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Mass extinction of peat-forming plants and the effect on fluvial styles across the Permian–Triassic boundary, northern Bowen Basin, Australia

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Abstract

The most spectacular extinction event in Earth's history occurred across the Permian–Triassic boundary. In the northern Bowen Basin, a major coal-bearing sedimentary basin in eastern Australia, a long-lived (c. 9 Myr), cold climate, peat mire ecosystem collapsed at the Permian–Triassic boundary when the vast majority (c. 95%) of peat-producing plants became extinct. The environmental change marked by the Permian–Triassic boundary is expressed as an abrupt and sharp change in sedimentary regime at the contact between the Rangal Coal Measures and the Sagittarius Sandstone. The stratigraphic record shows no diminution in the thickness, lateral extent or spatial distribution of coal seams prior to the boundary event. The abrupt ecological shift at the Permian–Triassic boundary was coincident with and interrelated to a change in landscape attributes and fluvial style. The boundary shift is considered to reflect a short-period radical atmospheric change accompanied by an abrupt change in plant ecosystems. However, palynological data indicate that it was preceded by a more gradual gross taxonomic progression in the floral succession. The boundary shift is unlikely to reflect change in the tectonic setting of the northern Bowen Basin because the detrital character of clastic sediment supply shows no provenance change within the boundary sequence. The Late Permian fluvial style is characterised by large-scale (up to 1 km wide), sandstone-dominated, low sinuosity, trunk river channel deposits. The trunk river channels were flanked by extensive levee/composite crevasse–splay systems. Channel tracts were relatively stationary in position over enduring periods, and developed stacked sediment accumulations up to 30 m thick. The constrained character of the Late Permian trunk river systems was most likely due to progressive compaction of thick tracts of peat substrate, and the stabilising effect of vegetation adjacent to the channel complex. The well-developed crevasse splays, coupled with the low sinuosity style of the fluvial channels, might suggest a perennial fluvial system, characterised by short discharge periods, as common in high-latitude settings. The fluvial architecture of the Sagittarius Sandstone, the basal formation of the Lower Triassic Rewan Group, is characterised by sheet-like elements, suggestive of broad, shallow channels in a deforested braid-plain setting. The channel deposits are considered to represent highly mobile sandy systems, dominated by a flashy runoff regime. The mass extinction of plants in the northern Bowen Basin at the Permian–Triassic boundary thus had a significant impact on the Early Triassic landscape and fluvial architecture.

Keywords: Permian–Triassic boundary; sedimentology; stratigraphy; Bowen Basin; Australia

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1. Introduction

The Permian–Triassic boundary event represents the most extensive mass extinction in the geological record (e.g. Erwin, 1990; Hallam and Wignall, 1997; Lucas and Yin, 1998; Hansen et al., 2000; Jin et al., 2000), marking the extinction of 80–97% of all species (Retallack, 1995). The Permian–Triassic boundary is well constrained in the northern sector of the Bowen Basin of eastern Australia (Fig. 1) by palynology (Michaelsen et al., 1999), organic carbon isotopes (Hansen et al., 1999, 2000) and stratigraphic and sedimentological records (Michaelsen et al., 2000). The boundary is essentially conformable but marks a major environmental shift which is reflected in the basinal stratigraphy by separation of the coal-bearing Blackwater Group from the coal-barren Rewan Group (Fig. 2).

The end-Permian mass extinction event marked the collapse of marine and terrestrial ecosystems on a world-wide scale (e.g. Erwin, 1993, 1994). Significantly, the boundary event extinguished c. 95% of peat-forming plants in Australia (Retallack, 1995). In the northern Bowen Basin a long-lived (c. 9 Myr) peat mire ecosystem was abruptly terminated (Michaelsen et al., 1999). The mass extinction is represented in the stratigraphic record by a global fungal event (e.g. Eshet et al., 1995; Visscher et al., 1996), recording excessive dieback of arboraceous vegetation, an event documented in the Bowen Basin by Foster (1982). The mass extinction of peat-forming plants was followed by a global Early Triassic coal gap, which lasted some 6 million years (Retallack et al., 1996; Retallack, 1999).

The aim of this contribution is to examine how the mass extinction of peat-forming plants at the Permian–Triassic boundary affected the fluvial architecture across the boundary succession in the northern sector of the Bowen Basin. Fluvial architecture is thought to be essentially controlled by three factors: accommodation space, sediment supply and hydrodynamics (e.g. Puigdefabregas, 1993). However, this study highlights a fourth element, vegetation, as an architectural control of considerable importance affecting channel morphology and behaviour through bank stability (e.g. Smith, 1976; Stanistreet et al., 1993; Miall, 1996; Ward et al., 2000).

2. Geological setting

2.1. Strato-tectonic context of the Permian–Triassic succession

The northern Bowen Basin forms the northernmost extension of the Early Permian–Middle Triassic Bowen–Gunnedah–Sydney Superbasin, a major feature in the crustal fabric of eastern Australia, extending for > 2000 km north–south. The basin has a complex, polyphase history with an early extensional, back arc phase followed by an episode of thermal recovery with a subsequent retro-arc foreland stage of evolution (Murray, 1983). The northern sector of the Bowen Basin has a maximum stratal thickness of 10 km of volcanic and shallow marine and terrestrial sediments, reflecting the polyphase basinal development. The northern part of the basin was little affected by inversion tectonism (Dickins and Malone, 1973) which strongly influenced the central and southern part of the basin during the Triassic (e.g. Fergusson, 1991; Henderson and Davis, 1993). During the Triassic the basin fill was warped into a regional-scale synform, the Nebo Synclinorium, and it contains sporadic low-angle thrust faults (Fig. 1) with offsets ranging to 1000 m. Late Permian to Middle Triassic sedimentation, represented by the Blackwater, Rewan and Clematis Groups, occurred during the foreland phase of basinal development (Fig. 2). Compressive deformation and contemporaneous volcanism to the east facilitated the supply of abundant volcaniclastic detritus, resulting in rapid alluvial aggradation during the Late Permian (Michaelsen and Henderson, 2000a,b).

2.2. Depositional rates across the Permian–Triassic succession

Age constraints for the up to 1550 m thick coal-bearing Upper Permian Blackwater Group (Fig. 2) indicate an average depositional rate of 130 m/Myr in the depocentre and 70 m/Myr for more

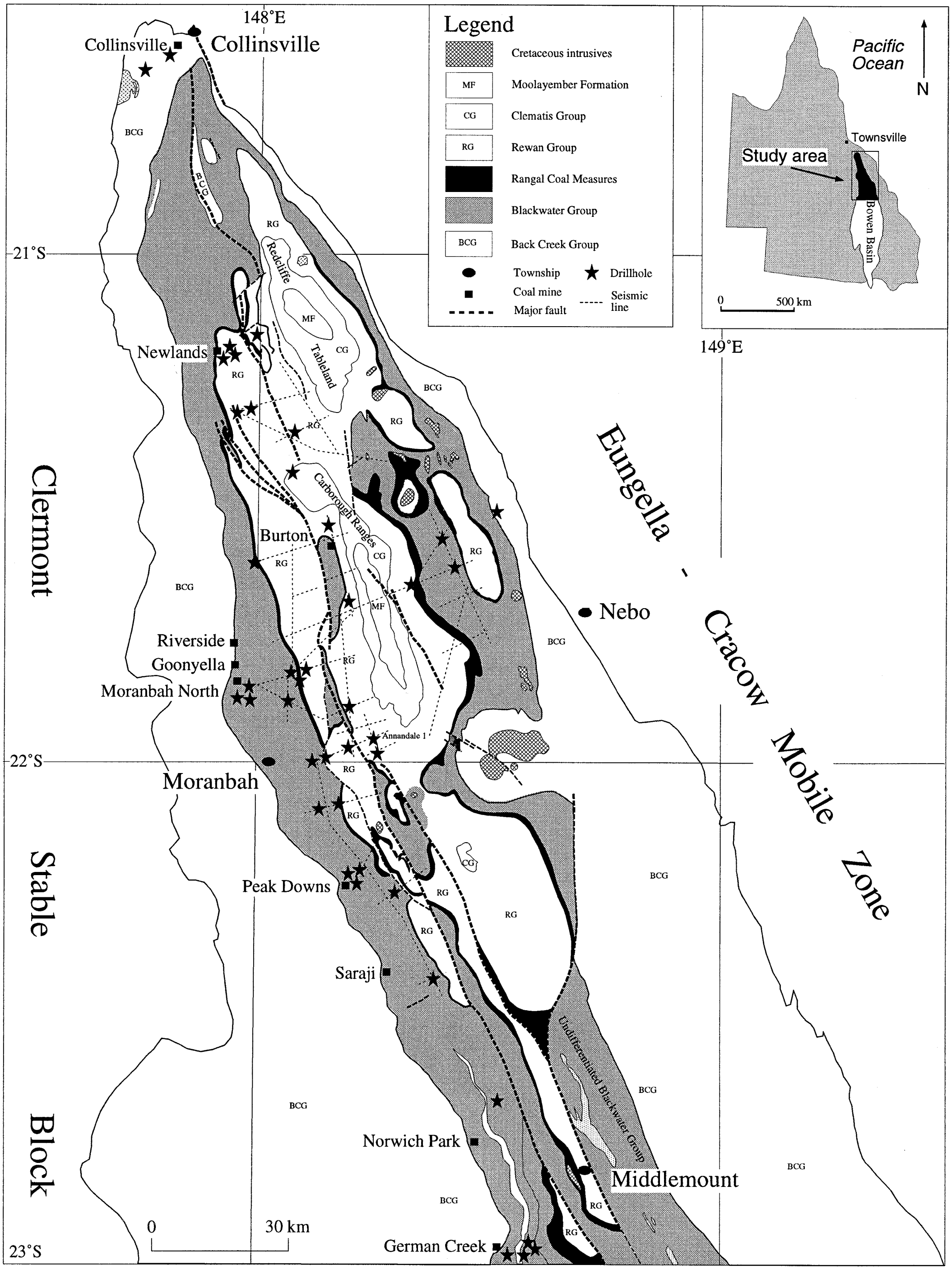

Fig. 1. General setting of the Bowen Basin showing the regional distribution of the Permian–Triassic succession and location of seismic lines, logged drill holes and major thrust fault systems. Abbreviations: MF, Moolayember Formation; CL, Clematis Group; RG, Rewan Group; BCG, Back Creek Group. Modified from Beck (unpublished data) and Michaelsen (1999).

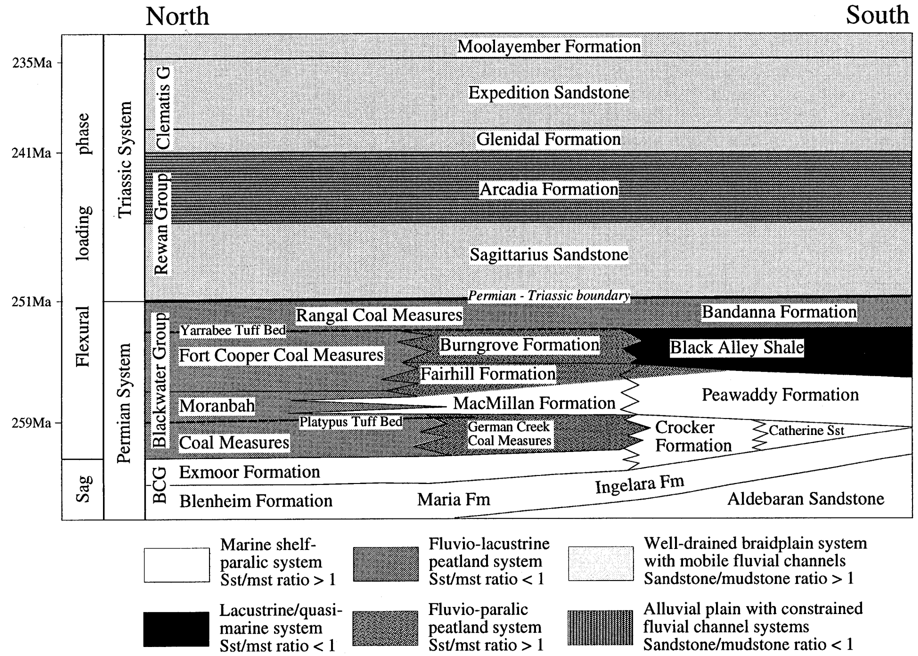

Fig. 2. Generalised stratigraphic framework for the Permian–Triassic succession in the northern and central Bowen Basin (modified from Falkner and Fielding, 1993). Dates from Bowring et al. (1998), Veevers et al. (1994) and Michaelsen et al. (2001).

marginal settings (Michaelsen et al., 2001). The time span of the Triassic System rocks in the Bowen Basin is poorly restrained. However, the age span of the Triassic succession in the northern Bowen Basin is estimated by Veevers et al. (1994) to represent c. 14 Myr. Regional compilations of drilling records and interpretation of extensive seismic profiles indicate that the Triassic succession in the northern Bowen Basin has a maximum development of c. 1100 m in the eastern depocentre (Fig. 1). Using the time frame from Veevers et al. (1994), maximum depositional rates of c. 78.5 m/Myr can be calculated for the Lower Triassic succession in the northern Bowen Basin. Similarly, age estimates from Veevers et al. (1994) suggest that the Rewan Group accumulated over some 10 million years. The Rewan Group has a maximum development of 510 m in the depocentre (Jensen, 1975). A maximum depositional rate of 51 m/Myr is thus indicated. As such, it marks a dramatic decrease in depositional rates compared to Late Permian times. However, in the southeastern part of the Bowen Basin, the Rewan Group is up to 3000 m thick (Baker et al., 1995). This reveals a major shift in the locus of maximum sedimentation (see also Dickins and Malone, 1973). Significantly, the along-basin variation in subsidence probably had a pronounced effect on the depositional dynamics.

2.3. Palaeoclimate

Palaeomagnetic data indicate that the basin was located at c. 65°S during the Late Permian (Embleton, 1984), consistent with a cold climate setting (e.g. Rigby, 1971; Crowell and Frakes, 1971; Johnson, 1984). A similar high-latitude setting is inferred for Early Triassic times (Baker et al., 1995). The general scenario of wet conditions during the Permian, characterised by peat mires, succeeded by ‘red beds’ attributed to dry conditions during the Triassic (e.g. Veevers et al., 1994), has recently been challenged. Noncalcareous kaolinitic palaeosols from the Sydney Basin suggest humid climates persisted during Early Triassic times in Australia (Retallack, 1999). However, the palaeosols in the Sydney Basin also suggest a warmer climate during Early Triassic times, generated by a catastrophic addition of CO_2 or CH_4 into the atmosphere (Retallack, 1999).

2.4. Boundary stratigraphy

The Blackwater Group is a major sediment system of the Bowen Basin. The group is of Late Permian age (Michaelsen et al., 2001) and is divided into three coal-bearing formations in the northern part of the basin (Fig. 2). It has a maximum thickness of 1550 m and is distributed throughout the northern Bowen Basin (Michaelsen, 1999). The Rangal Coal Measures comprise the youngest formation of the group and constitute the stratigraphic unit beneath the Permian–Triassic boundary. The thickness of the measures increase in thickness from c. 50 m in the west to over 200 m in the depocentre to the east (Michaelsen, 1999). The Rangal Coal Measures reflect the final stage of a long-lived (c. 9 Myr) peatland depositional system which came to an abrupt termination at the Permian–Triassic boundary.

The Rangal Coal Measures are succeeded abruptly, but with apparent conformity, by the Lower Triassic Rewan Group (Staines and Koppe, 1980). Two formations, the basal Sagittarius Sandstone and the overlying Arcadia Formation, make up the group. The group is characterised by an absence of coal and a coincident change in sandstone colour from grey to green, reflecting a distinct change in both depositional environment and diagenetic overprint (Mallett et al., 1995). The Sagittarius Sandstone is extensively exposed in the highwalls of the Burton and Newlands coal mines. However, there are very few natural exposures in the northern sector of the Bowen Basin (Jensen, 1975).

The sandstone/mudstone ratio for the Sagittarius Sandstone is notably higher than for the underlying Blackwater Group, which is quantitatively dominated by heterolithic strata (Michaelsen, 1999). It is worthy of note that there is a marked difference in sandstone/mudstone ratios across the Bowen Basin. In its southern part the ratio is 1:1 (Jensen, 1975), whereas in the northern sector it is significantly higher ($>2:1$). The red-brown mudstone, which is so characteristic of the Rewan Group in the south, is predominant only in the upper part of the group (i.e. Arcadia Formation) in the northern part of the basin (Dickins and Malone, 1973).

The overlying Arcadia Formation is characterised by a thick succession of red-brown mudstone (Jensen, 1975), marking a significant change of depositional dynamics on a regional scale. This change might be interpreted in terms of increased subsidence, which allowed the fine-grained clastic fraction to be stored and preserved instead of being transported beyond the basin as during Sagittarius Sandstone time.

3. Methods

This study has drawn on a new database compiled in the context of regional exploration work targeting coal seam gas in the early 1990s by Mitsubishi Gas Chemical Resources Australia. This database consists of 611 line-km of seismic profiles, calibrated with deep, well-distributed drillholes (Fig. 1). The present study is based on detailed logging of 88 drillholes, totalling almost 9.5 km in composite length, 11 of which penetrate the Permian–Triassic boundary. Event signatures, lithofacies contacts, sandstone attributes, biogenic features, sedimentary structures and coal characteristics were given special attention during the logging programme. Many kilometres of highwalls in large-scale coal mines were examined, and selected segments were logged and mapped in detail (Fig. 1). This study has also drawn on previously published results and unpublished company data.

4. Sandstone petrology across the Permian–Triassic boundary

Sandstone petrology analyses were conducted on 38 samples from the Rangal Coal Measures and 28 samples from the Sagittarius Sandstone (Fig. 3). In the Rangal Coal Measures the highest proportion of framework grains are lithics (62%), followed by quartz (29%) and feldspar (9%), with the source being an undissected to transitional magmatic arc flanking the basin to the east (Mi-

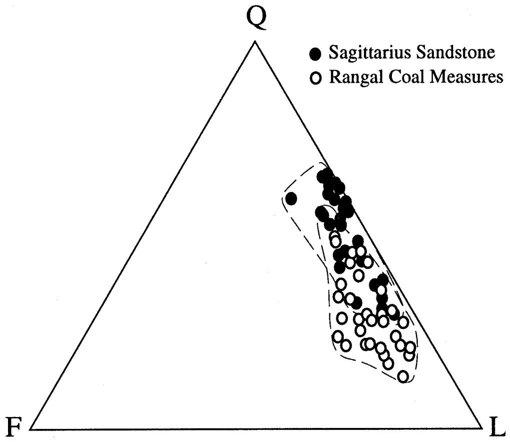

Fig. 3. Recalculated quartz–feldspar–lithics plots of sandstone composition across the Permian–Triassic boundary. See text for discussion.

chaelsen and Henderson, 2000a). Within the Sagittarius Sandstone a significant enrichment of quartz and decrease in feldspars (Q49F6L45), relative to the Rangal Coal Measures, is attributed to a climatic change and increase in palaeotemperature at the Permian–Triassic boundary (Michaelsen and Henderson, 2000a). The spatial distribution of plots in the QFL diagram (Fig. 3) clearly shows a significant overlap between the Rangal Coal Measures and the Sagittarius Sandstone. However, the general trend is towards enhanced quartz values in the Sagittarius Sandstone, a trend which continues throughout the Early and Middle Triassic succession. As an example, the Middle Triassic Expedition Sandstone (Fig. 2) is almost entirely composed of quartz framework grains (see Jensen, 1975).

5. Organic carbon isotope data across the Permian–Triassic boundary

A new comprehensive record of organic carbon isotope across the Permian–Triassic boundary sequence at the Newlands coal mine (Fig. 1) has recently been disclosed by Hansen et al. (1999, 2000). The organic carbon isotope record, derived from 55 samples, shows a prominent negative excursion 1.5 m beneath the lithostratigraphic boundary between the Rangal Coal Measures and the Sagittarius Sandstone (Fig. 4). This excursion is also reflected in data from the southern sector of the Bowen Basin reported by Morante et al. (1994). Significantly, this feature provides a new tie point which allows accurate calibration with the global Permian–Triassic boundary event (e.g. Hansen et al., 2000).

6. Palynological record across the Permian–Triassic boundary

A palynological investigation of the Permian–

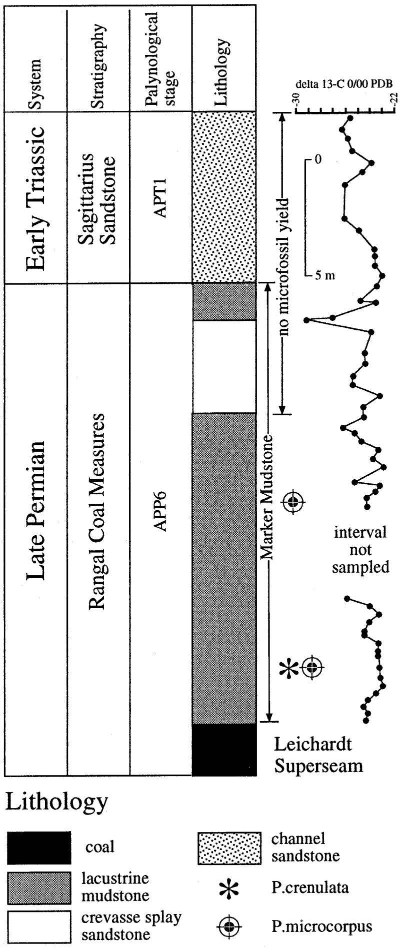

Fig. 4. Record of organic carbon isotopes across the Permian–Triassic boundary sequence, exposed in the Newlands open-cut coal mine (for location see Fig. 1). Modified from Hansen et al. (2000).

Triassic boundary sequence exposed in the Newlands coal mine based on a limited number of samples found a gradational floral change with the proportion of 'Triassic' taxa gradually increasing through the boundary succession (Michaelsen et al., 1999). Samples from the Rangal Coal Measures were found to be quantitatively rich in species such as *Triplexisporites playfordii* and *Falcisporites australis*, which become persistent and characteristic components of Triassic palynofloras. As such, the record makes a transition between the Permian and Triassic palynofloras. The first appearance of species within the peat ecosystems, which continued to flourish in younger Triassic assemblages, is regarded as a significant temporal and evolutionary event.

Foster (1979) described and named large fungal-shaped palynomorphs from the Permian–Triassic boundary interval in the Bowen Basin, which supports the global fungal event advocated by Visscher et al. (1996). However, fungal remains in Australia account for no more than 10% of the boundary assemblages, whereas they make up 90+% of assemblages in some European sections (Michaelsen et al., 1999).

The palynological and the carbon isotope records now available across the Permian–Triassic boundary in the northern Bowen Basin are significant as they constrain the boundary event in time and space. The records thus allows more accurate calibration with the global Permian–Triassic boundary event.

7. Late Permian fluvial style

Facies and stacking patterns of the Rangal Coal Measures have been investigated in drillcores from extensively drilled exploration areas and in spaced regional drillcores (Figs. 1 and 5). Highwall exposures of the Rangal Coal Measures in three coal mines in the northern Bowen Basin, provided an excellent opportunity to calibrate drillcore data with outcrop information (Fig. 6A). This integrated approach has identified six recurring fluvio-lacustrine depositional systems: (1) sandstone-dominated fluvial channels, (2) levee and proximal crevasse–splay complex, (3) distal

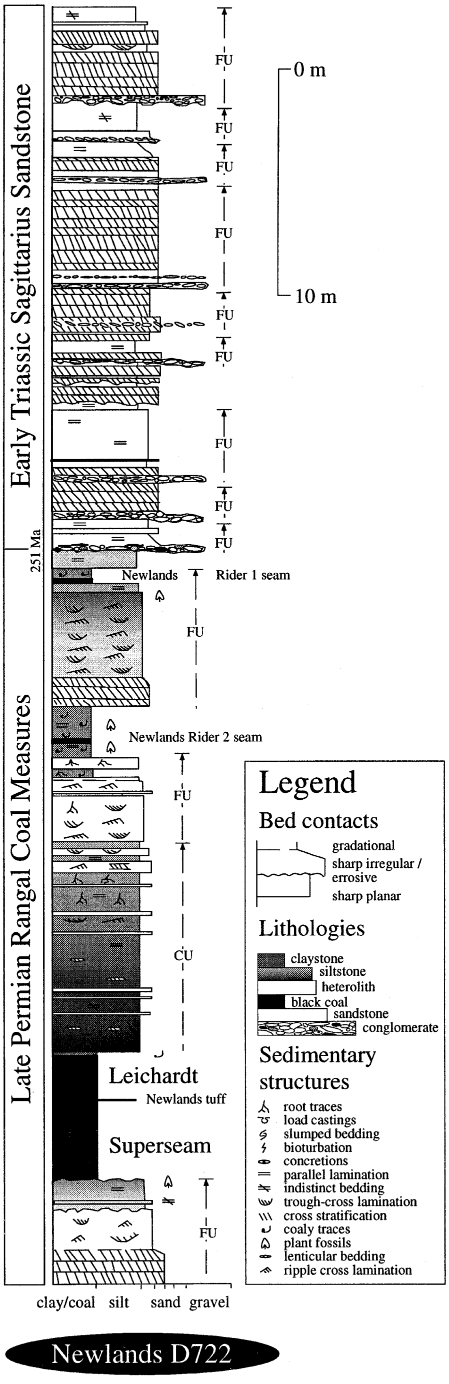

Fig. 5. Lithostratigraphic log of the Permian–Triassic succession in drillcore Newlands D 722 (see Fig. 1 for location).

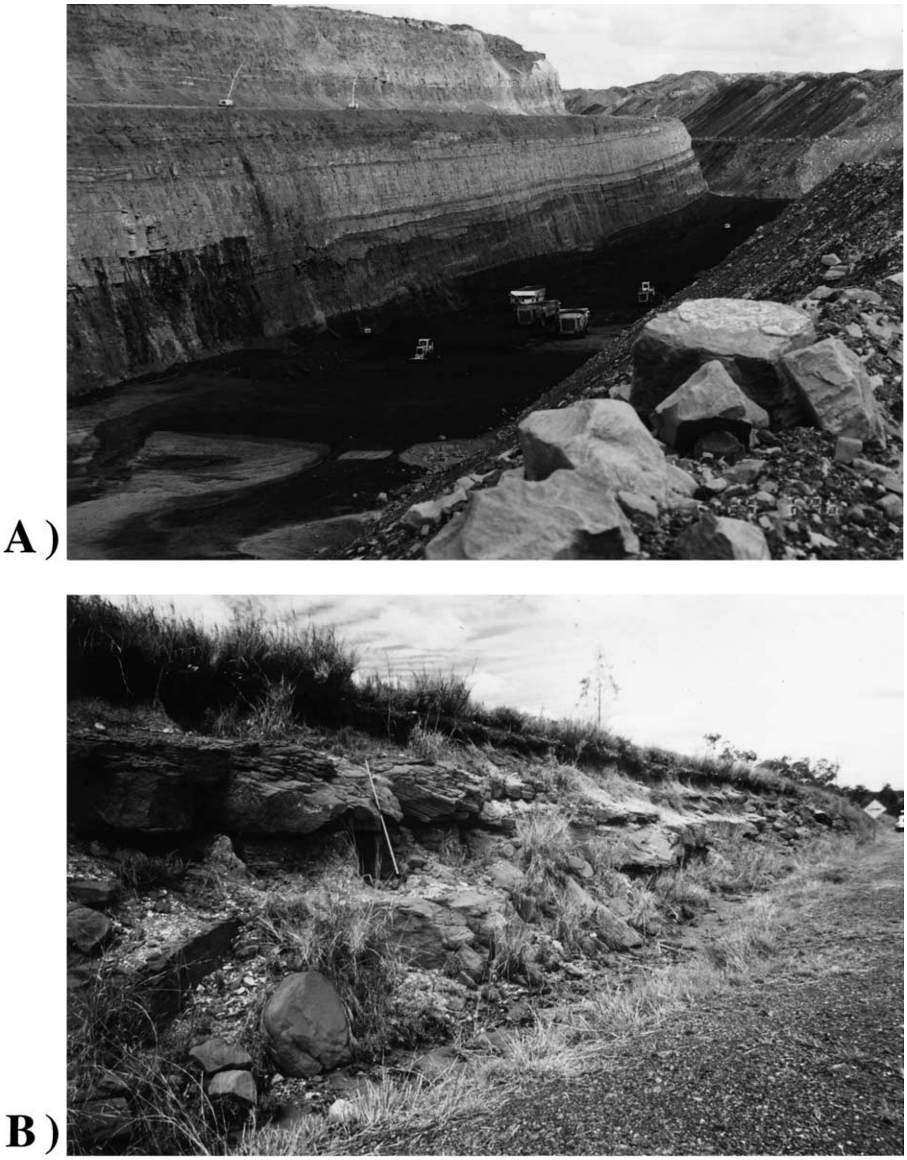

Fig. 6. (A) Photographic examples of the sheet-like succession architecture of the Lower Triassic Sagittarius Sandstone in the upper part of the Newlands highwall (face is c. 50 m high). (B) At a road cut at Suttor Creek (1 m tape measure for scale). (C) Well-developed trough cross-stratification in a road cut near Hillalong (10-cm scale). (D) Example of erosion associated with the Permian–Triassic boundary in the northern sector of the Bowen Basin. Abundant rip-up clasts, consisting of organic debris (as depicted here) and elongate siltstone, ranging to 25 cm in size, are unequally distributed along the contact between the Rangal Coal Measures and the Sagittarius Sandstone.

crevasse splays/overbank, (4) marsh, (5) peat mire and (6) shallow lake.

The fluvial style of the Rangal Coal Measures is characterised by two significantly different but genetically related systems: (A) large-scale trunk river channel fills, which form stacked sheets up to 30 m thick and 1 km wide; (B) ribbon-shaped crevasse feeder channel fills, up to 5.8 m thick and 0.1 km wide. These channels have significantly different width/thickness ratios: (A) c. 65–100;

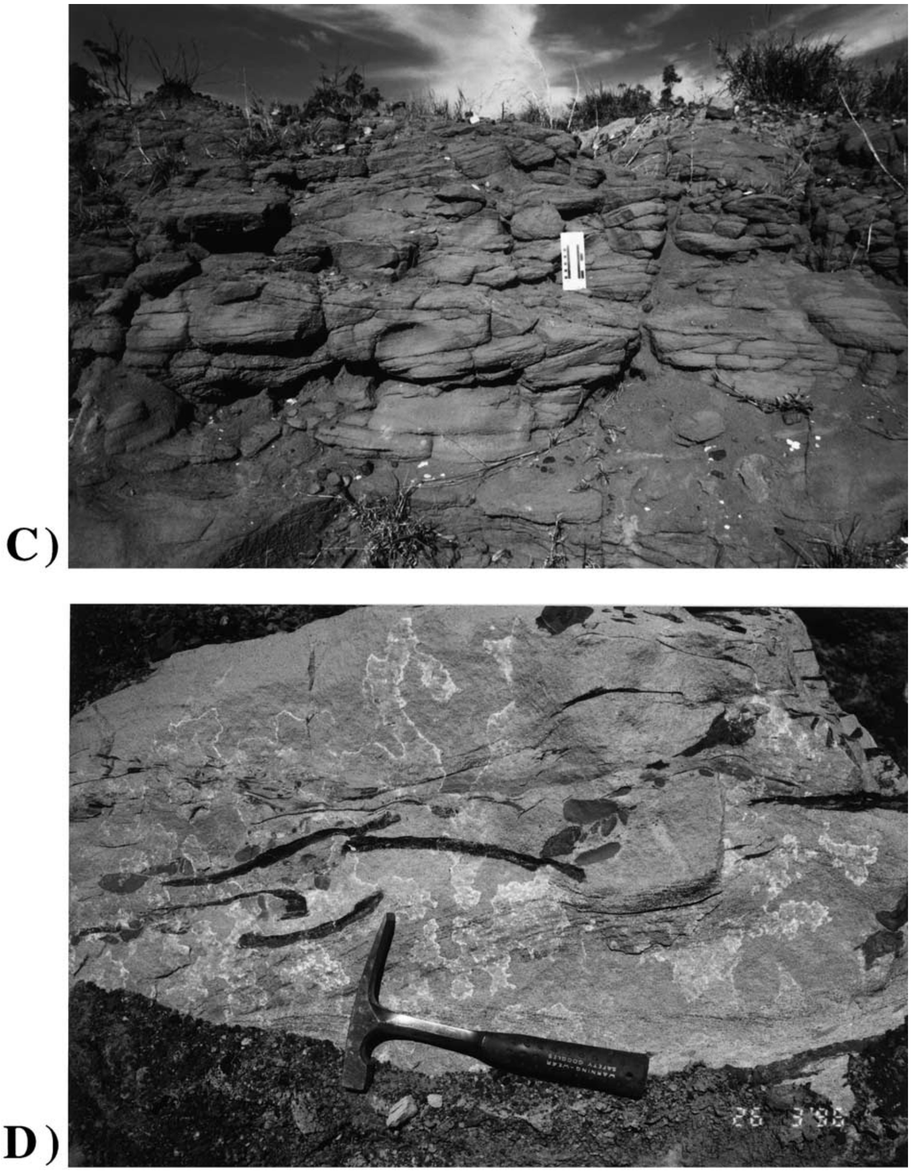

Fig. 6 (*Continued*).

(B) c. 6–19. Both types of channel fills are dominated by trough cross-stratification. Type A channel fills include elements characterised by epsilon cross-stratification, with sets up to 10 m thick, interpreted as point bar deposits. The trunk river systems were flanked by exceptionally well-developed major, composite, elongate crevasse–splay deltas (up to 26 m thick and >3 km wide), with well-preserved multiple anabranching feeder channels (Fig. 7A). This indicates that crevassing was responsible for distributing significant amounts of clastic sediment across a wet and poorly drained floodplain (Fig. 7A). The abundant crevassing is considered to mirror a flashy runoff regime, which is best rationalised in terms of annual thaw conditions of a volcanic arc catch-

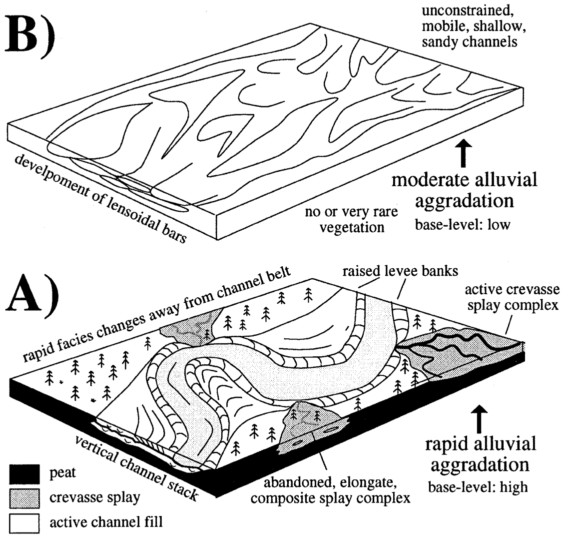

Fig. 7. Summary architectural models of fluvial styles across the Permian–Triassic boundary in the northern Bowen Basin. (A) Late Permian peatland with major, constrained, trunk river channel systems, flanked by extensive tracts of crevasse–splay deposits. (B) Early Triassic deforested braid plain with unconstrained shallow channels.

ment area, which in part lay above the snowline (Michaelsen et al., in review).

In the absence of active clastic sedimentation, peat mire environments expanded, extending across abandoned depositional lobe systems. The well-developed crevasse splays, coupled with the low sinuosity style of the fluvial channels documented by Michaelsen et al. (2000) at Newlands, might suggest a perennial fluvial system, characterised by short discharge periods, as is common in high-latitude settings (see Jones, 1977).

Stratigraphical control, afforded by thin tuff beds and coal seams, shows that clastic deposition developed as a succession of prograding fluvio-lacustrine lobe systems during Rangal Coal Measures time (Michaelsen et al., 2000). The geometry of the fluvio-lacustrine deposits largely reflects accommodation space provided by the compaction of the two thick and laterally extensive coal superseams of the Rangal Coal Measures. The behaviour of the peat under compactional load seems to have controlled the facies stacking pattern observed in the Rangal Coal Measures. This model explains the constrained nature of trunk river channel belts over enduring time periods, the vertical stacking of channel belts as well as the extremely rapid facies changes away from the sandstone-dominated channel belts (Fig. 7A).

The fine-grained and organic-rich nature of the formation is considered to reflect accumulation during rapid aggradation and underfilled basinal conditions (subsidence < sediment supply). However, the regional distribution of two coal superseams within the Rangal Coal Measures clearly shows that the rapid clastic aggradation was punctuated by prolonged periods of clastic sediment starvation/bypassing on a basin-wide scale (Michaelsen, 1999).

Regional palaeocurrent distributions and detailed isopach data of fluvial tracts indicate south-southwestward (axial) sediment dispersal during Late Permian times (e.g. Fielding et al., 2000; Michaelsen and Henderson, 2000a,b; Michaelsen et al., 2000).

The Upper Permian Blackwater Group lacks classic palaeosols. This might be due to a combination of factors: (1) continuous sedimentation in a rapidly aggrading depositional system, (2) a high-latitude, cold climate setting and (3) waterlogged conditions. A cold climate setting explains the very limited chemical weathering of the Upper Permian clastic deposits. Peat mire systems represented the ambient conditions of sedimentation. In the absence of active clastic sedimentation, peat mire environments expanded, extending across abandoned depositional systems (Michaelsen et al., 2000).

8. Early Triassic fluvial style

The Sagittarius Sandstone is dominated by green, well-sorted, fine- to coarse-grained sandstone, with subordinate conglomerate, siltstone and mudstone. The basal part of the Sagittarius Sandstone is characterised by abundant rip-up clasts consisting of elongate siltstone and organic debris, ranging up to 25 cm in size (Figs. 5 and 6D). The Sagittarius Sandstone is characterised by a rarity of thick beds, they are typically 0.3–1 m. The formation is characterised by a signifi-

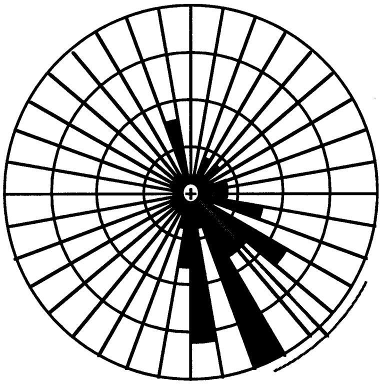

Fig. 8. Palaeocurrent directions for the Sagittarius Sandstone, Suttor Creek district ($n = 29$).

cantly higher proportion of sandstone than in the underlying Rangal Coal Measures, which is dominated by heterolithic facies. The sandstone/mudstone ratio for the Sagittarius Sandstone in the northern Bowen Basin is estimated from exposures and drillhole information to be $>2{:}1$.

No palaeosols were observed within the sandstone-rich sequences. The preservation potential of palaeosols might have been low in the Sagittarius depositional system. Alternatively they were never developed. Ichnofossils are rare. However, disturbed bedding in the basal part of the Sagittarius Sandstone was observed at interval 398.10–399.98 m in drillhole MGCRA Annandale 1, in fine-grained overbank deposits (Fig. 1). The ichnofossils include small (<2 cm) *Planolites* isp., *Skolithos* isp. and inclined biogenic structures. A substantial (1×7 cm) *Planolites* burrow was also observed in sandstone channel fill in a road cutting near Hillalong (Fig. 6C).

The fluvial architecture of the Sagittarius Sandstone is less evident than in the underlying Rangal Coal Measures, due to less exposures and drillhole information. However, extensive seismic records suggests a general sheet-like architecture. This is confirmed by an up to 40-m-thick, amalgamated, sandstone sheet exposed (until recently) along the 6.4-km-long Newlands highwall (Fig. 6A). Isopach data imply that this sandstone exposure represents an oblique view of a large-scale, north-northeast–south-southwest oriented channel body, but no palaeocurrent information is available from this sandstone body.

Detailed logging of four selected drillholes and two highwall sections reveals that internally the sandstone sheet is dominated by well-sorted, medium-grained sandstone, conglomerate and siltstone. Trough cross-stratification, with sets 0.2–2.0 m thick, is the predominant sedimentary structure, with subordinate planar stratification, and ripple and trough cross-lamination. The sandstone sheet contains a planar laminated siltstone unit, up to 10 m thick, which can be traced for 2.3 km along the northern part of the highwall. The sandstone sheet has a maximum development where it is directly overlying the c. 6.5-m-thick Upper Newlands Seam. It thins slowly towards the south where the thickness of the clastic packages of the Rangal Coal Measures gradually increases (Michaelsen et al., 2000).

In the Suttor Creek area, c. 18 km southeast of Newlands, the Sagittarius Sandstone is exposed in a road cut (Fig. 6B). The exposure reveals a c. 115 m long flow-parallel view of an up to 2.4-m-thick sheet-like sandstone body. It consists of well-sorted, medium-grained sandstone with occasional, elongate, rip-up clasts ranging in size to 2×3 cm. It is dominated by trough cross-stratification with a set height averaging 0.6 m. Internally the sandstone body is organised as lensoidal bars, up to 18 m long and 0.7 m thick. The sheet-like architecture might suggest derivation from thin broad bars developed in a braid-plain setting (Fig. 7B). The multistore, fining-upwards bodies documented in drillcores (e.g. Fig. 5) indicate different magnitudes of active channel fill, which can be interpreted in terms of braiding (e.g. Bristow and Best, 1993; Bristow, 1993, 1996; Miall, 1996).

The dimensions of the succession exposed at Newlands, combined with measured bars and inferred channel fill, all suggest a vast braid plain, characterised by shallow and highly mobile sand-dominated channels (Fig. 7B). Measured palaeocurrent directions from the Suttor Creek area shows southwestward sediment dispersal during Early Triassic times (Fig. 8). This drainage pattern is consistent with previous published work by Jensen (1975), and indicates that the general system of axial clastic sediment dispersal continued across the Permian–Triassic boundary.

9. Discussion

The Permian–Triassic boundary in the northern sector of the Bowen Basin appears conformable but marks a dramatic environmental shift reflected in the basinal stratigraphy by separation of the coal-bearing Blackwater Group from the coal-barren Rewan Group. The boundary is well constrained by a prominent negative organic carbon isotope anomaly (Fig. 4), palynology and stratigraphic data.

The sedimentary architectural record shows a significant change in fluvial style across the Permian–Triassic boundary. The poorly drained peatland environment characterised by major, sinuous, trunk river systems flanked by extensive crevasse splays and shallow lakes of the Late Permian period (Fig. 7A) was replaced by a well-drained braid plain with highly mobile, bedload-dominated channel systems during Early Triassic times (Fig. 7B). The fluvial architecture of the Sagittarius Sandstone is characterised by sheet-like elements, suggestive of broad, shallow channels. The Sagittarius channel deposits are considered to represent highly mobile systems, dominated by a flashy runoff regime. The fluvial style may have been similar to pre-Devonian ephemeral sandy sheetflood-style channel systems which were largely characterised by flashy runoff and high sediment yields (Schumm, 1968). The dramatic shoaling of preserved channel fills across the Permian–Triassic boundary is best rationalised in terms of readily erodible channel banks, generated by frequent avulsion events which are typical in braided river systems (e.g. Bristow and Best, 1993; Miall, 1996).

The demise of peat-forming plants had a significant impact on the Early Triassic landscape and fluvial architecture. The complete lack of rootlets and organic material on bedding planes in the Sagittarius Sandstone in the northern Bowen Basin implies an entirely deforested depositional setting. The lack of vegetation or extremely low vegetation density is largely thought to have controlled the low channel bank stability and resulting fluvial architecture within the Sagittarius Sandstone. Vegetation is an architectural control of considerable importance, affecting channel morphology and shifting behaviour through increasing bank stability (Smith, 1976). Changes in river behaviour when forests in upland catchment areas are destroyed by fire or deforestation are significant: (1) runoff becomes more flashy, (2) sediment load increases, and (3) debris flows are more common (Miall, 1996).

These important processes have recently been documented by Stanistreet et al. (1993) on the modern Okavango Fan system.

This contribution highlights the significant effect the mass extinction of peat-forming plants had on the fluvial styles across the Permian–Triassic boundary. A brief assessment of this floral mass extinction is thus appropriate. The termination of the vast majority (> 95%) of peat-forming plants can be achieved in two different ways, either separately or in combination:

1. The stratigraphic record shows no diminution in the thickness, lateral extent or spatial distribution of coal seams prior to the Permian–Triassic boundary event. The mass extinction of peat-forming plants may thus be attributed to a short-period radical global atmospheric change, where the flora did not have sufficient time to adapt to rapidly changing environmental conditions. This interpretation is supported by the negative carbon isotopic anomaly (Fig. 4) which is recognisable world-wide (Erwin, 1993) and which marks the collapse of terrestrial and marine ecosystems on a global scale (Hallam and Wignall, 1997). However, both sandstone petrology data and the palynological record suggest a more gradational climatic change in the northern sector of the Bowen Basin. The palynological record shows a gradational floral change prior to the mass extinction event, with the proportion of ‘Triassic’ taxa gradually increasing through the boundary succession at the Newlands coal mine (Michaelsen et al., 1999). Sandstone petrology data from the Sagittarius Sandstone show a substantial decrease in feldspars and enrichment of quartz relative to the Rangal Coal Measures (Fig. 3). This might be linked to enhancement of chemical weathering in the sedimentary hinterland. As such it strongly suggests a rise in palaeotemperature at the Permian–Triassic boundary. It conforms with the change in global climate at the Permian–Triassic

boundary as advocated by Holser and Magaritz (1987), Hallam (1994) and Retallack (1999). It could thus be concluded that the stratigraphic record supports an instantaneous extraterrestrial impact scenario (e.g. Xu et al., 1985), whereas the results from sandstone petrology and palynology work argue for a more gradational atmospheric change, which could be explained in terms of major volcanic eruptions (e.g. Gurevitch et al., 1995). The gradational atmospheric change scenario across the boundary is supported by recent geochronological work from southern China, which indicates that the end-Permian mass extinction event occurred over a time frame of < 0.5 Myr (Bowring et al., 1998). It is considered by Campbell et al. (1992) and Renne et al. (1995) to be linked to the eruption of the Siberian flood basalts.

2. The Lower Triassic succession in the northern Bowen Basin is considered to mirror a significant decrease in basinal subsidence. Significantly, the decrease in basinal subsidence in the northern sector of the Bowen Basin could have lowered the water table. This could have had a terminating effect on peat mire development. The observed high sandstone/mudstone ratio in the Sagittarius Sandstone in the northern part of the basin may indicate sedimentary bypassing of much of the fine-grained fraction, generated by overfilled basinal conditions in the northern sector of the Bowen Basin. However, the sedimentary record suggests that the southern part of the basin experienced underfilled conditions at the same time (Kassan and Fielding, 1996). Nonetheless, termination of the long-lived peat mire ecosystem by tectonic events seems very unlikely, because the Bowen Basin experienced substantial along-arc variation in subsidence and hence depositional dynamics, and the ecosystem was terminated throughout the entire basin.

The dramatic environmental shift at the Permian–Triassic boundary with mass extinction of peat-forming plants is thus attributed to an extraordinary and rapid global atmospheric change. This interpretation is endorsed by oxygen isotope data from the Carnic Alps in Austria, which suggest a 6–11°C increase in temperature across the boundary in tropical settings (Holser et al., 1991). The inferred increase in palaeotemperature is reflected by the increase in chemical weathering of volcaniclastic debris across the boundary succession in the northern Bowen Basin (Fig. 3). The ecological shift at the boundary was coincident with and interrelated to a change in landscape attributes and fluvial style. The boundary shift is very unlikely to reflect a change in the tectonic setting of the Bowen Basin because the detrital character of terrigenous sediment supply shows little provenance change within the boundary sequence (Fig. 3).

The end-Permian mass extinction of peat-forming plants occurred not only in the Bowen Basin, but on a global scale (e.g. Retallack et al., 1996; Retallack, 1999). It probably affected the fluvial styles to some extent across boundary successions in similar Gondwana depositional systems in the Antarctica (e.g. Webb and Fielding, 1993), India (e.g. Bose et al., 1990) and South Africa (e.g. Smith, 1995; Ward et al., 2000). Some important common patterns in fluvial style across the boundary might be present throughout the Gondwana system; however, variations are to be expected and are equally important if not more so. Every single depositional complex is unique. In this context, recent work by Retallack and Krull (1999) on palaeosols from the Trans-Antarctic Mountains suggests forested fluvial environments persisted in this high-latitude setting during Early Triassic times. As such, it was very unlike the northern Bowen Basin, where the Permian–Triassic boundary extinction event had a devastating effect on the gymnosperm flora.

Individual basinal tectonic events have been used to explain the changes in fluvial environments across the boundary in some Gondwana settings (e.g. Smith, 1995), while the influence of vegetation has received little attention (Michaelsen et al., 1999; Ward et al., 2000). Strictly speaking, individual regional tectonic events cannot adequately explain the world-wide nature of the mass extinction of peat-forming plants, as well as the c. 6 Ma global coal gap during the Early Triassic.

10. Summary

The Permian–Triassic boundary in the northern

Bowen Basin is marked by ecological disaster. A long-lived (c. 9 Myr) peat mire ecosystem collapsed when c. 95% of all peat-producing plants became extinct. The stratigraphic record shows no diminution in the thickness, lateral extent or spatial distribution of coal seams prior to the boundary event. However, the palynological record indicates a gradational floral change with the proportion of 'Triassic' taxa gradually increasing prior to the boundary event, which might suggest a peat mire ecosystem under considerable stress. The petrological sandstone record across the boundary conforms to a similar gradual change. Nonetheless, the environmental change marked by the Permian–Triassic boundary, expressed as a sharp change in sedimentary regime at the contact between the Rangal Coal Measures and the Sagittarius Sandstone, was more abrupt. The dramatic extinction of peat-forming plants was coincident with and interrelated to a change in landscape attributes and fluvial style.

The Late Permian landscape was characterised by a poorly drained peatland, with major, sinuous, trunk river systems, flanked by extensive crevasse splays and shallow lakes. It was abruptly succeeded by a completely deforested and well-drained braid plain during Early Triassic times. This system was characterised by shallow, highly mobile, bed-load-dominated channel systems with readily erodible channel banks.

The dramatic boundary shift is attributed to atmospheric change, accompanied by an abrupt change in plant ecosystems. An inferred increase in palaeotemperature is reflected by the increase in chemical weathering of volcaniclastic sandstones. The boundary shift is unlikely to reflect change in the tectonic setting of the Bowen Basin because the detrital character of clastic sediment supply shows no provenance change within the boundary sequence.

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