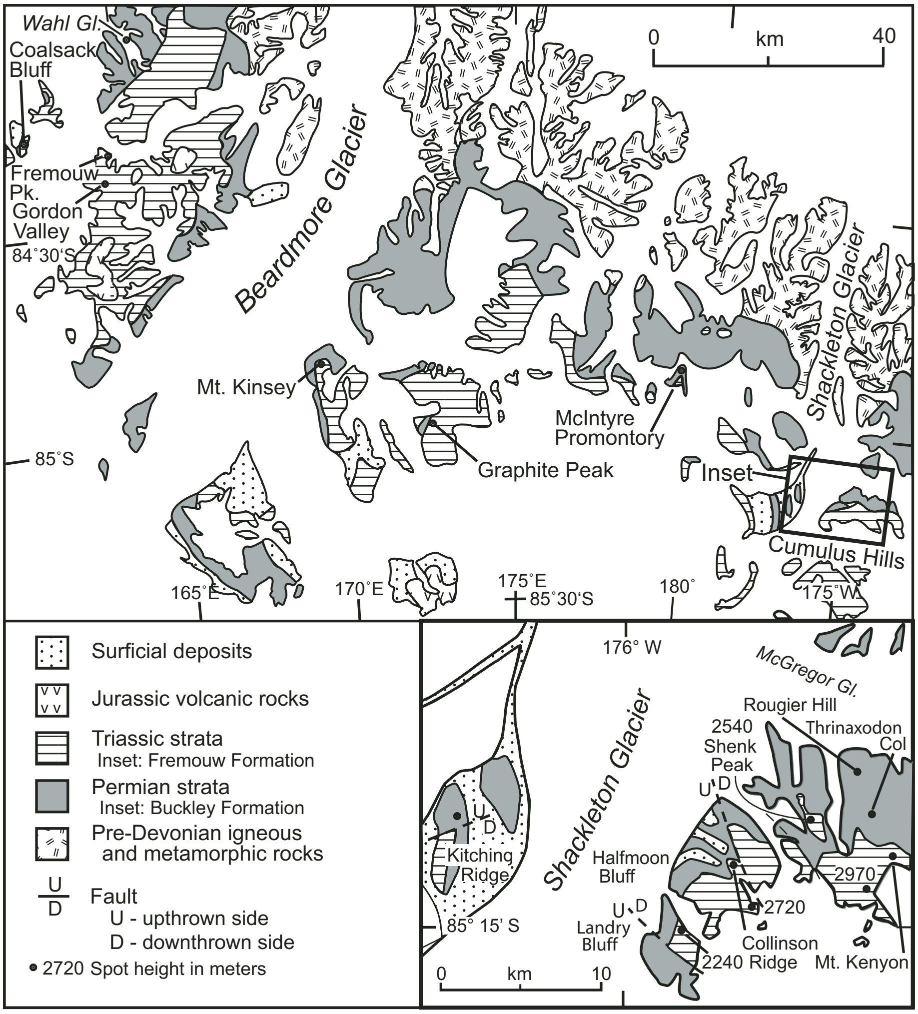

Figure 3. Locality and simplified geologic map of the Shackleton and Beardmore Glacier region (see Fig. 2). Inset shows the Cumulus Hills region.

in the Beardmore Glacier region (Barrett et al., 1986), and in the uppermost Permian just below the boundary in the Shackleton Glacier area. Silicic volcanic rocks increasingly dominated the Early Jurassic, but were replaced by basaltic phreatomagmatic deposits and flood basalts in the latest Early Jurassic (181 Ma; Elliot and Fleming, 2004), which heralded the breakup of Gondwana (Elliot, 1992).

PERMIAN-TRIASSIC BOUNDARY STRATA

The Permian Buckley Formation, which consists of coal measures that crop out extensively throughout the central Transantarctic Mountains (Fig. 3), is at least 745 m thick (Barrett et al., 1986). The formation has a lower arkosic member and an upper volcaniclastic member (Barrett et al., 1986; Isbell, 1990). Similar coal measures characterize the Permian throughout the Transantarctic Mountains and Ellsworth Mountains, although those in the Victoria Land sector do not contain volcanic detritus (Collinson et al., 1994).

The Triassic Fremouw Formation can be traced for 475 km along the central Transantarctic Mountains. The type section at Fremouw Peak (Fig. 3) in the Beardmore Glacier area is 615 m thick (Barrett, 1969). The thickest and most complete section is 653 m on Mount Kenyon (Fig. 3) near the Shackleton Glacier (La Prade, 1982). Barrett (1969) recognized three informal members. The lower member consists of more-or-less equal proportions of coarse- to medium-grained sandstone and green-gray or red fine-grained beds. Reptiles and amphibians

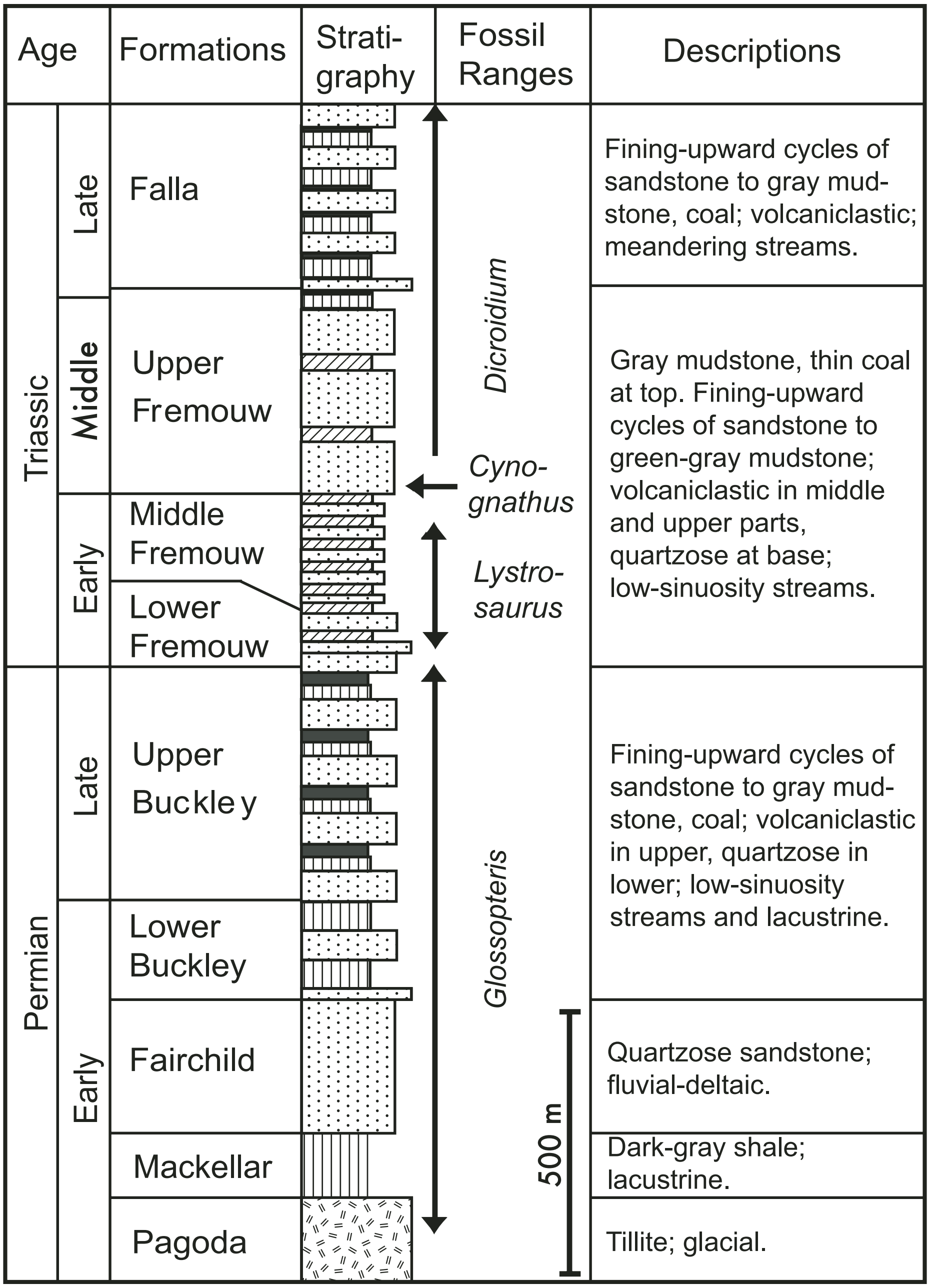

Figure 4. Generalized Permian-Triassic stratigraphic sequence in the central Transantarctic Mountains. Symbols in stratigraphic section: coarse dots—conglomerate, fine dots—sandstone, vertical lines—dark-gray shale, black—coal; diagonal lines—green-gray fine-grained beds.

of the *Lystrosaurus* fauna occur sporadically in the lower member. Fine-grained green-gray or red beds dominate the middle member. The upper member is predominately fine- to medium-grained sandstone. A *Cynognathus* fauna of Middle Triassic age occurs at the base of the upper member at several localities in Gordon Valley (Fig. 3; Hammer, 1990; Hammer et al., 1990). In the same general area, fossil wood (including a fossil forest), carbonaceous mudstone, and minor coal occur near the top of the Fremouw (Barrett et al., 1986; Del Fueyo et al., 1995; Taylor et al., 2000; Cúneo et al., 2003).

The noncarbonaceous, green-gray fine-grained strata of the lower Fremouw Formation are easily distinguished from the gray coal measures of the Permian Buckley Formation. However, in other ways, the two formations are similar. Both are composed of fining-upward fluvial cycles beginning with coarse- to medium-grained sandstone. The sandstones are trough cross-bedded, multistory, and have a sheet-like geometry. They change abruptly into fine-grained sandstone, siltstone, and mudstone in the upper part of cycles. They both contain similar trace fossil faunas (Miller, 2000).

Silicic volcanic detritus dominates sandstone in the upper Buckley Formation (Fig. 5A; Barrett, 1969; Isbell, 1990). Sandstone in the lower Fremouw is predominantly quartzose in the Beardmore Glacier area (Barrett, 1969), but is increasingly volcaniclastic toward the Shackleton Glacier area (Vavra, 1982). In the Shackleton Glacier area, the composition of basal Fremouw sandstone is intermediate between the volcaniclastic upper Buckley and the quartzose sandstone above the lowest vertebrate horizon (Fig. 5A–B). While volcanic detritus came from the magmatic arc, nonvolcanic quartz and granitic and metamorphic rock fragments came from both the orogenic belt and the East Antarctic craton.

The Buckley (Isbell, 1990) and Fremouw Formations (Barrett, 1969) have been interpreted as low-sinuosity, sandy braided stream deposits. Late Permian and Triassic streams apparently flowed off the orogen onto low-gradient alluvial fans and then along the axis of the foreland basin toward the Australian sector of Gondwana (Fig. 1; Collinson, et al., 1987; Isbell, 1991). In addition to coal-forming swamps, the Buckley Formation also contains extensive lacustrine deposits (John L. Isbell, 2003, personal commun.). Lacustrine strata are uncommon in the Triassic, but a 50-m-thick lacustrine unit dominated by dark shale occurs in the middle Fremouw member at Halfmoon Bluff (Fig. 3).

The differences in color between the Buckley and Fremouw Formations are a reflection of paleosol alteration. In a series of publications, Retallack, Krull, and colleagues described and classified the paleosols in the Buckley and Fremouw Formations at Graphite Peak (Retallack et al., 1996a; Retallack and Krull, 1999; Krull and Retallack, 2000). Their paleosol designations are applicable to Upper Permian and Lower Triassic strata throughout the central Transantarctic Mountains. At Graphite Peak, they recognized eight pedotypes in the upper Buckley and 12 in the lower and middle Fremouw. Most of the Buckley paleosols are gray or olive-gray and carbonaceous, whereas Fremouw paleosols exhibit mostly green or red hues and contain little organic matter. They attributed the green and red colors in Triassic paleosols to the oxidation of organic material and chemical reduction of oxides during decomposition of organic material in soils that were originally yellowish brown to gray. They interpreted the upper Buckley paleosols as forming in woodlands on swampy floodplain environments in a humid and seasonally snowy climate. The Triassic paleosols were interpreted as indicating much warmer paleoclimate conditions and as forming in woodlands on a seasonally wet, well-drained floodplain.

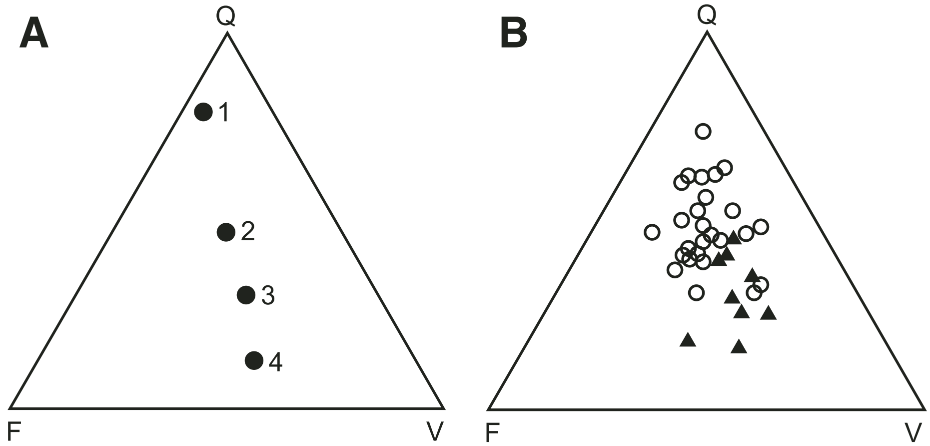

Figure 5. (A) Quartz (Q)-feldspar (F)-volcanic (V) ternary diagram showing average composition of sandstones in the upper Buckley and lower Fremouw Formations in the Beardmore and Shackleton glacier areas. (1) Lower Fremouw Formation, Beardmore Glacier area (Barrett, 1969); (2) lower Fremouw Formation above lowest vertebrate locality, Shackleton Glacier area (Vavra, 1982); (3) lower Fremouw Formation below lowest vertebrate horizon, Shackleton glacier area (Vavra, 1982); (4) upper Buckley Formation (Barrett, 1969; Isbell, 1990). (B) Comparison of compositions of sandstone in the basal Fremouw versus the vertebrate-bearing lower Fremouw (Vavra, 1982). Closed triangles are from the Fremouw Formation below the vertebrate-bearing beds. Open circles represent samples from the vertebrate-bearing beds.

Contact between the Buckley and Fremouw Formations

The Buckley-Fremouw contact has always been recognized as a disconformity, but Barrett's (1969) placement of the contact in the Beardmore Glacier area may not have been the same as that of Collinson and Elliot (1984a) in the Shackleton Glacier area. Barrett defined the Fremouw Formation at Fremouw Peak where the basal contact is not exposed, but he described four sections where this contact can be seen. On Mount Kinsey and at the head of the Wahl Glacier (Fig. 3), the basal bluff-forming sandstone of the Fremouw disconformably overlies carbonaceous shale of the Buckley Formation. In the sections on Graphite Peak and McIntyre Promontory (Fig. 3), Barrett noted that the contact is less certain. On Graphite Peak, the lowest fluvial cycle with green-gray fine-grained beds contains *Glossopteris* in the sandstone part of the cycle, so he placed the contact at the base of the next higher cycle. On McIntyre Promontory, fossil wood occurs in the lowest cycle with green-gray beds, so Barrett again placed the contact at the base of the next higher cycle. When Collinson and Elliot (1984a) described the Fremouw Formation in the Shackleton Glacier area, they placed the lower contact at the base of the lowest fining-upward cycle with green-gray fine-grained beds and above the highest carbonaceous beds. They wrongly assumed that the fossil wood, which occurs in the basal Fremouw cycle at several localities in the Shackleton Glacier area, is Triassic in age. Now that *Glossopteris* has been identified with the fossil wood on Collinson Ridge, it is likely that fossil wood–bearing strata at other lower Fremouw localities in the Shackleton Glacier area are also Permian.

Lower Fremouw Boundary Sections

The lower Fremouw is a cyclical sequence of sandstone and fine-grained deposits ranging from 80 m to 130 m thick (Fig. 6). The basal bluff-forming sandstone is coarse- to medium-grained, typically 5 m to 15 m thick, and is in erosional contact with the Buckley Formation. Major sandstone units are sheet-like in geometry, and thicker sandstone units can be traced for hundreds of meters before pinching out (Collinson et al., 1981). Sandstone units become thinner upward in the section. The thicker units are multistory with internal scours up to several meters deep. Angular rip-up clasts of fine-grained sandstone and mudstone, rounded phosphate pebbles, rounded quartz pebbles, and bones are concentrated at the base of and above scour surfaces within channel-form sandstones. Large-scale trough cross-beds with trough heights averaging ~0.3 m dominate coarse- to medium-grained sandstone. Cross-beds are commonly distorted by soft-sediment deformation. Fine-grained sandstone beds are typically ripple-laminated. Clay drapes, which overlie some truncation surfaces, are burrowed, and in some cases have mud cracks.

Vertical burrow tubes (*Skolithos*), abundant at some localities, penetrate as much as 1 m (Miller and Collinson, 1994b). Large burrows occur in two distinct sizes. Tetrapods probably inhabited the largest burrows (Miller et al., 2001), while crustaceans or small tetrapods could have made the smaller burrows (Babcock et al., 1998). Possible tetrapod burrowers include *Lystrosaurus*, *Thrinaxodon*, and *Procolophon*. The forelimbs of both *Procolophon* and *Lystrosaurus* have been suggested as adapted to digging (Colbert and Kitching, 1975; King and Cluver, 1991). A *Thrinaxodon* skeleton has been found preserved in the cast of a burrow in South Africa (Damiani et al., 2003). None of the Antarctic burrows found thus far have body fossils preserved within them.

The mid-cycle transition from major-channel sandstone units to overlying fine-grained units is typically abrupt. The tops of major sandstone units are avulsion surfaces, preserving stream-bottom features, such as dunes and depressions, with thin clay drapes containing small burrows (Fig. 7). The upper fine-grained parts of lower Fremouw cycles are dominated by green-gray mudstone with thin interbeds of fine-grained sandstone and siltstone. Bedding is commonly preserved in siltstone and mudstone. Small-scale cross-bedding and ripple laminae occur in fine-grained sandstone. White root casts similar to those described by Retallack and Alonso-Zarza (1998) in the Triassic of southern Victoria Land are abundant near the tops of mudstone units.

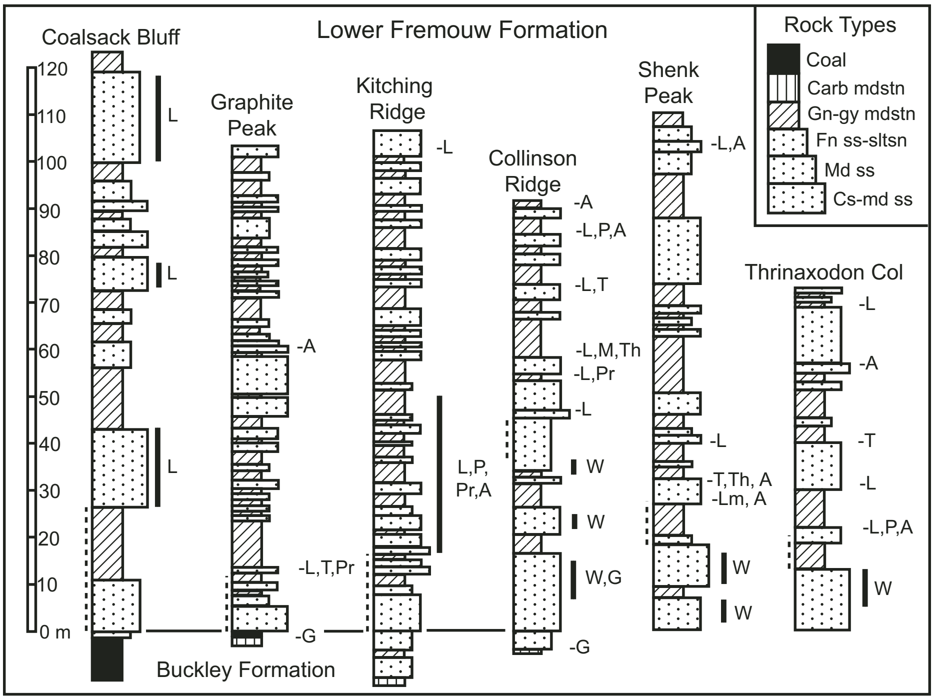

Figure 6. Stratigraphic sections of Lower Fremouw and uppermost Buckley formations showing fossil horizons. Dashed vertical line on left of each column shows transition or level of uncertainty of Permian-Triassic boundary between highest *Glossopteris* flora and lowest *Lystrosaurus* fauna. In addition to field and laboratory notes, data are from Colbert (1974, 1982, 1987), Colbert and Cosgriff (1974), Colbert and Kitching (1975, 1977, 1981), Collinson and Elliot (1984a, 1984b), Collinson et al. (1981), Collinson and Hammer (1996), Cosgriff (1983), Cosgriff and Hammer (1984), Cosgriff et al. (1982), Hammer (1990), Hammer and Cosgriff (1981), Hammer et al. (1990), Hammer et al. (1996), and Vavra (1982). A—amphibian; G—*Glossopteris*; L—*Lystrosaurus* (*curvatus* or *murrayi*); Lm—*Lystrosaurus maccaigi*; M—*Myosaurus gracilis*; P—*Procolophon trigoniceps*; Pr—*Prolacerta broomi*; T—*Thrinaxodon liorhinus*; Th—thecodont, W—fossil wood. Rock types: Carb mdstn—Carbonaceous mudstone; Gn-gy mdstn—Green-gray mudstone; Fn ss-siltsn—fine-grained sandstone to siltstone; Md ss—medium-grained sandstone; Cs-md ss—coarse- to medium-grained sandstone.

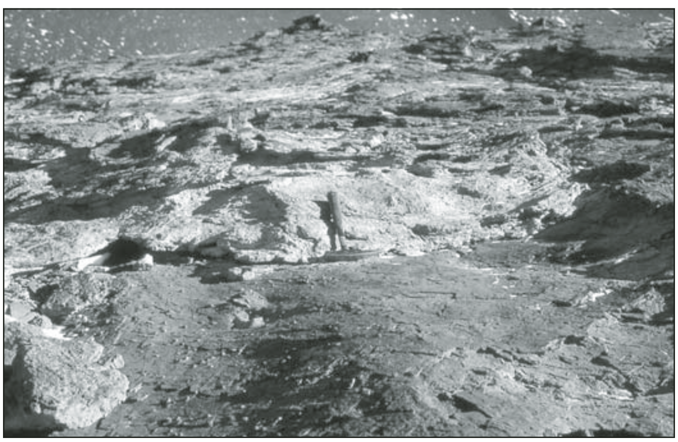

Figure 7. Avulsion surface from 61 m above the base of the Thrinaxodon Col section. Mudstone drapes are intensely burrowed. More photos of outcrops and sedimentary structures are included in the Data Repository.[1]

The stratigraphic sections discussed here and shown in Figure 6 are those with abundant vertebrate fossils. At most localities bones are rare, and their preservation required special conditions. Individual bones scattered within sandstone units, typically on scour surfaces, are the most common and show signs of having been reworked and transported. Complete to partial skeletons are typically found in mudstone directly above avulsion surfaces. Corpses were apparently stranded on avulsion surfaces and were soon buried during a subsequent flood from another channel (e.g., Smith, 1993). Specimens that were quickly buried are better preserved and less scattered (Fig. 8). We did not find evidence of scavenging, even though predators (e.g., thecodonts) are part of the fauna. Bones are rarely preserved in beds with abundant root casts, probably owing to soil processes.

Coalsack Bluff

The lower Fremouw is ~130 m thick and consists of four distinct fining-upward sequences (Collinson and Elliot, 1984b). Fossil vertebrates occur as redeposited bones in the sandstone part of the upper three cycles (Colbert, 1974), beginning ~28 m above the base of the formation. The fine-grained parts of cycles, composed mostly of green-gray mudstone, are poorly exposed because of the steep exposures covered by colluvium. The basal contact is exposed along the west side of Coalsack Bluff (Fig. 3) near the south end (map in Collinson and Elliot, 1984b). In our measured stratigraphic section (Fig. 6), trough cross-bedded, medium-grained sandstone at the base of the Fremouw disconformably overlies 1.2-m-thick carbonaceous, fine-grained sandstone with poorly preserved plant stems and *Glossopteris* leaves in the Buckley Formation. The basal Fremouw channel-form sandstone locally cuts through the uppermost Buckley sandstone down to an 8-m-thick coal. Rip-up clasts of carbonaceous shale and sandstone lie above the contact. If the Permian-Triassic boundary is not at this disconformity, it is within the lower 28 m of the Fremouw below the first occurrence of bones.

Another excellent locality for vertebrates is on the west side of Coalsack Bluff on a downdropped fault block of steeply dipping beds (map in Collinson and Elliot, 1984b). Here diabase

[1]GSA Data Repository item 2006080, color photographs of outcrops and fossils, is available on the Web at http://www.geosociety.org/pubs/ft2006.htm. Requests may also be sent to editing@geosociety.org.

intrudes along the contact, but a thin layer of contact-metamorphosed shale or coal underlies the basal Fremouw sandstone. The lowest vertebrates here were found in the second fining-upward cycle in a cross-bedded, coarse-grained sandstone 25 m above the base.

In another stratigraphic section, which includes the upper 14 m of the Buckley and the lower 28 m of the Fremouw (up to the lowest occurrence of bones), Retallack et al. (2005) reported a large negative $\delta^{13}C$ anomaly at ~5 m above the contact. This was the only sample listed in a 12-m-thick interval between samples with normal values. They placed the Permian-Triassic boundary below a claystone breccia at the base of the Fremouw.

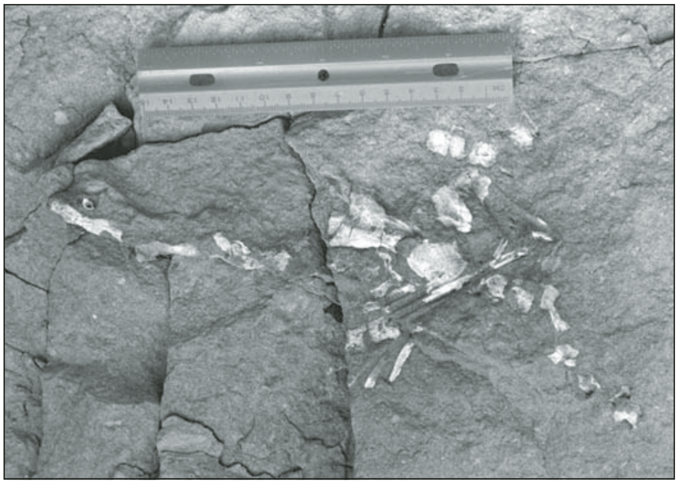

Figure 8. *Lystrosaurus* skeleton buried in mudstone just above avulsion surface. The ruler is 15 cm long. More photos of vertebrate fauna are included in the Data Repository.

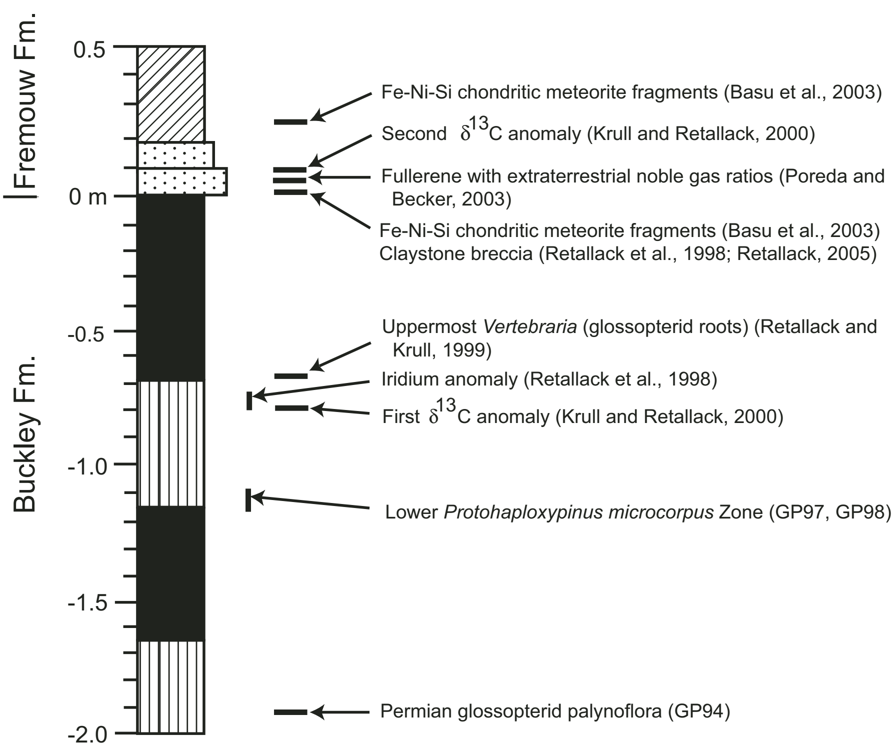

Figure 9. Detailed measured section at Graphite Peak of uppermost Buckley Formation and lowermost Fremouw Formation. Lithologic symbols are the same as in Figures 6 and 11.

Graphite Peak

This is one of the best-known Permian-Triassic sections in Antarctica, because the first Triassic tetrapod fossil, an amphibian jaw, was found here in the lower Fremouw Formation (Barrett et al., 1968). It is one of the few continuous Upper Permian to Middle Triassic sequences that is not interrupted by a major diabase sill, although several minor sills and dikes are found throughout the section (Plate 1b in Barrett et al., 1986). Dikes in this region commonly have intruded small faults that displace stratigraphic sequences (Collinson and Elliot, 1984a, 1984b). As at other localities, the rocks have undergone thermal alteration.

Barrett (1969) noted that the position of the Buckley-Fremouw contact at Graphite Peak is unclear. He placed the lower contact of the Fremouw at the disconformity above sandstone containing a thin lenticular shale with leaves of *Glossopteris*. In our stratigraphic section (Fig. 6), measured at a different but nearby place, we found a clear-cut disconformity where a fining-upward cycle of 6 m of gritty sandstone followed by 3 m of green-gray fine-grained beds overlies and is erosional into a carbonaceous mudstone and coal of the Buckley Formation. Whether a significant amount of time is missing at this disconformity is uncertain, but the contact does cut down through the uppermost coal bed. The lowest vertebrate occurrence is 13 m above the Buckley-Fremouw contact in our measured section.

Retallack and colleagues reported a detailed stratigraphic section in which they described paleosols and analyzed samples for $\delta^{13}C$ (Retallack et al., 1996a, 1998; Retallack and Krull, 1999; Krull and Retallack, 2000). They identified a pronounced negative shift in $\delta^{13}C$ values just below the uppermost Buckley coal (0.7 m thick) and several more additional excursions in the overlying noncarbonaceous lower Fremouw (Fig. 9; Krull and Retallack, 2000). Presumably the 0.7-m-thick coal lens would have taken some time to accumulate, possibly 20–50 k.y. (Retallack and Krull, 1999). A Permian age for the paleosol underlying the uppermost Buckley coal is indicated by the glossopterid roots (*Vertebraria*) reported by Retallack and Krull (1999). Although the pronounced negative shift in $\delta^{13}C$ values and an iridium anomaly occur just below the uppermost Buckley coal (Fig. 9), they place the boundary in a claystone breccia at the base of the Fremouw Formation. We did not observe the "boundary breccia" described by Retallack et al. (1998), but we did see mudstone rip-up clasts near the base of, and within, many channel-form sandstones in the lower Fremouw. Retallack (2005) coined the term "sepic pedolith" for these unusual breccias, which he describes as occurring in Permian-Triassic boundary rocks in Antarctica, Australia, and South Africa. According to Retallack, "These rocks differ from other breccias in having a high proportion of clasts with birefringence microfabrics (sepic plasmic fabrics) characteristic of soils, and can be called sepic pedoliths in the terminology of soil science." He attributes their formation to massive erosion of soils after forest destruction at the boundary.

Possible evidence of extraterrestrial impact has been suggested from laboratory analyses of the boundary beds at Graphite Peak (Fig. 9). Retallack et al. (1998) reported a faint iridium anomaly just below and at the base of the uppermost Buckley coal, and rare grains of shocked quartz in a claystone breccia at the stratigraphic boundary and within the basal Fremouw sandstone immediately above that breccia. The authors have since retracted their identification of the shocked quartz (Langenhorst et al., 2005). Poreda and Becker (2003) reported fullerenes with extraterrestrial noble gas abundances (He^3) and isotope ratios ($^3He/^{36}Ar$) in the claystone breccia. Basu et al. (2003) described Fe-Ni-Si chondritic meteorite fragments from the same claystone breccia and also in the overlying sandstone.

Samples from the same detailed section that Retallack and colleagues analyzed (collected at the same time as their field study) were processed for palynomorphs. Samples below the uppermost Buckley coal contain poor, though discernible, typical Permian glossopterid palynofloras, dominated by bisaccate and taeniate bisaccate pollen. A slightly better-preserved assemblage from sample GP94 (Table 1), 1.9 m below the Buckley-Fremouw contact, includes typical Permian taxa, including *Scheuringipollenites ovatus, Protohaploxypinus limpidus, Striatopodocarpidites cancellatus, Praecolpatites sinuosus,* and *Bascanisporites undosus* (the latter is restricted to the Late Permian). It also includes rare *Playfordiaspora crenulata*. A similarly preserved assemblage from sample GP97 (coaly shale), 1.2 m below the contact, lacks the *P. sinuosus* and *B. undosus,* includes *Striatoabieites multistriatus* and *Plicatipollenites gondwanensis* (both Permian, but occurring rarely in the very earliest Triassic), and, importantly, includes *Lunatisporites* sp. and increased numbers of lycopsid taxa, including common *Playfordiaspora crenulata*. A sparse assemblage from GP98 (green-gray siltstone), 1.1 m below the contact, contains *Protohaploxypinus microcorpus, Lunatisporites* sp., and *Playfordiaspora crenulata*. *P. microcorpus* and the latter lycopsid spore species first appear sporadically in uppermost Permian Australian deposits, immediately below the *Protohaploxypinus microcorpus* zone (e.g., Helby et al., 1987). However, they are not common until the *P. microcorpus* zone, where *Lunatisporites* spp. first occur. *P. microcorpus, P. crenulata, and Lunatisporites* spp. (including *L. pellucidus*, an Early Triassic indicator in Australia) all occur together in the Upper Permian in New Zealand (Campbell et al., 2001; see also Crosbie, 1985). The two reported Late Permian occurrences of *P. microcorpus* in Antarctica are from the upper Buckley Formation on Mount Achernar, 15 km west of Coalsack Bluff (Farabee et al., 1991), and from the McKinnon Member, uppermost Bainmedart coal measures in the Prince Charles Mountains (Fig. 2; McLoughlin et al., 1997).

We correlate the Graphite Peak assemblages of GP97 and GP98 with the eastern Australian *Protohaploxypinus microcorpus* zone (as in Helby et al., 1987). These assemblages still show close similarities to underlying Permian

TABLE 1. PALYNOMORPH DATA ACROSS THE PERMIAN-TRIASSIC BOUNDARY AT GRAPHITE PEAK

Sample	Position (m)	Lithologic and palynomorph data
GP106	4.5	Green-gray shale—barren of palynomorphs
GP105	4.3	Green shale—barren of palynomorphs
GP104	4.2	Light-gray, very fine sandstone—barren of palynomorphs
GP103	4.1	Medium-gray sandstone—barren of palynomorphs
		—Fremouw contact—
GP102	4.0	Coal—effectively barren of palynomorphs
GP101	3.7	Coal—effectively barren of palynomorphs
GP100	3.4	Coal—effectively barren of palynomorphs
GP99	3.3	Yellow/olive-green weathering mudstone—barren of palynomorphs
GP98	3.0	Green-gray siltstone— *Protohaploxypinus microcorpus* zone—sparse palynomorphs include *P. microcorpus*, *Lunatisporites* sp., *Playfordiaspora crenulata*
GP97	2.9	Coaly shale—*P. microcorpus* zone—typically Permian assemblage plus *Lunatisporites* sp., common *Playfordiaspora crenulata*
GP96	2.8	Coal—effectively barren of palynomorphs
GP95	2.7	Coaly shale—effectively barren of palynomorphs
GP94	2.2	Medium-gray siltstone—Permian glossopterid palynoflora including *Praecolpatites sinuosus* and *Bascanisporites undosus*, plus rare *Playfordiaspora crenulata*
GP93	1.7	Light-gray siltstone—barren of palynomorphs
GP92	1.2	Medium-gray siltstone—barren of palynomorphs
GP91	1.0	Light-gray siltstone—poorly preserved Permian glossopterid palynoflora with bisaccate and taeniate bisaccate pollen
GP90	0.6	Light-gray siltstone—poorly preserved Permian glossopterid palynoflora with bisaccate and taeniate bisaccate pollen
GP89	0.3	Light-gray siltstone—barren of palynomorphs
GP88	0.0	Light-gray siltstone—barren of palynomorphs

assemblages. The occurrence of the *P. microcorpus* zone palynomorphs below the base of the last Buckley coal is well before, in terms of time elapsed, the Buckley-Fremouw contact immediately above the coal. From the Bowen Basin, Queensland, Foster (1982) described a separate zone, the *Playfordiaspora crenulata* zone, between the Permian Upper Stage 5 and the *P. microcorpus* zone. Following Helby et al. (1987), the *Playfordiaspora crenulata* zone is here included in and considered a basal subzone of the *P. microcorpus* zone. Our material is too poorly preserved to be able to differentiate between Foster's *P. crenulata* and *P. microcorpus* zones. In addition to lacking other diagnostic taxa, we consider a quantitative count, which might help distinguish these zones, to be of little value, since many palynomorphs are fragmentary or too heavily carbonized to be identifiable, and we are unable to differentiate between many taeniate and non-taeniate bisaccates. Indeed, we suspect that the lycopsid spores *P. crenulata* are preferentially preserved, and even in fragmentary form they are more easily recognizable than some other taxa.

The *P. microcorpus* zone is transitional between Permian and Triassic floras. In Australia it was included in the uppermost Permian (e.g., Helby et al., 1987), though more recent analyses have shown an increasingly negative $\delta^{13}C$ excursion occurring at or near the base of the zone, which led Morante et al. (1994) and Morante (1996) to suggest that the *P. microcorpus* zone should be considered mainly Triassic. The Bowen Basin is the only example where Foster's (1982) *P. crenulata* zone appears to be a separate unit underlying the *P. microcorpus* zone, and Morante et al. (1994) and Morante (1996) included it in the uppermost Permian. The "inclusive" *P. microcorpus* zone as used by Helby et al. (1987) may span the Permian-Triassic boundary in Australia. Foster et al. (1997, 1998), however, questioned the correlative value of the carbon isotope excursion. In New Zealand, assemblages, including *P. microcorpus*, *P. crenulata*, and, significantly, *L. pellucidus*, have been found associated with Permian marine invertebrates at the type locality of the Permian Puruhauan Stage in Southland (discussed by Raine, Appendix in Campbell et al., 2001). We include the Graphite Peak *P. microcorpus* zone and the uppermost Buckley, with its last coal bed, within the Permian.

Identifiable palynomorphs were not recovered from the uppermost Buckley coal, which is high rank. The gray sandstone immediately above the coal contains a small amount of black organic matter, possibly reworked, but it is barren of palynomorphs, as are samples of the overlying green-gray mudstone, which barely yielded a trace of organic matter. Parallel, more widely spaced samples taken from both the upper Buckley and lower Fremouw further along the exposure all were nearly or essentially barren of organic material, including a dark-gray shale lens in sandstone immediately below the stratigraphic contact similar to that noted by Barrett (1969). Judging from the baked nature of many of these rocks (hence the name Graphite Peak), it is probable that diabase intrusions, not all readily apparent in outcrop, played a part in destruction of organics at this locality.

Kitching Ridge

A fining-upward cycle of 8 m of medium-grained sandstone followed by 5 m of green-gray fine-grained strata disconformably overlies olive-gray siltstone and carbonaceous shale of the Buckley Formation. No fossil wood was found at this locality. The lowest vertebrate horizon is 13 m above the base. The Permian-Triassic boundary lies at the base or within the lower 13 m of the Fremouw Formation.

In the 1970 field season, most vertebrates were collected on the west side of Kitching Ridge from slope-dipping beds (Kitching et al., 1972). Specimens were collected at 6 levels on bedding-plane surfaces, but exact stratigraphic position of each fossil was not recorded. In Figure 6, these vertebrate-bearing beds are extrapolated to our stratigraphic section on the east side of Kitching Ridge where the Buckley-Fremouw contact is exposed. We later collected additional vertebrate material at the 25 m and 102 m levels on the east side (Hammer et al., 1996). Large burrows, some of which probably belonged to tetrapods, occur in the upper part of this section (Miller et al., 2001).

Collinson Ridge

The best-exposed boundary sequence in the Shackleton Glacier area occurs on Collinson Ridge (Figs. 10 and 11). This locality has also been referred to by its field name "Sentinel Hill" by Colbert (1974, 1987). The stratigraphic section, presented in Hammer and Cosgriff (1981) and described by Vavra (1982) from the 1977 field season, was measured again in the 1995–1996 field season when we located the Buckley-Fremouw contact 3 m above the diabase sill. The section was measured in greater detail, this time taking into account the entire exposure as seen in Figure 11.

A thick diabase sill generally follows the basal Fremouw contact. A sliver of Buckley lithic sandstone is exposed on the northeast side of the ridge above baked shale with *Glossopteris* impressions at the top of the diabase sill. The basal Fremouw is pebbly, medium-grained sandstone. The lower 36 m of the Fremouw contains abundant fossil wood. In the first fining-upward cycle at ~12 m above the base, silica-permineralized tree stumps up to 1 m in diameter (Fig. 12) are surrounded by medium- to fine-grained trough cross-bedded sandstone. Thin, shallow roots extend laterally for several meters into the surrounding bedrock. One fallen log is 40 cm in diameter at its base, but tapers abruptly to 12 cm and then gradually to 10 cm over its length of 6.3 m. A lens of permineralized peat, 0.6 m thick and 2 m across, occurs near the top of the first fining-upward cycle at ~16 m above the base of the formation. McManus et al. (2002) described a *Glossopteris* flora from this peat. The organic material in this peat is too baked for recovery of identifiable palynomorphs.

Associated with the plant-bearing beds in the lower Fremouw are light-gray aphanitic tuffs, 0.2–0.6 m thick, that weather white. They are faintly laminated and locally contain mud cracks and impressions of stems and leaf fragments. They can be traced only a few tens of meters and may have been deposited in small ponds. Thin sections of two samples are very fine-grained, low in phyllosilicates, and siliceous looking. Glass shards are not preserved, but are found in a similar sample from the middle Fremouw on Shenk Peak.

The lowest vertebrate fossils occur in a coarse-grained sandstone with quartz pebbles 47 m above the base of the section and 10 m above the highest plant fossils. The Permian-Triassic boundary lies within this 10-m-thick fine-grained sandstone.

Shenk Peak

Shenk Peak is the best-exposed section of the lower and middle members of the Fremouw Formation in the Shackleton Glacier area. Unfortunately, the base of the formation is not exposed here. Fossil wood of probable Permian age is abundant in a medium- to coarse-grained sandstone in the lower 18 m of section. Fine-grained strata are composed of green-gray

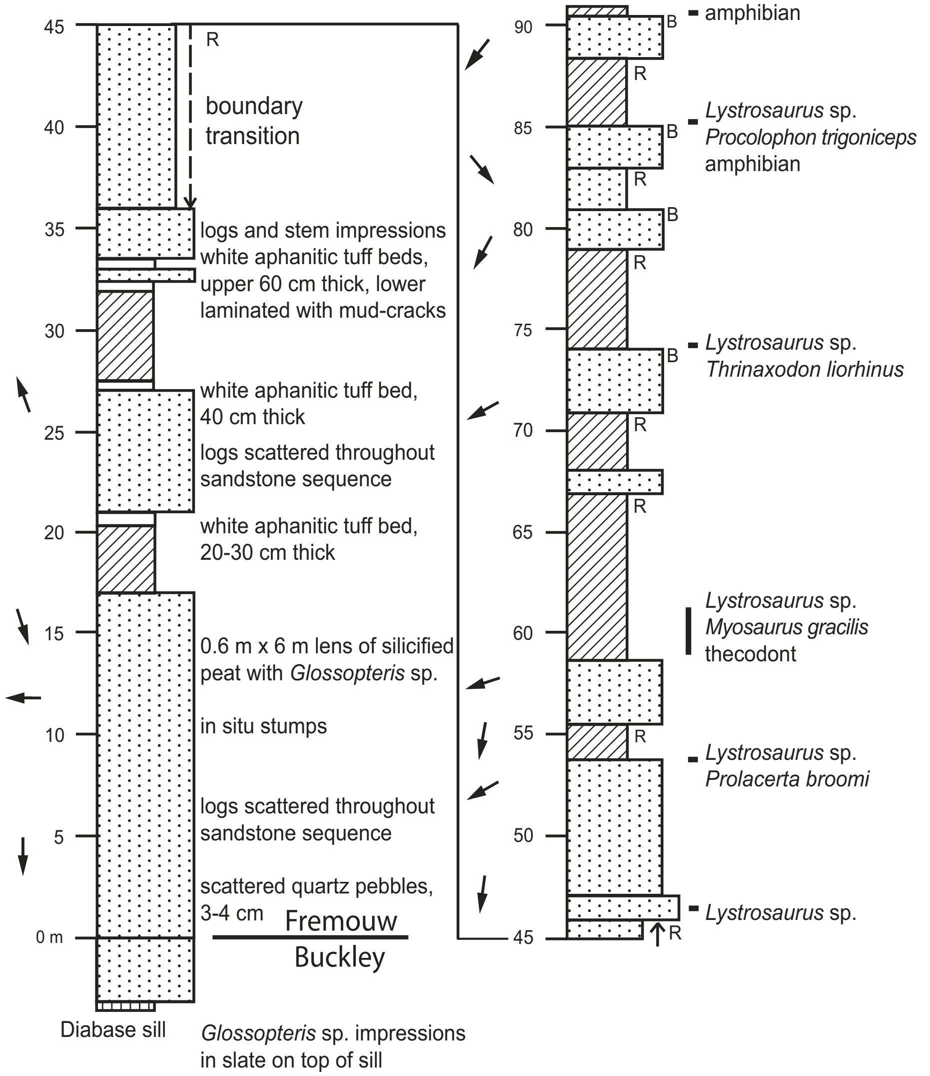

Figure 10. Detailed Collinson Ridge stratigraphic section showing lithologies, paleosols (roots), fossils, and paleocurrents. *Lystrosaurus* is represented by the smaller forms, probably *L. murrayi* or *L. curvatus*. More photos of the fauna are included in the Data Repository (see text footnote 1). Lithologic symbols are the same as in Figure 6, except for the white aphanitic tuff beds, which are represented by no pattern. B—bioturbation; R—root casts. An earlier version of the section was published in Hammer and Cosgriff (1981) and described in Vavra (1982). The stratigraphic section reported here was measured in 1995–1996, and other versions were published in Collinson and Hammer (1996) and McManus et al. (2002). Vertebrate horizons noted in the earlier section in Hammer and Cosgriff (1981) converted to this section are: 29.7 m = 47 m; 43 m = 59–61 m; 53 m = 75 m; 57 m = 82 m.

mudstone. The lowest vertebrate horizon occurs in the third fining-upward cycle at 28 m above the base of the section and 10 m above the top of the fossil wood–bearing sandstone. The boundary occurs within this 10-m-thick interval. The lowest vertebrate horizon includes a skull of *Lystrosaurus maccaigi*, the largest of the dicynodonts in the Antarctic fauna, and bone fragments of brachyopid, lydderinid, and rhytidosteid amphibians (Cosgriff et al., 1982; Cosgriff and Hammer, 1984). Triassic amphibians, *Thrinaxodon liorhinus*, and a thecodont occur close to the base of the vertebrate-bearing sequence (Fig. 6).

The most abundant fossil horizon is at 102 m, where reptile, amphibian, and fish scales have been found (Hammer and Cosgriff, 1981; Cosgriff and Hammer, 1984). Small indeterminate bone pieces were found at 239 m in the section within the middle Fremouw member 64 m below the base of the upper Fremouw. Their small size suggests that they may belong to a procolophonid or an eosuchian. The base of the upper Fremouw member may be Middle Triassic if it correlates with the upper Fremouw in the Beardmore Glacier area, where it contains a Middle Triassic *Cynognathus* fauna (Hammer et al., 1990).

Thrinaxodon Col

This locality was named for the dozen skeletons of *Thrinaxodon* that were collected here in 1970 (Kitching et al., 1972; Colbert and Kitching, 1977). Multiple occurrences of specimens at some localities in South Africa have led to speculation that these mammal-like animals lived in colonies (Colbert and Kitching, 1977). The basal sandstone of the Fremouw is in contact with a diabase sill at this locality. The lowest fining-upward cycle in the Fremouw begins with a 1.3-m-thick coarse-grained sandstone that grades upward into a 12-m-thick medium-grained sandstone containing claystone clasts, quartz pebbles, and fossil logs (Fig. 6). The upper 6 m of the cycle is composed of green-gray siltstone and mudstone with abundant rootlets near the top. The lowest vertebrate horizon occurs in sandstone about 7 m above the log-bearing sandstone that is now interpreted to be Permian. A large dicynodont tusk was collected here, but its stratigraphic level was not recorded (Cosgriff et al., 1982). The Permian-Triassic boundary lies within the 7-m-thick interval above the uppermost log horizon and below the first appearance of vertebrate fossils.

COMPARISONS WITH THE KAROO BASIN

Permian-Triassic sequences in the Transantarctic Mountains and South Africa are similar in that they were deposited in foreland basins related to orogenic events along the Panthalassan margin (Veevers et al., 1994a). In a reconstructed Gondwana, the Transantarctic and Karoo foreland basins are contiguous (Fig. 1). Although the stratigraphic sequences are similar, their timing is different (Fig. 13). Similar facies appear to have followed the Gondwana plate as it moved across the geographic pole (Table 2). In southern Africa, widespread coal measures deposition ceased in the early Late Permian at the diachronous contact between the Ecca and Beaufort Groups (Rubidge et al., 2000), while in Antarctica and eastern Australia, coal measure deposition continued throughout the Late Permian. Upper Permian sequences in South Africa in the lower part of the Beaufort Group contain blue-gray to green-gray floodplain deposits with tetrapod faunas (Smith, 1995). In the central Transantarctic Mountains, deposition of green-gray floodplain strata with tetrapod faunas did not begin until the Early Triassic.

Meandering stream deposits characterized the Karoo Basin until the change to low-sinuosity braided stream deposits at the Permian-Triassic boundary (Ward et al., 2000; Smith and Ward, 2001). The entire Upper Permian and Lower to Middle Triassic fluvial sequence in the central Transantarctic Mountains was deposited by low-sinuosity braided streams (Barrett et al., 1986). In both foreland basins, Upper Permian deposits contain abundant volcanic detritus derived from an active magmatic arc (Collinson et al., 1994; Johnson, 1991). The Early Triassic influx of quartzose sandstone in the Katberg Sandstone (Upper Beaufort Group in Fig. 13) has been interpreted as an alluvial fan system spreading into the foreland basin from the tectonically active Cape fold belt (Fig. 1; Hiller and Stavrakis, 1984; Smith, 1995; Catuneanu and Elango, 2001). Much of the Early Triassic influx of quartzose sediments in the lower Fremouw came from the orogenic belt (Vavra et al., 1981).

The Permian-Triassic contact in the northern Karoo Basin is located along an unconformity (Hancox et al., 2002), but to the south it is within a transitional sequence, the Palingkloof Member, at the top of the Balfour Formation (Lower Beaufort Group in Fig. 13; Smith, 1995). This member, 40 to 80 m thick, is gradational into the overlying Katberg Sandstone (Upper Beaufort Group in Fig. 13; Hiller and Stavrakis, 1984). The Permian-Triassic boundary coincides with the change from deposition by meandering streams to low-sinuosity streams (Smith, 1995; Ward et al., 2000). In a biostratigraphic study of vertebrate distribution, Smith and Ward (2001) narrowed the boundary in the central and southern part of the Karoo Basin to above a bed containing large brown-weathering calcareous nodules and below a 3- to 5-m-thick laminated maroon mudstone. MacLeod

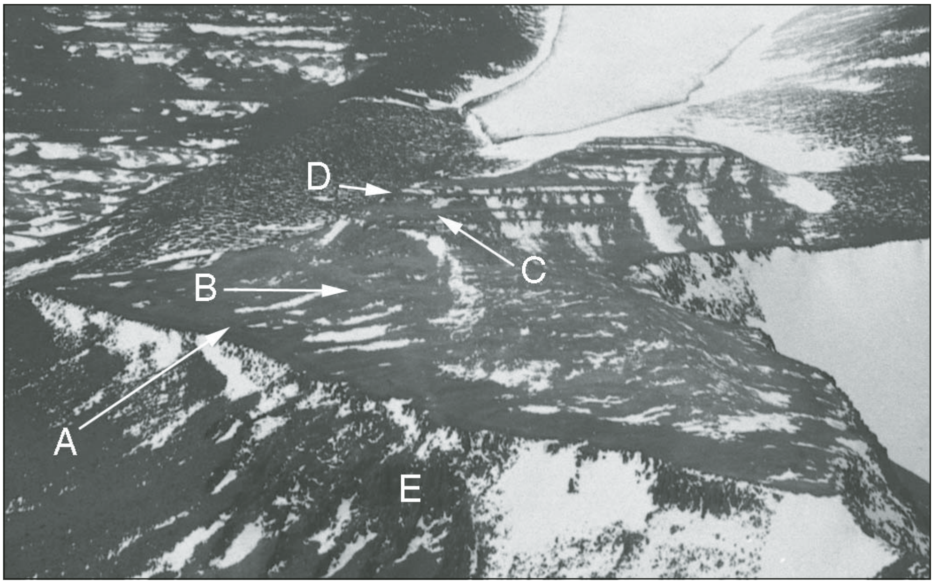

Figure 11. Collinson Ridge showing: (A) Fremouw-Buckley contact, (B) permineralized peat horizon with *Glossopteris* flora, (C) highest plant fossils, (D) lowest vertebrate fossils, and (E) Jurassic diabase sill.

Figure 12. In situ fossil tree trunk on Collinson Ridge at ~12 m above the base of the Fremouw Formation. The rock hammer is 32 cm long. More photos of the flora are included in the Data Repository.

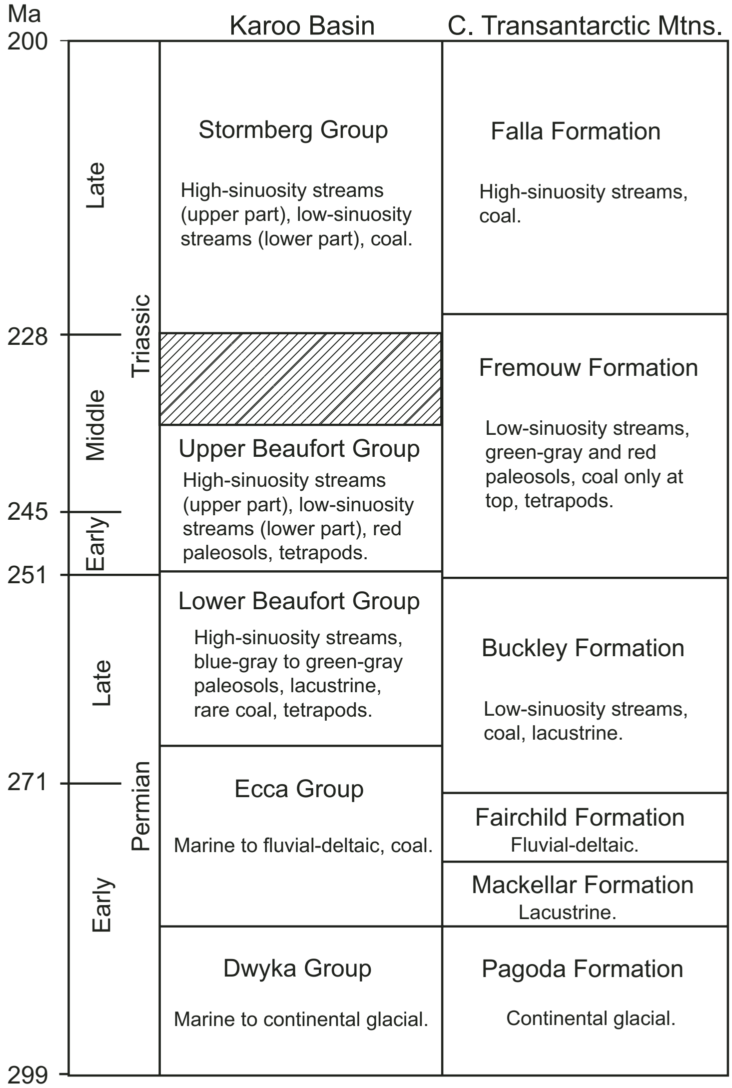

Figure 13. Comparison of time-stratigraphic sections of the Permian and Triassic in the Karoo Basin and the central Transantarctic Mountains. The Balfour Formation composes most of the Lower Beaufort Group in the central Karoo Basin, and the Palingkloof Member, which contains the Permian-Triassic boundary, is at the top. More photos of outcrops are included in the Data Repository. Rare coal occurs in the Lower Beaufort Group in the northern Karoo Basin (Groenewald, 1990). Karoo descriptions are from Catuneanu et al. (1998). The Late Triassic age for the top of the Fremouw Formation is based on palynomorphs (Kyle and Schopf, 1982).

et al. (2000) reported a large negative $\delta^{13}C_{carb}$ anomaly close to the boundary. Retallack et al. (2003) suggested that the boundary lies within the laminite unit, which they interpreted as representing widespread playa deposition. They noted a marked difference in the purple-red and gray paleosols below the inferred boundary and the brownish red and green above, indicating a climate change from strongly seasonal arid conditions in the latest Permian to warmer, less seasonal, semiarid to subhumid conditions in the Early Triassic. Smith and Ward (2005) proposed that drought conditions at the Permian-Triassic boundary in the Karoo facilitated the change in fauna.

Marine and terrestrial extinctions at the Permian-Triassic boundary have not been correlated biostratigraphically, although widespread extinctions in the marine and terrestrial realm have been assumed to be chronostratigraphic. This view is supported by the correlation of reptile extinctions in South Africa (MacLeod et al., 2000) with rapid, negative $\delta^{13}C$ excursions at and below the boundary in global marine sections (Yang et al., 1996; Jin et al., 2000). In the Karoo Basin, the boundary has been placed between the *Dicynodon* and the *Lystrosaurus* assemblage zones (Rubidge et al., 1995; Smith, 1995). The ranges of some *Lystrosaurus* species have been shown to extend down into the *Dicynodon* assemblage zone in the Karoo Basin (Hotton, 1967; Smith, 1995; Smith and Ward, 2001; Retallack et al., 2003). These include *L. murrayi*, *L. curvatus*, and *L. maccaigi*, all of which are part of the Antarctic fauna, which is interpreted to be Early Triassic in age (Colbert, 1982). Only *L. maccaigi* has not been found in the Triassic of South Africa (Botha and Smith, 2004). As in Antarctica, the *Glossopteris* flora in the Karoo Basin extend up to the boundary, but diagnostic plant fossils are poorly preserved to nonexistent in the basal Triassic (Gastaldo et al., 2005).

DISCUSSION

Locating the Permian-Triassic boundary in high-latitude terrestrial sequences poses significant problems, because the boundary has been defined by biostratigraphic analyses of abundant marine biota. In the global stratotype at Meishan, China, the base of the Triassic is defined by the first appearance of the conodont *Hindeodus parva*. The boundary is several centimeters above a major negative shift in $\delta^{13}C$ and the major extinction event (Yin et al., 1996; Jin et al., 2000). Marine and Gondwana terrestrial faunas of this age have not been directly correlated with each other.

In Antarctica, faunal correlation is limited by the probable absence of the uppermost Permian *Dicynodon* zone. Three species of *Lystrosaurus* in Antarctica are holdovers from the Permian. *L. murrayi* and *L. curvatus* are relatively small compared to the large herbivore *Lystrosaurus maccaigi*, which occurs at the base of the vertebrate-bearing sequence at Shenk Peak. In South Africa, specimens of *L. maccaigi* are rare and have been reported only from the *Dicynodon* zone (Botha and Smith, 2004). Benton et al. (2004), in discussing the end-Permian extinction of tetrapods in Russia, noted an absence of large herbivores in the Lower Triassic. The occurrence of a skull of *L. maccaigi* with distinctive Early Triassic taxa confirms that its range extends into the Triassic in Antarctica. Range charts of various taxa in the Karoo Basin show

TABLE 2. PERMIAN AND PERMIAN-TRIASSIC BOUNDARY PALEOLATITUDES

Age range	Paleopole position	Central Transantarctic Mountains (°S)	Karoo Basin (°S)	References
Permian-Triassic boundary	SE Australia	65	35	Powell and Li (1994)
Permian-Triassic boundary			40.7	Ward et al. (2005, supplement)
Late Permian	Northern Victoria Land	80	45	Powell and Li (1994)
Late Permian	South Australia–Antarctica	75	45	Grunow (1999)
Middle and Late Permian	West Antarctica (Marie Byrd Land)	80	60	Scotese (2000)

that several Antarctic taxa, such as *Prolacerta*, *Myosaurus*, *Procolophon*, and *Thrinaxodon*, first appeared well above the Permian-Triassic boundary (Groenewald and Kitching, 1995; Ward et al., 2005).

The extinction of Permian vertebrate faunas has been hypothesized to be the result of hypoxia caused by global warming and an atmosphere with low oxygen content (Sheldon and Retallack, 2002; Ward, 2004; Huey and Ward, 2005; Berner, 2005). Large terrestrial vertebrates such as *L. maccaigi* may have been able to survive into the Triassic under low-oxygen conditions in paleopolar regions where the climate was relatively cool (Huey and Ward, 2005). Retallack et al. (2003) and Huey and Ward (2005) have hypothesized that some dicynodonts, such as the smaller *Lystrosaurus* species, which spans the boundary, were physiologically able to adapt to low-oxygen conditions, enabling them to survive the extinctions. Many of the smaller animals may have hibernated in burrows, requiring less oxygen in winter, and therefore were more able to adapt to low-oxygen conditions. Animals suspected of constructing the large burrows in the Lower Fremouw Formation include *Lystrosaurus*, *Procolophon*, *Myosaurus*, and *Thrinaxodon* (Miller et al., 2001). A burrow cast in South Africa contains the articulated skeleton of *Thrinaxodon liorhinus* (Damiani et al., 2003), the same species found in Antarctica. Other members of the Antarctic fauna, such as the large crocodilian-like thecodonts, small lizards, and amphibians, would have needed ways to cope with the Antarctic winter as well as low-oxygen conditions.

The path of Early Triassic migrations of tetrapods was probably along low-lying foreland basins that bordered the Panthalassa Ocean margin (Fig. 1). A climate simulation for the latest Permian that couples ocean and atmosphere shows warm ocean temperatures even in the polar regions and a temperate climate along the central Transantarctic Mountains sector of the continental margin (Kiehl and Shields, 2005). Presumably temperatures were even warmer in the Early Triassic.

Palynofloras aid with the correlation of Permian and Triassic sequences in parts of Gondwana, but are less useful in the Transantarctic Mountains and South Africa, where organic fossils have been degraded by heat from Jurassic diabase intrusions. Morante (1996) correlated marine and terrestrial sections in Australia using palynomorphs and $\delta^{13}C$ chemostratigraphy. He concluded that the Permian-Triassic boundary lies above the last coal and near the base of the *Protohaploxypinus microcorpus* zone. In the Graphite Peak section, the first major $\delta^{13}C$ excursion occurs just above the base of this zone and below the uppermost Buckley coal (Fig. 9). Although the base of the *P. microcorpus* zone is less than 2 m below the Buckley-Fremouw contact (Fig. 9), the top of the zone has not been identified. The presence of the *P. microcorpus* zone, which may be entirely Permian or span the boundary, is the only well-defined biostratigraphic marker close to the boundary in Antarctica. It, combined with $\delta^{13}C$ chemostratigraphy, is the most reliable means of correlation with other sequences in the world. Unfortunately, paleomagnetic methods such as those used in the correlation of sections in South Africa (De Kock and Kirschvink, 2004; Ward et al., 2005) are not useful in the Transantarctic Mountains because of heating by Jurassic diabase sills.

A stratigraphic sequence across the boundary in East Greenland contains both marine fossils and terrestrial pollen and spores, which may provide an indirect means of correlation with the central Transantarctic Mountain sequence. Two steps in the collapse of the Permian flora are documented in Greenland (Twitchett et al., 2001; Looy et al., 2001). The first step, the demise of dense gymnosperm woodlands and expansion of herbaceous vegetation dominated by lycopsids, is below the major negative shift in $\delta^{13}C$ near the boundary. The second step, a renewed dieback of woody plants and the extinction of the remaining typical Late Permian gymnosperms, occurs well above the negative $\delta^{13}C$ excursion and just below the lowest Triassic marine fauna. This pattern is similar to the floral changes that bracket the first major negative shift in $\delta^{13}C$ in the Graphite Peak section. The floras in these widely separated regions are from different floral provinces, but evidence is substantial that these changes reflect global catastrophic events. Unusual abundances of fungal remains in latest Permian rocks suggest destabilization and subsequent collapse of terrestrial ecosystems (Eshet et al., 1995; Visscher et al., 1996; Looy et al., 2001). Visscher et al. (2004) noted a worldwide proliferation of tetrads of lycopsid microspores near the boundary, a condition that they attributed to mutations caused by an external stress factor such as enhanced ultraviolet exposure (UV-B). Fungal remains have not been identified in palynomorph samples from Graphite Peak, and spore tetrads are rare, but if such phenomena did occur in the high polar Antarctic paleolatitudes, it is possible that the relevant information has been lost within the coal (from which palynologic data could not be retrieved), within a hiatus, or within the overlying noncarbonaceous interval. We note that the recovered *P. microcorpus* zone assemblages represent just the beginning of the latest Permian central Antarctic ecosystem collapse.

Retallack et al. (2005) contended that the most reliable field criteria for recognizing the boundary in Antarctica is the change from gray carbonaceous paleosols to green-gray (Delores) paleosols, which in the Beardmore Glacier region occurs at the contact between the Buckley and overlying Fremouw Formation. In this region, the change from volcanic sandstone to quartzose sandstone also defines the contact. However, in the Shackleton Glacier area, the top of the Permian is noncarbonaceous and has been placed in the Fremouw Formation (Collinson and Elliot, 1984a). The glossopterid wood and *Glossopteris* are up to 35 m above the base of the Fremouw. The plant-bearing sandstone in these sections is intermediate in composition between the more volcaniclastic Buckley and the more quartzose lower Fremouw (Fig. 5A).

The change in paleosol color across the boundary is not at the same biostratigraphic level everywhere in Antarctica. In the Shackleton Glacier area, the color change occurs well below the boundary. In the Prince Charles Mountains along the Indian Ocean sector of East Antarctic (Fig. 2), McLoughlin et al. (1997) placed the boundary at the top of Permian coal measures, but fine-grained carbonaceous beds continue into the Lower Triassic. No vertebrates have been found, but an excellent palynomorph sequence is preserved. Here, the change to red and green paleosols did not occur until the late Early Triassic.

The cessation of coal deposition in the Transantarctic Mountains is part of an important regional, and possibly global, event. The absence of coal anywhere in the world in the Early Triassic led Veevers et al. (1994b) to introduce the concept of an Early Triassic "coal gap." Retallack et al. (1996b) summarized possible causes for the coal gap and theorized that a sudden atmospheric shift to greenhouse conditions at the Permian-Triassic boundary caused the extinction of peat-producing plants. Coal and significant woody plant remains did not return in Antarctica, and elsewhere, until the Middle Triassic (e.g., Looy et al., 1999).

Global climate change at the boundary apparently affected fluvial morphology. Ward et al. (2000) suggested that a basin-wide change from high- to low-sinuosity streams in South Africa was the result of catastrophic die-off of rooted plant life at the boundary. Michaelsen (2002) offered evidence from the Bowen Basin in eastern Australia that the extinction of peat-forming plants at the boundary transformed a landscape of rivers and swamps into a braided stream setting. Although low-sinuosity stream deposits dominate both the Permian and Lower to Middle Triassic sequences in Antarctica, climate and vegetative changes could have been responsible for an increase in prominent sandstone ledges that characterize the lower Fremouw. Alternatively, uplift in source areas could have also increased the supply of quartzose sediment.

Evidence of meteorite impact in the central Transantarctic Mountains in the Graphite Peak section has been mostly discounted. The presence of shocked quartz (Retallack et al., 1998) has been retracted (Langenhorst et al., 2005). The report of fullerenes with extraterrestrial noble gas isotope ratios (Fig. 9) (Poreda and Becker, 2003) has been seriously questioned (e.g., Buseck, 2002; Koeberl et al., 2004). We question that the Fe-rich and other chondritic fragments (Fig. 9) described by Basu et al. (2003) could have survived the flow of hot fluids produced by burial and then intrusion of diabase during the Jurassic. The Buckley-Fremouw contact was buried beneath more than 1 km of Triassic and Jurassic sediments before being intruded by Jurassic diabase sills and overlain by more than 500 m of Jurassic basalt (Elliot, 2000). The thickness of diabase sills in the Triassic section is difficult to document, but could have increased the overlying column of rock by several hundred meters. The large volumes of diabase that intruded the Graphite Peak region (Elliot et al., 1974) also elevated temperatures. The Fremouw zeolite-facies mineral assemblages suggest that Jurassic alteration was controlled by simple heat-driven rock-fluid reactions with temperatures higher than 200 °C immediately adjacent to sills and 130 °C to 160 °C elsewhere (Vavra, 1989). The occurrence of prehnite in the claystone breccia bed also suggests elevated temperatures, possibly more than 200 °C (Schiffman and Day, 1999). Fullerenes may be extremely resistant, but it is surprising that they, with their encapsulated noble gases and Fe-Ni-Si meteoritic fragments, could have survived such conditions in the Jurassic and also survived younger hydrologic regime changes related to uplift (Fleming et al., 1999). However, such fragments might have been isolated by enclosure within the berthierine nodules reported by Sheldon and Retallack (2002).

In terms of time, just how complete are the terrestrial sections in the central Transantarctic Mountains? Each of the major sandstone cycles in the lower Fremouw is underlain by an erosional disconformity representing the migration of a stream channel and a possible hiatus. The Permian-Triassic boundary could be along one of these surfaces. However, the central Transantarctic Mountains region was in a subsiding foreland basin that preserved much of the stratigraphic record. In terms of time, the transitional interval bracketing the boundary can be defined by the change in palynofloras at the base of the *Protohaploxypinus microcorpus* zone, which is between 1 and 2 m below the top of the coal measures in the Graphite Peak section, to the lowest Triassic tetrapod horizon, which is 7–10 m above the last of the glossopterid flora in the Shackleton Glacier area. Lower Triassic sections at Shenk Peak and Graphite Peak are ~300 m thick. Using the most-recent time scale recognized by the International Commission on Stratigraphy, the Early Triassic lasted 6 m.y. (Gradstein et al., 2005). The average rate of rock accumulation in this part of the foreland basin was ~50 m/m.y. The thickness of the transitional sequence would represent on the order of 200 k.y.

CONCLUSIONS

The Permian-Triassic boundary lies within a well-exposed terrestrial sequence in the central Transantarctic Mountains. In the Graphite Peak section, two changes in flora occur in the upper 1–2 m of the Permian coal measures. The first is the change from a typical *Glossopteris* palynoflora to the *Protohaploxypinus microcorpus* zone palynoflora, which in New Zealand is latest Permian in age. This zone has also been used to locate the boundary in Australia. The second change is the final extinction of the Permian *Glossopteris* flora and the end of coal deposition until the Middle Triassic. These events bracket the lowest major negative $\delta^{13}C$ excursion in the boundary interval. A similar sequence of events around the boundary in the section in East Greenland with marine fauna confirms the position of the boundary just above the coal measures at Graphite Peak and above glossopterid wood occurrences in the Shackleton Glacier area. This correlation also suggests that the extinction of the Permian woodland floras and their replacement by herbaceous vegetation in the basal Triassic was a global event. The boundary sequence in Antarctica lends support to the hypothesis that floral destruction by enhanced ultraviolet-B is part of the extinction equation. Also, the change in floras would have affected terrestrial vertebrate survival and extinctions.

In the Shackleton Glacier area, the boundary is within a 7- to 10-m-thick interval of green-gray, fine-grained sandstone and siltstone with small root casts above a woody glossopterid flora and below the *Lystrosaurus* fauna. The migration of the reptilian and amphibian fauna from South Africa to Antarctica in the Early Triassic supports hypotheses of runaway global warming caused by CO_2 emissions from Siberian flood basalts and large methane gas releases. The hypoxia hypothesis is supported by the occurrence of *Lystrosaurus maccaigi*, a large dicynodont, in the Antarctic fauna. Found only in the Upper Permian in South Africa, it occurs at the base of the vertebrate-bearing sequence on Shenk Peak. Its survival into the

Early Triassic in paleopolar Antarctica may be attributable to cooler temperatures. Also, many taxa in the *Lystrosaurus* assemblage were probably burrowers, which may have helped them in coping with low-oxygen conditions and cold, dark winters.

The Permian-Triassic boundary transitional sequence in the central Transantarctic Mountains records a series of global events that occurred over a period of ~200 k.y. The changes from a glossopterid to a *Protohaploxypinus microcorpus* palynoflora, the appearance of the first of several major negative $\delta^{13}C$ excursions just below the boundary, disappearance of coal and large woody plants at the boundary, and the appearance of reptiles and amphibians in high latitudes just above the boundary are recorded in a 9- to 12-m-thick interval of strata.

ACKNOWLEDGMENTS

The U.S. National Science Foundation, Office of Polar Programs, supported this research, most recently through grants to Hammer (OPP9614928, OPP0229698), Askin (OPP9418093), and Elliot (OPP9420498). We benefited greatly from discussions with John L. Isbell, Molly F. Miller, Octavian Catuneanu, Ian Raine, Roger M.H. Smith, and Joseph L. Kirschvink. Anne M. Grunow and Christopher R. Scotese gave advice on paleopole positions. Jeff Linder helped with the construction of the graphics. We are grateful for thorough reviews of the manuscript by Gregory J. Retallack and an anonymous reviewer. We are indebted to the vertebrate paleontologists with whom we have worked and who have since passed on, namely Edwin H. Colbert, James A. Jensen, James W. Kitching, and John W. Cosgriff.

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Manuscript Received by the Society 4 October 2004
Revised Manuscript Received 30 November 2005
Manuscript Accepted 7 December 2005

Printed in the USA

Geological Society of America Bulletin

Permian-Triassic boundary in the central Transantarctic Mountains, Antarctica

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Geological Society of America Bulletin 2006;118, no. 5-6;747-763
doi: 10.1130/B25739.1

Notes