The Permian–Triassic boundary in Antarctica

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Abstract: The Permian ended with the largest of known mass extinctions in the history of life. This signal event has been difficult to recognize in Antarctic non-marine rocks, because the boundary with the Triassic is defined by marine fossils at a stratotype section in China. Late Permian leaves (*Glossopteris*) and roots *Vertebraria*), and Early Triassic leaves (*Dicroidium*) and vertebrates (*Lystrosaurus*) roughly constrain the Permian–Triassic boundary in Antarctica. Here we locate the boundary in Antarctica more precisely using carbon isotope chemostratigraphy and total organic carbon analyses in six measured sections from Allan Hills, Shapeless Mountain, Mount Crean, Portal Mountain, Coalsack Bluff and Graphite Peak. Palaeosols and root traces also are useful for recognizing the Permian–Triassic boundary because there was a complete turnover in terrestrial ecosystems and their soils. A distinctive kind of palaeosol with berthierine nodules, the Dolores pedotype, is restricted to Early Triassic rocks. Late Permian and Middle Triassic root traces are carbonaceous, whereas those of the Early Triassic are replaced by claystone or silica. Antarctic Permian–Triassic sequences are among the most complete known, judging from the fine structure and correlation of carbon isotope anomalies.

Introduction

Although both Permian and Triassic fossils have been known from Victoria Land and the central Transantarctic Mountains since the expeditions of Scott, Shackleton and Mawson (Seward 1914), finding the Permian–Triassic boundary in these thick sequences of non-marine sandstones and shales has remained difficult and controversial (Collinson *et al.* 1994, Isbell & Cuneo 1996, Isbell *et al.* 1999, McManus *et al.* 2002). This controversy is surprising because the terminal-Permian mass extinction was the largest in the history of life (Retallack 1995, Jin *et al.* 2000, Retallack *et al.* 2003), with profound consequences for sedimentary environments, such as delayed recovery of peat swamps and coral reefs (Retallack *et al.* 1996, Knoll *et al.* 1996), and spread of stromatolites, flatstone conglomerates (Wignall & Newton 2003), and braided streams (Ward *et al.* 2000). A part of the problem is that the boundary is defined by marine fossils in a stratotype section in China, which was deposited in palaeotropical shallow marine waters (Jin *et al.* 2000) remote from the high latitude Gondwanan interior basins of Antarctica (Collinson *et al.* 1994). Correlation with Chinese terrestrial plants and vertebrates gives a general guide (Lucas 2001, Wang & Chen 2001), but fossil localities are sparse near the Permian–Triassic boundary in Antarctica (Isbell *et al.* 1999). Fossil pollen and spores also give only general

indications, as many of the quartz rich sandstones are barren of organic microfossils, and those in shales are brittle and carbonized from nearby dolerite intrusions (Kyle 1977, Farabee *et al*. 1991, Askin 1997, 1998). The inadequacy of the local fossil record and the abundance of palaeochannel sandstones with locally erosive bases has led to the suggestion that as much as 8 million years of the latest Permian and earliest Triassic are missing within a major geological disconformity (Collinson *et al*. 1994, Isbell & Cuneo 1996).

In contrast, we here present evidence of Permian–Triassic boundary sections complete enough to inform the causes and consequences of end-Permian extinctions from new discoveries of Late Permian and Early Triassic plants, vertebrates, palaeosols, and from carbon isotope chemostratigraphy at four localities in Victoria Land and two in the central Transantarctic Mountains (Fig. 1). The most reliable criteria for the Permian–Triassic boundary in Antarctica are distinctive palaeosols (Dolores pedotype), root traces (*Vertebraria*), a negative excursion in carbon isotopic composition of organic matter, and a decline in total organic matter.

Magnetostratigraphy and radiometry of these rocks has proven inconclusive. The palaeomagnetic signal of Permian and Triassic sediments appears to have been reset during intrusion of early Jurassic dolerites (Nairn 1970, Funaki
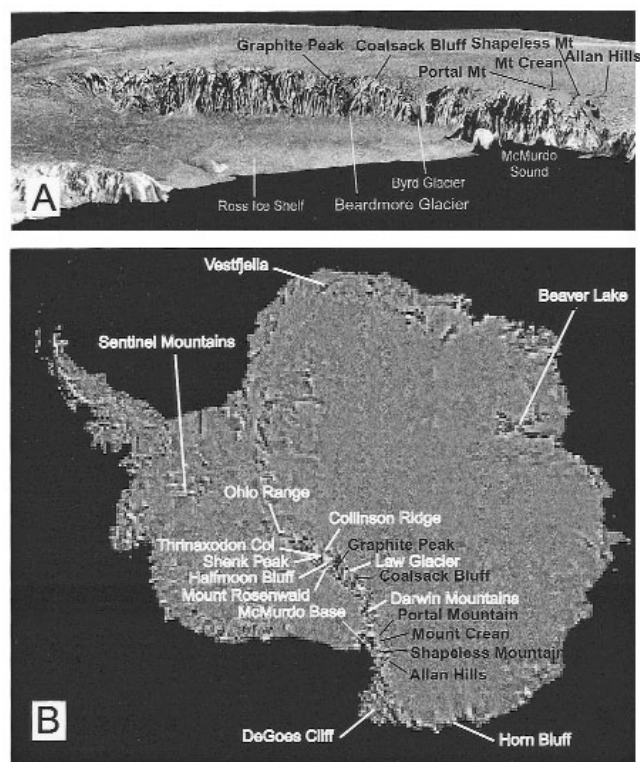
Fig. 1 Study sites in Victoria Land and the central Transantarctic Mountains (black) and other mentioned sites (white) in **a.** Antarctica, and **b.** study sites on a vertically exaggerated view oblique from the north-east. AVHRR (Advanced High Resolution Radiometer) images courtesy of US Geological Survey (http://terraweb.wr.usgs.gov/TRS/projects/antdemstr.html, accessed 16 April 2004).

1983, Christoffel 1981). Volcanic ashes are uncommon and appear to have been weathered shortly after deposition. Our samples submitted for ^{40}Ar/^{39}Ar dating have not yet yielded results.

Although this account emphasizes six localities in the central Transantarctic Mountains and southern Victoria Land, comparable stratigraphical completeness of Permian–Triassic boundary sections is likely throughout East Antarctica. Other Antarctic sequences worthy of comparable study are at Horn Bluff on the George V Coast (Pavlov 1958), De Goes Cliff in northern Victoria Land (Hammer & Zawiskie 1982, Hammer 1987), Darwin Mountains of the southern Victoria Land (Haskell *et al*. 1965), Law Glacier in the north-central Transantarctic Mountains (Norris 1965, Lambrecht *et al*. 1972), Beaver Lake in the Prince Charles Mountains (McLoughlin *et al*. 1997), and Vestfjella in Dronning Maud Land (Paech *et al*. 1991, Lindström 1994). Supposed Triassic plant beds on Livingston Island turned out to be Cretaceous (Rees & Smellie 1989, Poole & Cantrill 2001), so Permian–Triassic boundary sections have yet to be reported from the Antarctic Peninsula.

Materials and methods

Our fieldwork has resulted in six measured sections through the Permian–Triassic boundary (Figs 1 & 2):

1) Graphite Peak, sampled in 1996 and 2003 (S85.05211°, E172.36832°, 2744m),

2) Coalsack Bluff, sampled in 2003 (S84.23989°, E162.29979°, 2107m),

3) Portal Mountain, sampled in 2003 (S78.10784°, E159.36727°, 2198m),

4) Mount Crean, sampled in 1995 and 2003 (S77.87383°, E159.53333°, 2154m),

5) Shapeless Mountain, sampled in 2003 (S77.43797°, E160.47073°, 2220m), and

6) Allan Hills, sampled in 1995 (S76.70240°, E159.73623°, 1835m).

Illustrated fossil plants are in the Condon Collection of the University of Oregon, Eugene (W.N. Orr, curator).

For carbon isotope analysis, clean samples of coal and carbonaceous shale were dissolved in HF and HCl maceration, and the carbonaceous residue combusted in sealed tubes containing Cu, CuO and Ag. Released CO_2 was purified and collected for ^{13}C/^{12}C measurement relative to Vienna Peedee belemnite standard. Total organic carbon content was analysed as well, and did not show a significant direct correlation with δ^{13}C values (Retallack & Jahren 2005). Many of these new analyses from the John Hopkins University laboratory of A.H. Jahren replicate analyses reported by Krull & Retallack (2000) in the University of Illinois Laboratory of Jack Liu, and the Mainz Laboratory of Manfred Schidlowski.

Permian–Triassic plants

The most useful indicators of the general position of the Permian–Triassic boundary are fossil spores, pollen, leaves and roots of plants. Permian leaves of *Glossopteris* are found on fewer stratigraphic levels than the distinctive chambered root of glossopterids, *Vertebraria* (Fig. 3f). Large, vertically-penetrating *Vertebraria* are common in Gondwanan Late and Middle Permian rocks, but not found in Early Permian rocks (Retallack 1980). Their last appearance is an important biostratigraphic marker for glossopterids. Also Late Permian in age is *Phyllotheca australis* (Holmes 2001), found in the Allan Hills (Retallack & Krull 1999a). Late Permian pollen and spores have been found in the upper Buckley Formation at Coalsack Bluff, Mount Piccioto, Mount Sirius, and Mount Achernar in the central Transantarctic Mountains (Kyle & Fasola 1978, Kyle & Schopf 1980, Farabee *et al*. 1991) and in the Bainmedart Coal Measures, near Beaver Lake, Prince Charles Mountains (McLoughlin *et al*. 1997). Pollen and
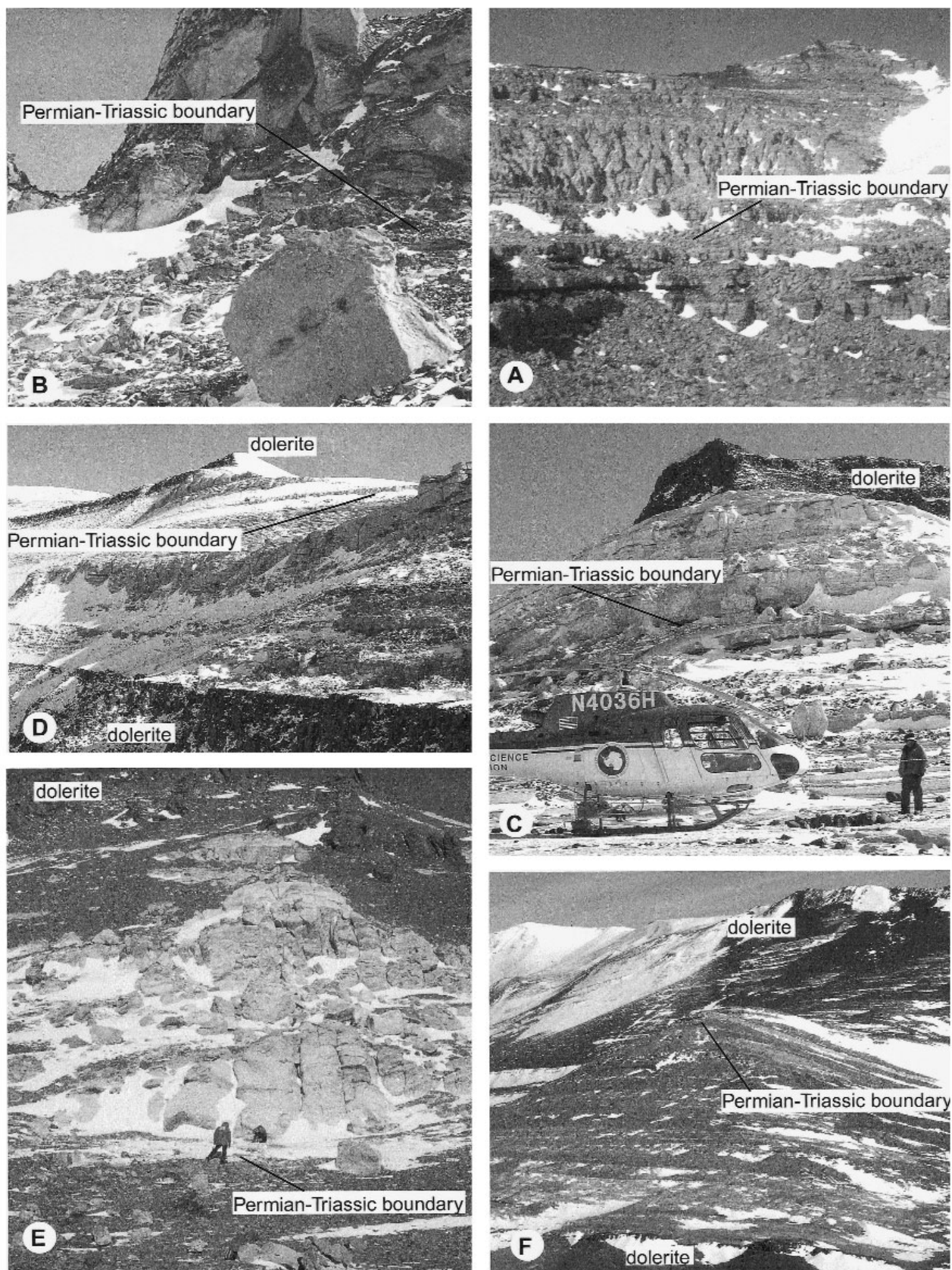
Fig. 2. Field placement of the Permian–Triassic boundary using mainly paleosols and carbon isotope chemostratigraphy **a.** in the Allan Hills, **b.** on Shapeless Mountain, **c.** Mount Crean, **d.** Portal Mountain, **e.** Coalsack Bluff, and **f.** in aerial view of Graphite Peak.

spores from the Weller Coal measures of southern Victoria Land are of Late Carboniferous to Late Permian age (Kyle 1977, Isbell *et al*. 1999).

Glossopterid fertile organs, particularly seed-bearing structures, allow discrimination between Middle and Late Permian (McLoughlin 1990a, 1990b, 1998) in the threefold Permian time scale of Jin *et al*. (1997). Our collections now include Late Permian species at the following localities (Retallack & Krull 1999a): Allan Hills (*Senotheca kingii*), Mount Crean (*Senotheca kingii, Squamella australis*), Portal Mountain (*Dictyopteridium walkomii, Plumsteadia*

jenseni, Rigbya arberioides, Squamella australis) and Graphite Peak (*Cometia biloba, Dictyopteridium walkomii, Plumsteadia jenseni, Squamella australis)*. Also of Late Permian age are glossopterid fructifications (*Rigbya arberioides*) from the Mount Glossopteris Formation in the Ohio Range (Schopf 1967, 1976). A distinctly different assemblage of Middle Permian glossopterid fructifications was seen low in the Weller Coal Measures in the Allan Hills (*Ottokaria* sp., *Plumsteadia ovata*; Schopf 1976), Mount Crean (*Plumsteadia* sp), Mount Feather (*Plumsteadia ovata*: Kyle 1974), and Portal Mountain (*Lanceolatus*
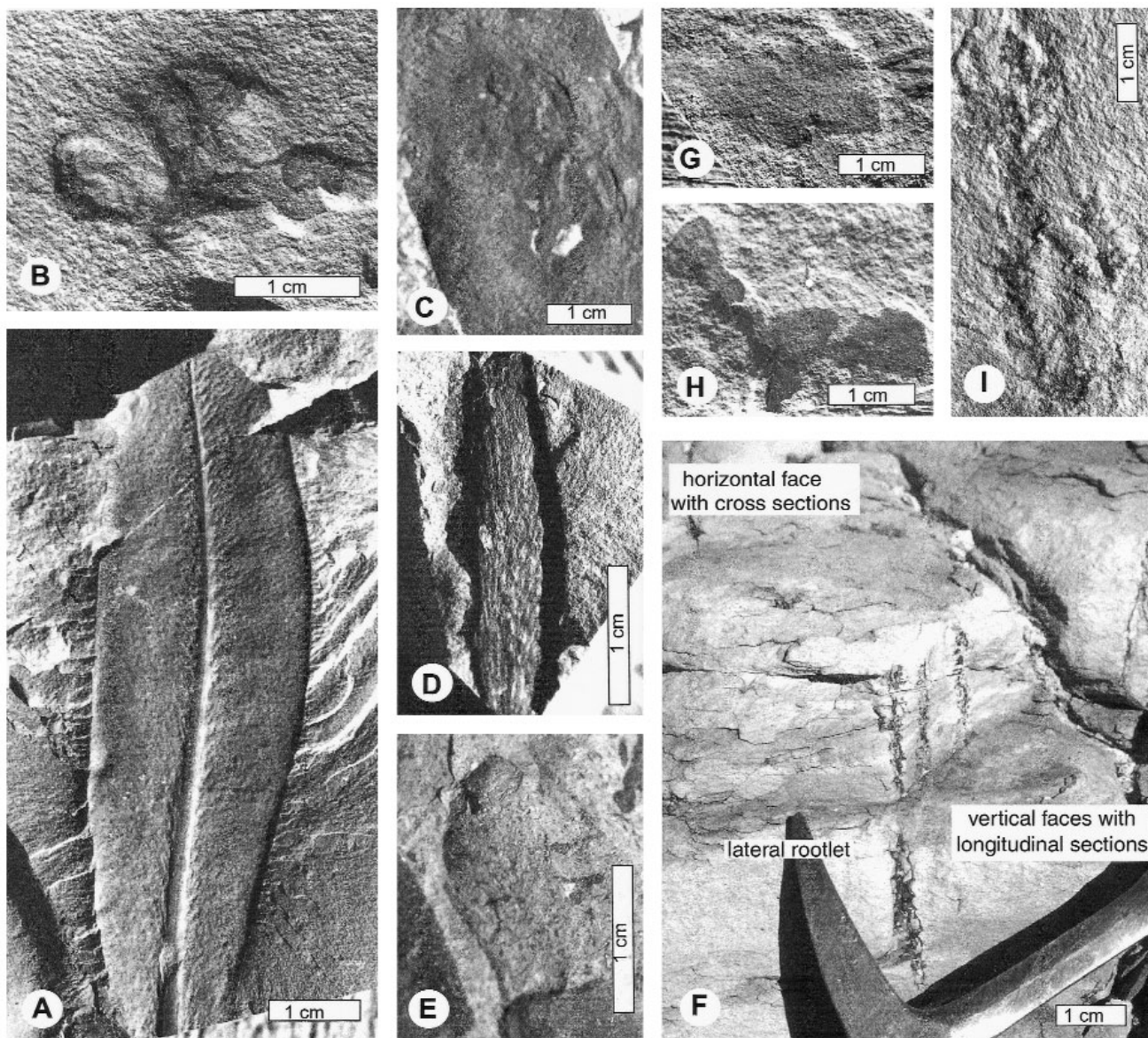

Fig. 3. Late Permian fossil plants from Graphite Peak **a.** *Glossopteris browniana*, **b.** *Cometia biloba*, **c.** *Plumsteadia jenseni*, **d.** *Dictyopteridium walkomii*, **e.** *Squamella australis*, **f.** Middle Permian fossil root from Allan Hills *Vertebraria australis*, and Early Triassic fossil plants from Mount Rosenwald (**g–h.** *Dicroidium zuberi*) and Graphite Peak (**i.** *Voltziopsis africanus*). Specimen (F) is a field photograph, other specimen numbers in Condon Collection are **a.** F35133, **b.** F35134, **c.** F35148A, **d.** F35136A, **e.** F35131, **g.** F35140A, **h.** F35140C, **i.** F35143A.
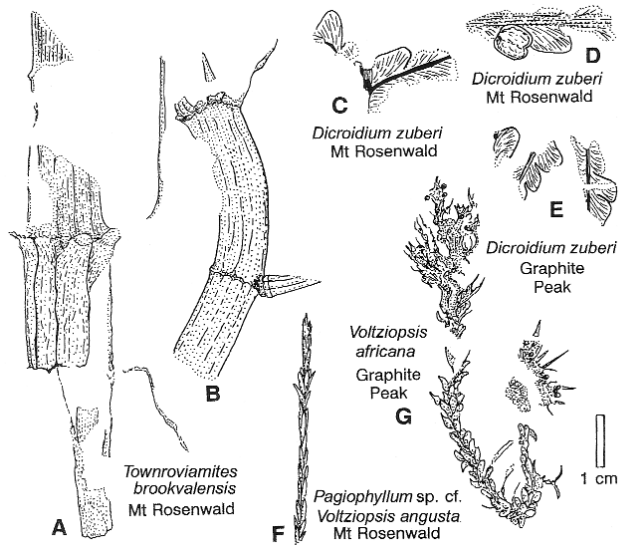
Fig. 4. Early Triassic fossil plants from Graphite Peak and Mount Rosenwald: A–B, *Townroviamites brookvalensis* leafy shoots (Condon Collection F35138A and B respectively); *Dicroidium zuberi* leaf fragments (F35140A, F35140C, and F35144 respectively); *Pagiophyllum* sp. indet (F35139B) from **a.** Graphite Peak, and **b–d.** Mount Rosenwald.

communis, Plumsteadia ovata), and in the lower Buckley Formation at Mount Achernar (*Plumsteadia ovata*: T.N. Taylor *et al.* 1989). The lower Weller Coal Measures and lower Buckley Formation also have different leaves, including prominent *Gangamopteris* and *Palaeovittaria*, in contrast to *Glossopteris*-dominated Late Permian upper portions of these formations (E.L. Taylor *et al.* 1989a, 1989b, Retallack & Krull 1999a). In contrast to the Middle Permian age assumed for the Weller Coal Measures by Isbell & Cuneo (1996, Isbell *et al.* 1999), our collections demonstrate both Late and Middle Permian floras in that formation in the Allan Hills, Mount Crean and Portal Mountain.

Supposed co-occurrences of *Glossopteris* and *Dicroidium* in India and Antarctica have been cited as confounding the stratigraphic significance of these plants (McManus *et al.* 2002). However, Permian *Glossopteris* was extinct several million years before the first appearance of Triassic *Dicroidium*, which presumably evolved from a peltasperm such as *Lepidopteris* (Retallack 1980, 1995, 2002). Supposed co-occurrences of *Glossopteris* and *Dicroidium* are based on outdated identifications. In Middle Triassic coal measures of the Lashly Formation in the Allan Hills a "*Glossopteris*" leaf reported along with abundant and diverse *Dicroidium* by Rigby & Schopf (1969) is better referred to *Gontriglossa*, known to be a different plant from its cuticle structure and whorled leaf arrangement (Anderson & Anderson 1989). The Nidpur site in the Damodar Valley of India, has yielded several species of *Glossopteris,* but supposed "*Dicroidium*" leaves from Nidpur (Bose & Srivastava 1971, Srivastava 1987) have
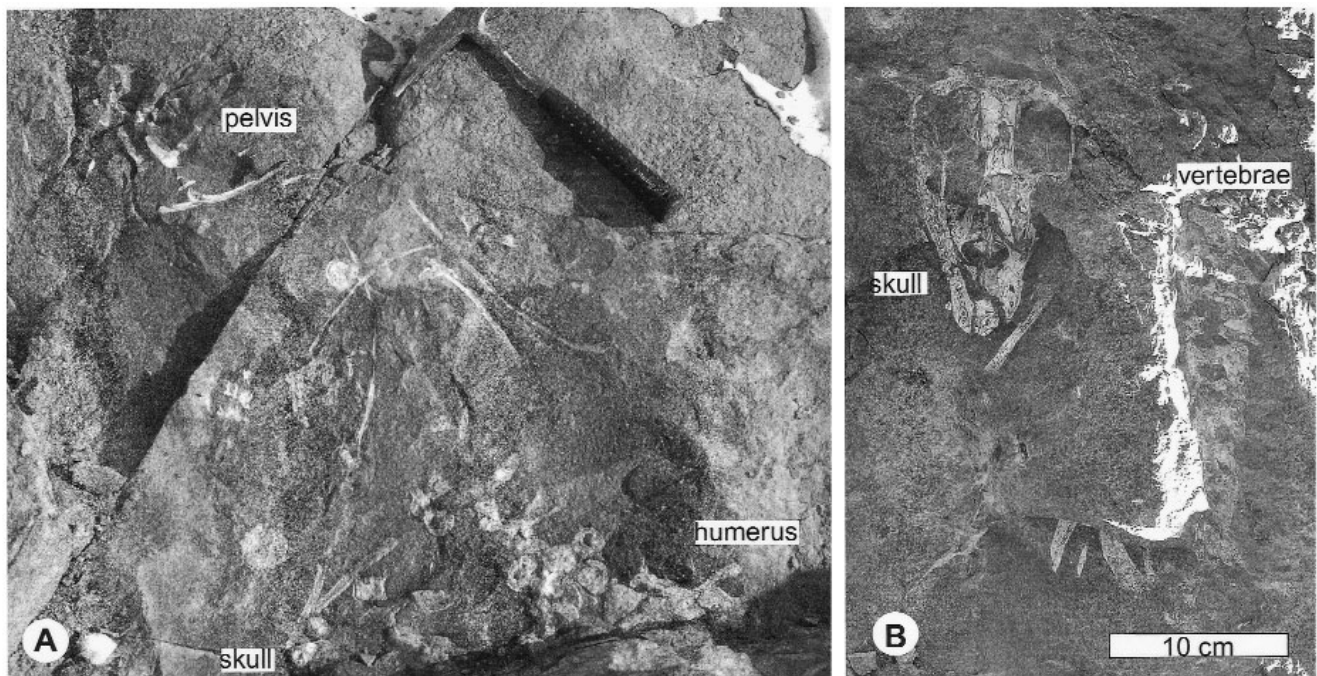

Fig. 5. Early Triassic vertebrate remains from Dolores paleosols at Graphite Peak: **a.** *Lystrosaurus murrayi* from 35 m above the last coal, and **b.** *Thrinaxodon liorhinus* from 25 m above the last coal. Specimen A was left in the field, and specimen B is in the South African Museum.
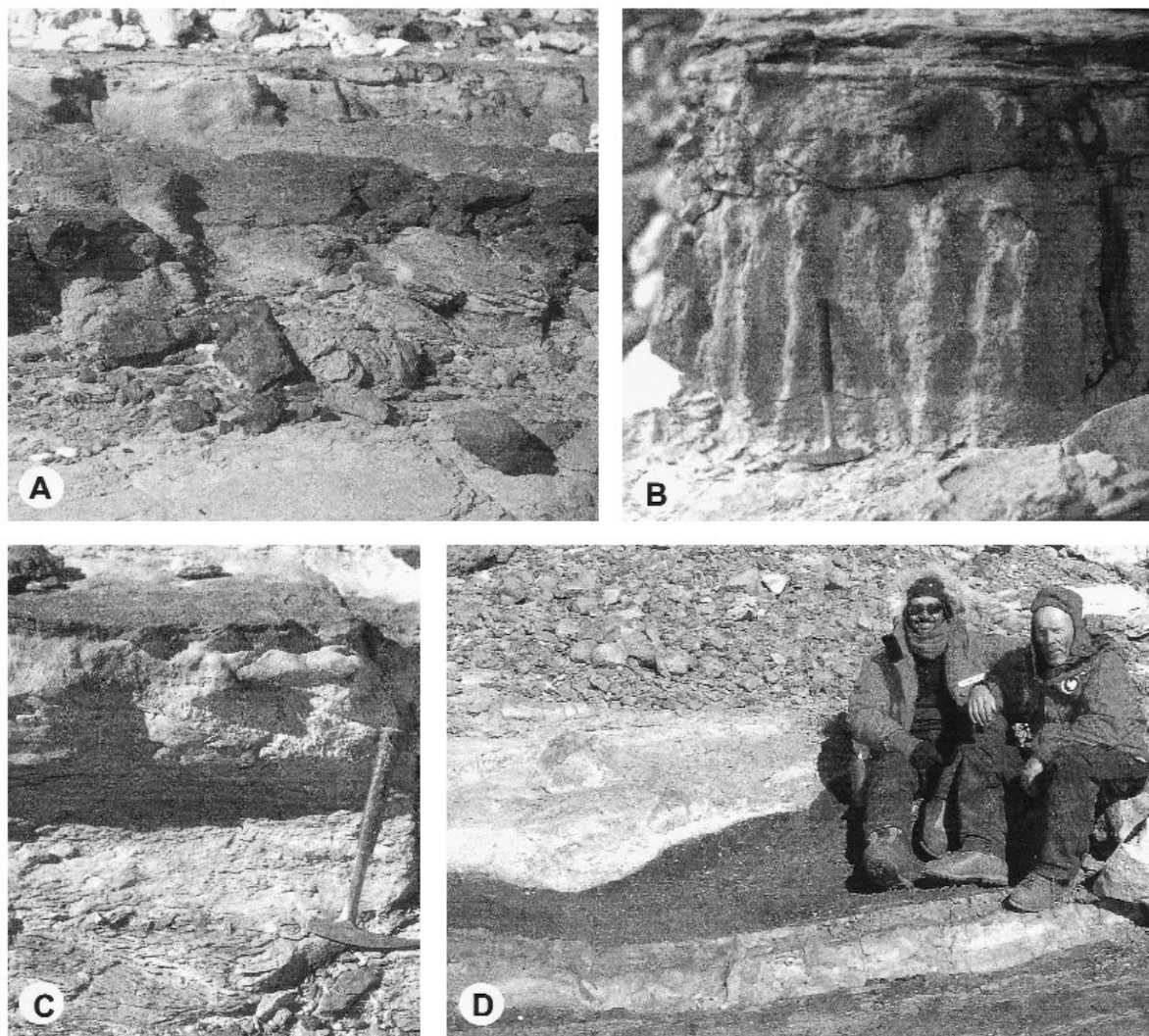
Fig. 6.a. Early Triassic Dolores pedotype at 67 m, **b.** Gregory pedotype at 182 m, and **c.** late Permian Suzanne pedotype at 64 m in the Allan Hills section, and **d.** the Permian–Triassic boundary at 256 m in Graphite Peak section with two Evelyn pedotype paleosols (coals) below white claystone breccia and an earliest Triassic Dolores paleosol. Hammers for scale (**a–c**) and Rama Chakrabarti and Shaun Norman (**d**).

cuticular anatomy and reproductive organs (*Nidia, "Pteruchus"* more likely *Permotheca*) which suggest closer affinities with *Lepidopteris* and other peltasperms, rather than corystosperms (Retallack 2002).

Triassic plants have been less useful for defining the Permian–Triassic boundary in Antarctica, because they are scarce, fragmentary, and poorly preserved. The lower Fremouw Formation in the central Transantarctic Mountains and the lower Feather Conglomerate in Victoria Land are barren of spores and pollen, and the middle and upper parts of these formations contain pollen assemblages and fossil leaves of late-Early to early-Middle Triassic age (Kyle 1977, Schopf & Askin 1980, Askin 1997, 1998, Retallack & Alonso-Zarza 1998). A permineralized peat 135 m above the base of the Feather Conglomerate in the Allan Hills has leptosporangia and spores of late Early Triassic age (Gabites 1985, Isbell *et al*. 1999). Only a

handful of Early Triassic fossil plants have been found in the Transantarctic Mountains (Figs 3 & 4): *Voltziopsis africana* (Townrow 1967a) 55 m above the last coal at Graphite Peak; *Dicroidium zuberi* (Retallack 1977) 302 m above the last coal at Graphite Peak; and *Dicroidium zuberi, Townroviamites brookvalensis* (Holmes 2001) and *Pagiophyllum* sp. indet. cf. *Voltziopsis angusta* (Townrow 1967a) at Mount Rosenwald, in red beds equivalent to about 129 m above the last coal in the Graphite Peak section (Retallack & Krull 1999a). Further afield, Early Triassic *Lepidopteris* and *Dicroidium* have been reported from near Beaver Lake in the Prince Charles Mountains (McLoughlin *et al*. 1997). A fossil flora from Mount Bumstead in the central Transantarctic Mountains is dominated by *Dicroidium zuberi* (Townrow 1967b) like many Early Triassic assemblages (Retallack 1977, Morel *et al*. 2003), but includes Late Triassic plants such as *Yabeiella* (Boucher
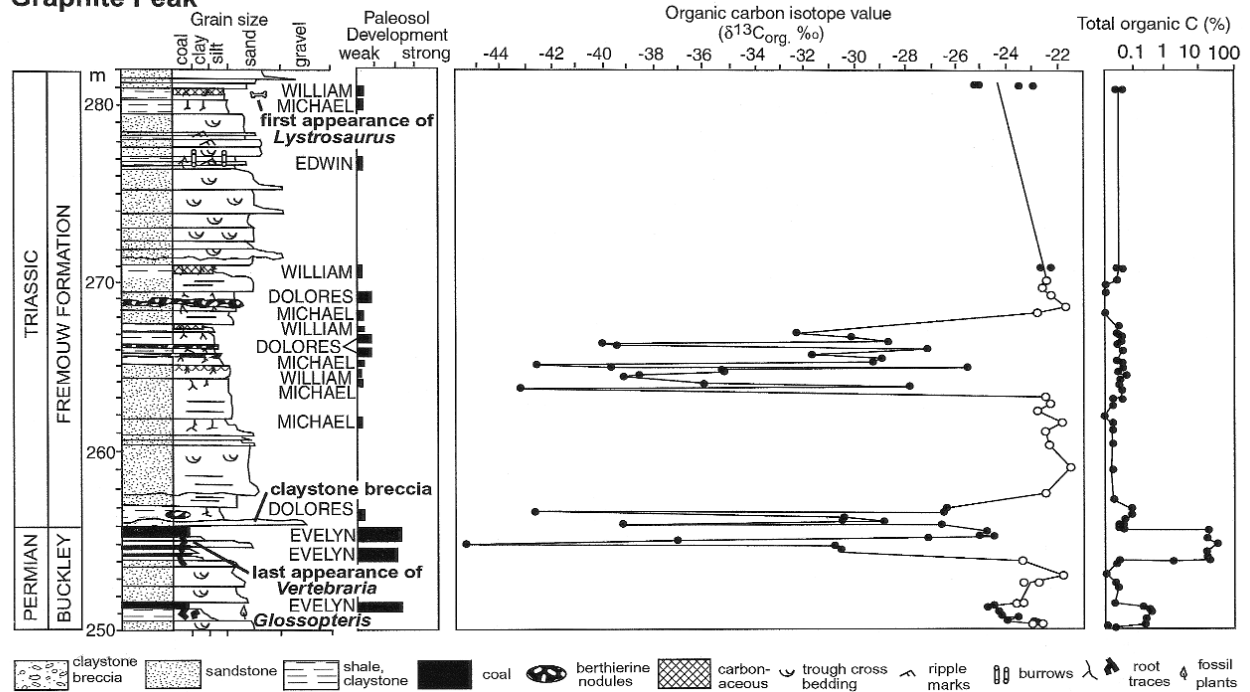
Fig. 7. Stratigraphical section of Graphite Peak, showing palaeosols (black boxes with width proportional to development), carbon isotope composition of organic matter and total organic carbon content. The lowest of two complex anomalies in carbon isotope value represents the Permian–Triassic boundary. Data from Krull & Retallack (2001) is in closed circles, supplemented here with new data as open circles.

1995).

Antarctica has locally abundant permineralized trees (E.L. Taylor *et al.* 1992, Retallack 1997) and peat (Taylor & Taylor 1990, 1992, Pigg & Taylor 1990, Meyer-Berthaud *et al.* 1993, Taylor 1996, Osborn *et al.* 2000, Klavins *et al.* 2001), which give unprecedented insights into the palaeobiology and systematic affinities of extinct plants. Unfortunately for the present biostratigraphic purpose, the unique preservation and the naming of permineralized specimens independent from impression and compression fossils, prevents their correlation with fossil plants at other localities.

Permian–Triassic animals

The only Permian vertebrates known in Antarctica are unidentified palaeoniscid fish scales within coprolites attributed to large lungfish (Retallack & Krull 1999b). These were found in a part of the Buckley Formation that is probably Middle Permian in age, because they were beneath a carbon isotopic excursion correlated with the end-Guadalupian isotopic excursion (Krull & Retallack 2000) of Australia (Compston 1960), England (Magaritz & Turner 1982), Texas (Magaritz *et al.* 1983), China (Wang *et al.* 2004), Spitsbergen (Mii *et al.* 1997), and Greenland (Magaritz & Stemmerik 1989). Among invertebrates, Late Permian conchostracans (*Leaia*) in the Ohio Range have been correlated with similar forms in Australia, South

Africa, South America and India (Tasch 1987). A Late Permian insect wing (Stenovicidae) from the Sentinel Mountains is most similar to fossil insects in Australia (Tasch & Riek 1969).

Triassic vertebrates are more useful for correlation, because they belong to species well known from South Africa (Colbert 1974, Hammer 1990) and China (Lucas 2001). Nevertheless, many bones are fragmentary and few can be identified with confidence: *Thrinaxodon liorhinus* and *Lystrosaurus murrayi* 22 and 32 m above the last coal, respectively, at Graphite Peak (Figs 5 & 7; Retallack & Hammer 1998, Retallack & Krull 1999a), *Myosaurus gracilis* and *Lystrosaurus curvatus* 25 m above glossopterid peat on Collinson Ridge (Cosgriff & Hammer 1981, Hammer & Cosgriff 1981, McManus *et al.* 2002), *L. mccaigi* 28 m above dolerite intruding the Permian–Triassic boundary interval on Schenk Peak (Cosgriff *et al.* 1982), *L. curvatus* 45 m above dolerite at nearby Halfmoon Bluff (Colbert 1974, Collinson & Elliot 1984a), *Thrinaxodon liorhinus* 82 m above dolerite on nearby Thrinaxodon Col (Collinson & Elliot 1984a), and *Lystrosaurus murrayi* 82 m above the last coal at Coalsack Bluff (Colbert 1974). In the Karroo Basin of South Africa, *Lystrosaurus mccaigi* is exclusively latest Permian, *L. curvatus* and *L. murrayi* are latest Permian and Early Triassic, but *Thrinaxodon liorhinus* appears well above the boundary (Smith & Ward 2001, Retallack *et al.* 2003, Botha & Smith 2004).
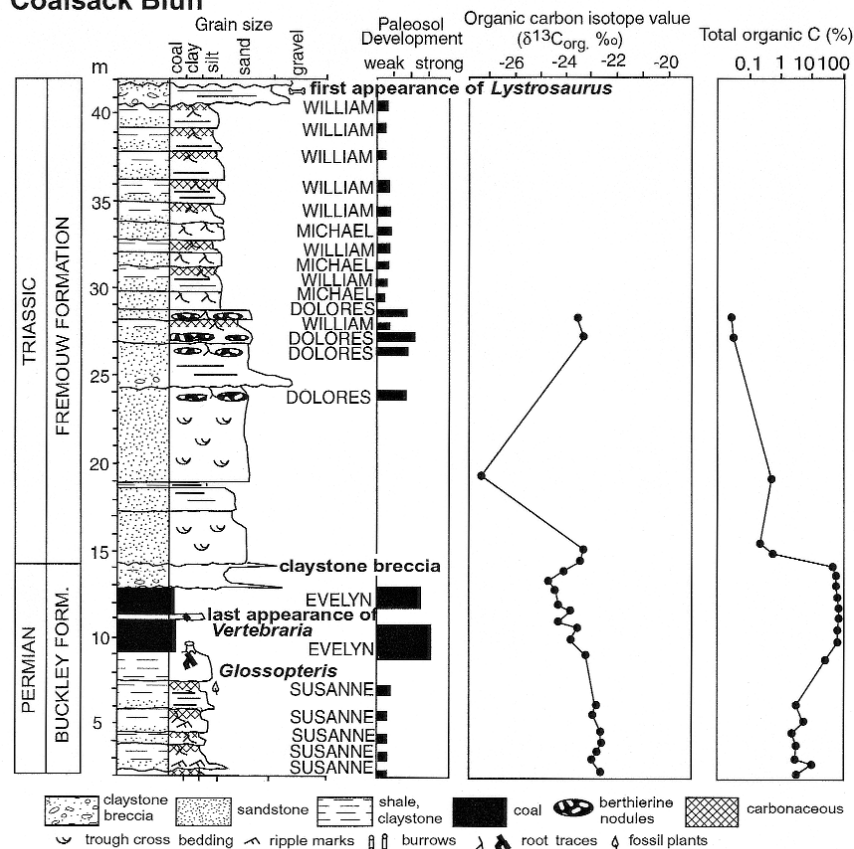
Coalsack Bluff

Fig. 8. Stratigraphical section of Coalsack Bluff, showing palaeosols (black boxes with width proportional to development), carbon isotope composition of organic matter and total organic carbon content. The negative anomaly in carbon isotope values represents the Permian–Triassic boundary.

Therapsid trackways (MacDonald *et al.* 1991) and burrows (Miller *et al.* 2001) have been found in the Lower Fremouw Formation in the central Transantarctic Mountains, but Permian *Dicynodon* and Triassic *Lystrosaurus* footprints cannot yet be distinguished (Retallack 1996). Several kinds of aquatic invertebrate burrows are found in both Permian and Triassic fluvial facies (Miller & Collinson 1994, Miller 1998), and do not help with dating either.

Permian–Triassic palaeosols

The most reliable field criterion for recognizing Permian–Triassic boundary in all the sections examined in Antarctica has proven to be the first appearance of Dolores palaeosols. These are distinctive thin, silty and sandy profiles, which have large nodules of berthierine at a shallow depth within the profile (Retallack & Krull 1999a). Berthierine is not normally found in soils, and indicates anomalously low atmospheric oxygenation (Sheldon & Retallack 2002), as predicted by some extinction scenarios of oxygen consumption by methane outburst, volcanism, and extinction (Berner *et al.* 2002). Dolores palaeosols are the "ferruginized palaeosols" used by Collinson *et al.* (1994) to mark the Permian–Triassic boundary throughout southern Victoria Land. Fresh Dolores palaeosols have only

ferrous iron and are dark green, but iron-rich berthierine commonly has a thin (2 mm) ferruginized weathering rind in outcrop. Dolores palaeosols were found immediately above the last coal in all six sections examined (Figs 7–12).

Another palaeosol criterion found without exception in all six sections is that Late Permian root traces are carbonaceous and Early Triassic root traces are all non-carbonaceous (Retallack & Krull 1999a). Late Permian *Vertebraria* are black with organic matter, as are non-chambered Permian gymnosperm roots, whereas earliest Triassic root traces of comparable gymnospermous form are grey or white with silica, zeolitic or clayey infills (Retallack & Alonzo-Zarza 1998). This field observation was confirmed by analysis for organic carbon, which became very carbon lean in the earliest Triassic (Figs 7–12). Permian coals and shales are carbonaceous, and even quartz sandstones may have as much as 0.1 weight percent organic carbon, but almost all rocks of the Early Triassic have less organic carbon. This change to carbon-poor composition has also been demonstrated for both marine and non-marine Permian–Triassic sections in New Zealand (Krull *et al.* 2000), Australia (Morante 1996), Canada (Wang *et al.* 1994), and Austria (Magaritz *et al.* 1992).

Finally, there is the global coal gap of the earliest Triassic, which was a time when peaty soils (histosols) were not formed anywhere in the world (Retallack *et al.* 1996). Using
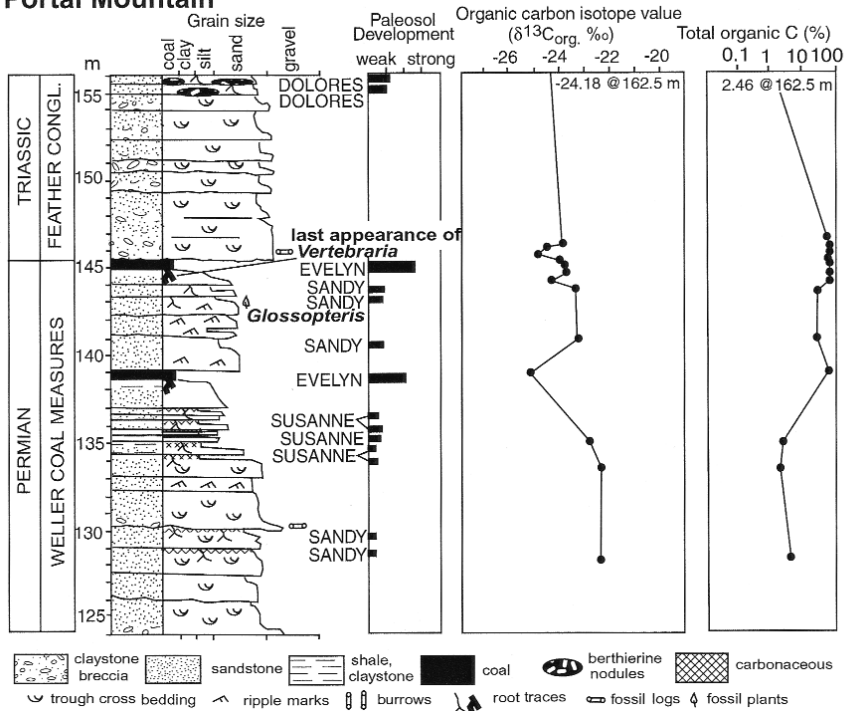
Portal Mountain

Fig. 9. Stratigraphical section of Portal Mountain, showing palaeosols (black boxes with width proportional to development), carbon isotope composition of organic matter and total organic carbon content. The decline in carbon isotope values and carbon content represents the Permian–Triassic boundary.

the last coal seam as a marker of the boundary is risky, because peat swamp accumulation could have been terminated for a variety of reasons in addition to the extinction of peat-forming glossopterids. Nevertheless the top of the last coal seam is very close to the boundary in all sections (Figs 7–12).

Permian–Triassic carbon isotope anomaly

The Permian–Triassic boundary is most precisely located using carbon isotopic chemostratigraphy (Krull & Retallack 2000). A negative carbon isotopic anomaly is now known from more than 52 sections of the Permian–Triassic boundary around the world (Retallack & Krull 2005), and

Mount Crean

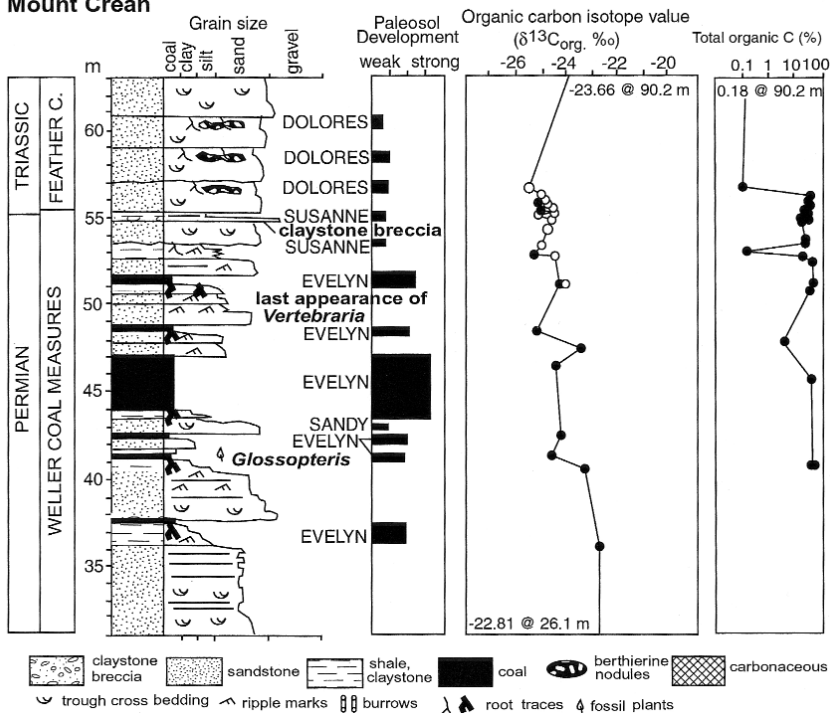**Fig. 10.** Stratigraphical section of Mount Crean, showing palaeosols (black boxes with width proportional to development), carbon isotope composition of organic matter and total organic carbon content. The decline in carbon isotope values and carbon content represents the Permian–Triassic boundary. Data from Krull & Retallack (2001) is closed circles; supplemented here with new data as open circles.

Fig. 11. Stratigraphical section of Shapeless Mountain, showing palaeosols (black boxes with width proportional to development), carbon isotope composition of organic matter and total organic carbon content. The decline in carbon isotope values and carbon content represents the Permian–Triassic boundary.

was found at all sections in Antarctica yielding reliable results (Figs 7–11). In some cases the isotopic excursion is very marked, as at Graphite Peak, where the excursion was -15.2‰, to as low as -39.6‰ from a Permian plateau of -24.4 ± 0.8‰ (Fig. 7). This is beyond the terminal Permian excursion's global mean and standard deviation (-6.4 ± 4.4‰ of 30 sections analysed for organic carbon: Retallack

& Krull 2005). Isotopic excursions more profound than this global mean at the Permian–Triassic boundary are mainly at high palaeolatitudes (Krull *et al.* 2004), in Australia (Morante 1996), New Zealand (Krull *et al.* 2000), Greenland (Twitchett *et al.* 2001), Madagascar (de Wit *et al.* 2002) and India (Sarkar *et al.* 2003). Other Antarctic sections with less profound carbon isotopic excursions than

Fig. 12. Stratigraphical section of central Allan Hills, showing palaeosols (black boxes with width proportional to development), carbon isotope composition of organic matter, and total organic carbon content. Unlike all other sections, this one failed to give replicable analyses in the organic-carbon-lean upper portion. The Permian–Triassic boundary is probably between Susanne and Dolores paleosols. Data from Krull & Retallack (2001) is closed circles, supplemented here with new data as open circles

at Graphite Peak (Figs 8–11) are also more sandy with high-energy, palaeochannel facies (Isbell & Cuneo 1996), so had less coal and claystone to sample for carbon and a greater likelihood of minor erosional disconformities. Localities with less profound isotopic excursions may also have been more distant from methanogenic carbon sources, as is likely for palaeotropical Permian–Triassic boundary sections (Krull *et al*. 2004).

Isotopic analyses across the Permian–Triassic boundary in the Allan Hills failed because carbon contents were so low in the upper part of the sequence that replicable isotopic values could not be obtained (Fig. 12). Unlike other sections examined, rocks in the Allan Hills were weakly calcareous and orange-yellow, perhaps because of early Cenozoic weathering, which has been inferred from Antarctic geomorphology (Marchant *et al*. 1993) and toreva blocks (Elliot 1995). Nevertheless, organic carbon content in the Allan Hills declines at the last Permian plant fossil (*Phyllotheca australis*) and directly below a Dolores palaeosol (Fig. 12), which in every other section examined

is earliest Triassic. This position of the Permian–Triassic boundary in the Allan Hills is 19.5 m below the top of the Weller Coal Measures and the base of the Feather Conglomerate. Thus our data from carbon analyses, fossil plants and soils indicate that the uppermost Weller Coal Measures here is Early Triassic.

Completeness of Permian–Triassic boundary sections

Isbell & Cuneo (1996) regard the contact of the Weller Coal Measures and Feather Conglomerate as a regional disconformity, which they consider to have eroded all record of Permian–Triassic boundary events in southern Victoria Land. Although the basal conglomerate contact is sharp in many places, it is not at the Permian–Triassic boundary and does not represent an hiatus of millions of years, for the following reasons.

Carbon isotopic and total organic analyses of individual detailed sections (Figs 7–12) offer evidence that latest Permian rocks are preserved. The isotopic decline used to
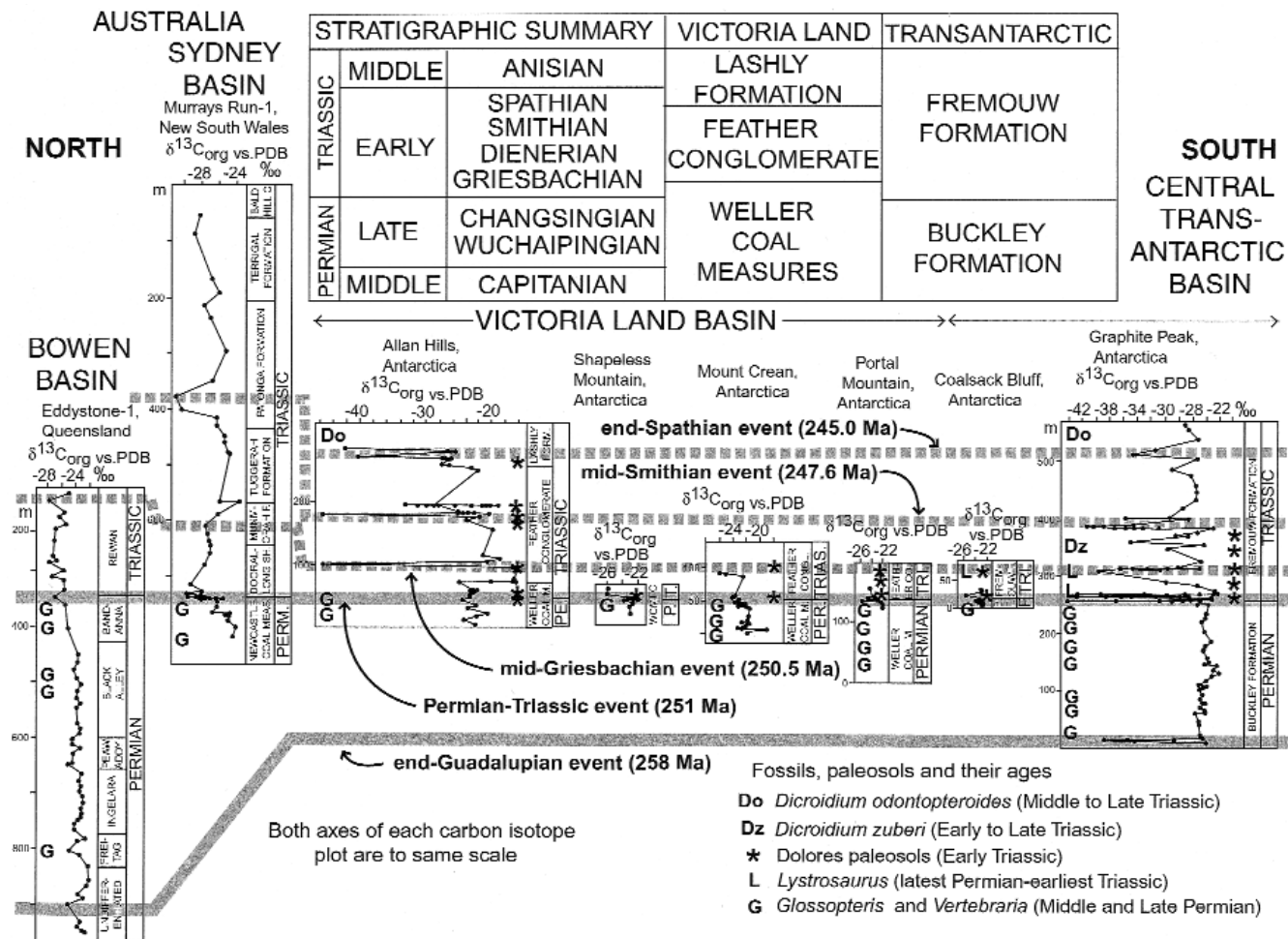

Fig. 13. Stratigraphical relationships and organic-carbon-isotope chemostratigraphy of Antarctic Permian-Triassic sections (data from Krull & Retallack, this paper), and their correlation with comparable sequences in eastern Australia (data from Morante 1996).

mark the Permian–Triassic boundary worldwide has a characteristic curve to lower values that is preserved in the most complete sections. In the Gartnerkofel core of Austria (Holser & Schönlaub 1991), typical Permian carbon isotope values change to the lowest value at the boundary over an interval from 251 to 220 m, showing a steady decline estimated to have lasted about 600 000 years from wavelet analyses (Rampino *et al.* 2000). Isotopic decline in marine rocks near Meishan is constrained to the last 612 000 years of the Permian by radiometric dating of volcanic ashes (Bowring *et al.* 1998, Mundil *et al.* 2001). Detailed isotopic studies of a varved shale section in the Murrays Run bore of New South Wales, Australia, showed that the isotopic decline occurred within the space of 6752 annual varves (Retallack & Jahren 2005). Because woody, vitrinite-rich coals accumulate at rates of 0.5–1 mm (Retallack 2001) and peat to coal thickness reduction in these coal measures is about 13% (Diessel 1992), the duration of isotopic decline seen in our sections also can be estimated as about 10 000 years. Thus the last 10 000 years of the Permian time is represented in these sections.

Carbon isotopic correlations though Antarctica north to Australia are evidence that the first half million years of the early Triassic also is preserved in every section (Fig. 13). The sequence and magnitude of carbon isotope negative excursions can be used like a bar code for international correlation with five chemostratigraphic events at the end-Guadalupian (258 Ma), Permian–Triassic boundary (251 Ma), mid-Griesbachian (250.5 Ma), mid-Smithian (247.6 Ma) and late Spathian (245 Ma: dating from Gradstein *et al.* 2005). The first or end-Guadalupian negative carbon isotope excursion is known from England (Magaritz & Turner 1982), Texas (Magaritz *et al.* 1983), Greenland (Magaritz & Stemmerik 1989), Spitsbergen (Mii *et al.* 1997), China (Wang *et al.* 2004), South Africa (Thackeray *et al.* 1990) and Australia (Compston 1960, Morante 1996). End-Guadalupian marine extinctions decimated fusulines (Stanley & Yang 1994), corals (Wang & Sugiyama 2000), brachiopods (Shen & Shi 2004), and therapsids (*Tapinocephalus* zone of Thackeray *et al.* 1990, Rubidge 1995), and coincide with eruption of the Emeishan plateau basalts in China (Zhou *et. al.* 2000).

The second and largest global carbon isotope anomalies are at the Permian–Triassic boundary (Retallack & Krull 2005), which terminated Permian marine faunas (Jin *et al.* 2000), the Gondwanan *Glossopteris* flora (Morante 1996, Krull & Retallack 2000), and the *Dicynodon* vertebrate fauna of South Africa (Smith & Ward 2001) and Russia (Benton *et al.* 2004). The Permian–Triassic boundary also coincides with eruption of Siberian flood basalts (Renne *et al.* 1995, Kamo *et al.* 2003), meteorite impact in north-western Australia (Basu *et al.* 2003, Becker *et al.* 2004: though this is contested by Renne *et al.* 2004 and Wignall *et al.* 2004), and submarine landslides in Greece (Baud *et al.* 1989) and New Zealand (Krull *et al.* 2000).

A third or mid-Griesbachian negative excursion of lesser magnitude is known in Austria (Holser & Schönlaub 1991), Armenia, Iran, Turkey (Baud *et al.* 1989), and China (Payne *et al.* 2004). This excursion is at the top of the ammonite zone of *Ophiceras* and conodont zone of *Isarcicella isarcica* in China and Austria (Holser & Schönlaub 1991, Yin *et al.* 1996), at the top of the palynozone of *Protohaploxypinus microcorpus* and its equivalent plant zone of *Lepidopteris callipteroides* in Australia (Morante 1996, Retallack 2002), and within the *Lystrosaurus* therapsid zone of South Africa (MacLeod *et al.* 2000).

A fourth minor negative carbon isotope excursion is found within the Smithian of China (Payne *et al.* 2004), Pakistan (Baud *et al.* 1996), Australia (Morante 1996) and Utah (Wilgus 1981). In southern Utah this excursion is within the ammonite zone of *Wasatchites tardus* (Wilgus 1981), and in eastern Australia within the palynozone of *Protohaploxypinus samoilovichii* (Morante 1996).

A fifth negative carbon isotope excursion is found in the Spathian of several sections in China (Payne *et al.* 2004), but is not reached by most other carbon isotopic studies focused on the Permian–Triassic boundary (Retallack & Krull 2005). This is the last of the big Early Triassic excursions. Carbon isotopic values are very stable though most of the Middle Triassic (Payne *et al.* 2004).

These five chemostratigraphic tie points are spaced at equal intervals in the Antarctic sections examined (Fig. 13), implying comparable sedimentation rates in different Antarctic Basins. Much higher sedimentation rates can be inferred for thicker correlative Australian sequences in outwash of the New England Orogen (Fig. 13). Because of their lower sedimentation rate, Antarctic sections probably do not have the fine temporal resolution of either Australian (Retallack 1999) or South African sequences (Retallack *et al.* 2003). Nevertheless, Antarctic earliest Triassic sequences do not have gaps of more than a few hundred thousand years (Fig. 13). Each of the four Early Triassic carbon isotope excursions in Antarctica correlate with abundant Dolores palaeosols, which indicate unusually anoxic soil conditions (Sheldon & Retallack 2002) probably as a result of massive methane outbursts thought responsible for unusually low carbon isotopic values (Krull & Retallack 2000). Dolores palaeosols can thus serve as field markers for future chemostratigraphic studies in Antarctica.

Finally it is remarkable that Permian–Triassic boundary sections of Antarctica include distinctive event beds and geochemical anomalies characteristic of complete and well studied sections of the boundary in South Africa (Retallack *et al.* 2003), Austria (Holser & Schönlaub 1991), and China (Bowring *et al.* 1998). These include distinctive claystone breccias from severe soil erosion (Retallack & Krull 1999a, Isbell *et al.* 1999, Retallack 2005), shocked quartz (Retallack *et al.* 1998), iridium anomalies (Retallack *et al.* 1998), fullerenes (C_{60} cages) with extraterrestrial ^{3}He

Table 1. Metre level of Permian–Triassic boundary indicators relative to C-chemostratigraphic boundary

Antarctica location	Last *Glossopteris*	Last *Vertebraria*	Last coal	Clay-stone breccia	First Dolores palaeosol	First clayey roots	First braided stream	First *Lystrosaurus*	First *Dicroidium*
Graphite Peak	-5	-0.68	0	0	+1.2	+1.2	+24	+24	+110
Coalsack Bluff	-5	-1.34	0	0	+11	+11	+11	+24	None
Portal Mountain	-2	-0.82	0	None	+10	+10	+0	None	+230
Mount Crean	-14	-4	-4	0	+2	+2	+0.24	None	None
Shapeless Mount	-22	-2	-1	0	+5.5	+5.5	+1	None	+245
Allan Hills	-15.5	-6	-3.5	0	+2	+2	+19.5	None	+190

(Becker *et al*. 2001, Poreda & Becker 2003), and carbonaceous-chondritic meteorite debris (Basu *et al*. 2003). Abundant pyrite at the Permian–Triassic boundary at Coalsack Bluff (Fig. 8) is similar to some South African sections (Maruoka *et al*. 2003). These markers record geologically brief events close in time to the Permian–Triassic boundary, yet they are recorded in Antarctica.

Implications for causes and consequences of mass extinction

Decline in both total organic carbon and carbon isotope value of kerogen pinpoints the Permian–Triassic boundary in six sections in Antarctica (Figs 7–12) and allows correlation of Antarctic sections with those of formerly contiguous Australia (Fig. 13). These indications of the boundary are at the level of distinctive claystone breccias and the last coal in most sections (Table I). Also useful were the first appearance of Dolores palaeosols, of clayey rather than carbonaceous root traces, and the loss of all known Permian palaeosol types. Glossopterid roots of *Vertebraria* also were useful in pinpointing the boundary, and were always associated with the last coal. Less useful because tens to hundreds of metres from the chemostratigraphically defined boundary were leaves of *Glossopteris* and *Dicroidium* and bones of *Lystrosaurus* (Table I), although these remain important general biostratigraphic constraints. The sections studied vary in their completeness, with the Allan Hills poorly resolved because of failure of carbon isotope analyses due to exceptionally low organic carbon. In contrast, Graphite Peak has carbon isotopic anomalies most like the best sampled marine section in Austria (Holser & Schönlaub 1991), and more shale and palaeosols than the other sections (Figs 7–13).

Antarctica shows the following sequence of Permian–Triassic beds. The last Permian coal persisted after a very slight iridium anomaly detected at Graphite Peak (Retallack *et al*. 1998). Within the last coal at Graphite Peak, Coalsack Bluff and Portal Mountain, carbon isotopic composition begins to decline some 10 000 years before the total extinction of this *Glossopteris*-dominated ecosystem at the globally synchronous isotopic nadir (Retallack & Jahren 2005). In the Allan Hills, Mount Crean and especially

Coalsack Bluff, the top of the last coal is marked by increased abundance of pyrite nodules, variably oxidized to jarosite and hematite. Directly overlying the last coal at most localities is a distinctive claystone breccia with clasts of sepic plasmic fabric indicating derivation from Permian palaeosols (Retallack *et al*. 1998, Retallack 2005). These claystone breccias contain shocked quartz (Retallack *et al*. 1998), ^{3}He-bearing C^{60} fullerenes (Becker *et al*. 2001, Poreda & Becker 2003) and carbonaceous-chondritic meteorite fragments (Basu *et al*. 2003). None of the characteristic Permian palaeosols are found above this level, where the most common palaeosols of the Doloroes pedotype have abundant nodules of berthierine, non-carbonaceous root traces and very low total carbon contents (Figs 7–13).

These various observations can be interpreted as consequences of initial extraterrestrial impact (modest iridium anomalies of Retallack *et al*. 1998) which did not curtail peat formation or extinguish *Glossopteris*. Carbon isotope values in coals subsequently declined, in a series of spikes, to such low values that they can only be explained by successive massive release of methane clathrates from marine continental shelves or permafrost (Krull *et al*. 2000, 2004). At the nadir of this carbon isotopic decline, peat-forming *Glossopteris* swamps became extinct (coal gap of Retallack *et al*. 1996), and lowland forest dieback ushered in a dramatic episode of soil erosion (claystone breccias of Retallack 2005). The debris flows also include further evidence of impact such as shocked quartz (Retallack *et al*. 1998), ^{3}He-bearing C_{60} fullerenes (Poreda & Becker 2003) and chondritic meteorite fragments (Basu *et al*. 2003). The fullerenes and meteoritic fragments are little weathered and indicate fresh extraterrestrial impact, perhaps from "Bedout Crater" of Western Australia (Becker *et al.* 2004: though evidence for that crater is disputed by Renne *et al.* 2004, Wignall *et al*. 2004). Explosive volcanic activity in the Gondwanide margin andesitic arc also continued, as represented by bipyramidal volcanic quartz in the boundary breccias (Retallack *et al*. 1998). Earliest Triassic palaeosols are more deeply weathered than late Permian ones, indicating a warmer and wetter climate (Retallack & Krull 1999a), and their berthierine nodules indicate unusually low soil oxygen content (Sheldon & Retallack 2002, Huggett *et al*. 2003). Both effects would have extinguished

seasonally-deciduous, high latitude plants such as *Glossopteris* in peaty soils already marginally aerated. Both heating and hypoxia can be modelled as consequences of massive atmospheric pollution with methane, consuming oxygen to create a carbon dioxide greenhouse (Berner *et al.* 2002). Within this postapocalyptic greenhouse, Antarctica was colonized by conifers such as *Voltziopsis* and seed ferns such as *Lepidopteris* immigrating from Australia or Madagascar to the north (McLoughlin *et al.* 1997, Retallack 2002). Among vertebrates, *Lystrosaurus* was preadapted to high carbon dioxide by burrowing habit, and by a variety of anatomical features (Retallack *et al.* 2003). Finally, all the Antarctica sites were overrun with massive palaeochannel sandstones of braided streams, resulting from widespread lowland deforestation (Ward *et al.* 2000).

If these were consequences, the initial cause of this catastrophic series of events remains imperfectly known. Two potential causes emerging prominently from Antarctic evidence are extraterrestrial impact (Poreda & Becker 2003, Basu *et al.* 2003) and methane clathrate dissociation (Krull *et al.* 2000). Impact could have released methane both by direct excavation of clathrate reservoirs, and by indirect greenhouse warming of near-surface reservoirs in shallow marine shelves and permafrost. Slight iridium anomalies before the boundary, shocked quartz, [3]He-bearing fullerenes and meteoritic debris at the boundary (Retallack *et al.* 1998, Poreda & Becker 2003, Basu *et al.* 2003) support the idea of impact both before and at the boundary. Multiple carbon isotope minima reported here (Figs 7–11) and in other sequences worldwide (Magaritz *et al.* 1992, de Wit *et al.* 2002, Payne *et al.* 2004) suggest four or more methane releases. These may reflect additional impacts, but also could be due to a cascade of methane outbursts associated with a rising greenhouse crisis (Retallack & Jahren 2005). There also remains the possibility that Siberian Trap volcanism destabilized clathrate reservoirs through their contribution to greenhouse gases (Benton 2003, Kidder & Worsley 2004). Siberian eruptions were remote from Antarctica, and even generous estimates of their gas emissions fall short of warming required to have initiated methane outbursts (Wignall 2002). Furthermore, the bulk of the Siberian eruptions appear to postdate the boundary (Renne *et al.* 1995, Kamo *et al.* 2003, Mundil *et al.* 2004). Nevertheless, it is possible that Siberian traps mobilized methane clathrates in permafrost over which they flowed (Vermeij & Dorritie 1996), or in other methane clathrate reservoirs through which they erupted (Svensen *et al.* 2004). Yet another possibility is release from the oceanic water column of methane (Ryskin 2003) or of carbon dioxide (Knoll *et al.* 1996). These mechanisms, which require unrealistic levels of marine productivity (Hotinski *et al.* 2001), are remote from Antarctic sections, which were inland of an Andean style calcalkaline continental volcanic arc (Collinson *et al.* 1994). Oceanic water degassing mechanisms also fail to explain why carbon isotope excursions are so much larger in inland and high latitude sites than in tropical low latitude marine sites (Krull *et al.* 2000, 2004, de Wit *et al.* 2002). Yet another mechanism is a "Verneshot" eruption of mantle CO_2 and SO_2, an entirely hypothetical eruption like that responsible for kimberlite pipes, only larger (Morgan *et al.* 2004). This kind of eruption may explain sulphur isotope anomalies (Maruoka *et al.* 2003), but not carbon isotope anomalies (Retallack & Krull 2005). Whatever the outcome of ongoing studies of this greatest of all life crises, our studies of Antarctic sequences indicates that they are more complete and informative records of the Permian–Triassic boundary than suspected in the past.

Acknowledgements

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