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Multiple Early Triassic greenhouse crises impeded recovery from Late Permian mass extinction

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ABSTRACT

The Late Permian mass extinction was not only the most catastrophic known loss of biodiversity, but was followed by unusually prolonged recovery through the Early Triassic. Opinion has been divided on whether delayed recovery was a legacy of especially profound ecological disruption, or due to additional environmental perturbations. New records from the Sydney Basin in southeastern Australia now reveal five successive Late Permian and Early Triassic spikes of unusually high atmospheric CO_2 and profound chemical weathering. These successive atmospheric CO_2 greenhouse crises coincided with unusually warm and wet paleoclimates for a paleolatitude of 61°S. Successive transient greenhouse crises punctuated long-term, cool, dry, and low-CO_2 conditions, and may account for the persistence of low diversity and small size in Early Triassic plants and animals.

1. Introduction

Plants and animals following the greatest known mass extinction during the Late Permian are distinctive and cosmopolitan. Animals on land were dominated by few taxa of small to medium sized therapsids, especially *Lystrosaurus* (Cosgriff et al., 1982; Benton et al., 2004; Retallack et al., 2003). Plants were mainly lycopsids (*Tomiostrobus* and *Pleuromeia*) and conifers (*Voltzia* and *Voltziopsis*: White, 1986; Retallack, 1995; Visscher et al., 2004). In the sea, small paper clams (*Claraia*) and inarticulate brachiopods (*Lingula*) abounded (Hallam and Wignall, 1997; Fraiser and Bottjer, 2004; Twitchett, 2007). Diversity within biotas, regional biotic differentiation, swamp woodlands, reef corals and bryozoans did not recover to Permian levels until the Middle Triassic (Retallack et al., 1996; Payne et al., 2004; Benton et al., 2004; Weidlich, 2007). Such prolonged recovery is well beyond the millennial tempo of ecological succession, which can often be detected even in ancient sequences (Calder et al., 2006). Prolonged recovery has been attributed to exceptional severity of Late Permian extinctions, which decimated key ecological components such as reefs (Pruss and Bottjer, 2004; Weidlich, 2007). An alternative hypothesis is lingering or recurrent environmental hazards, which frustrated full ecological recovery (Fraiser and Bottjer, 2007; Twitchett, 2007).

These alternatives are here re-examined using multiple proxy records from the Sydney Basin, southeastern Australia (Fig. 1). This is but one of many informative Permian–Triassic boundary sections around the world (Retallack and Krull, 2006; Richoz, 2006; Riccardi et al., 2007). Any succession is theoretically as good as another for understanding global CO_2 greenhouse crises of the past, because atmospheric CO_2 is globally mixed on time scales of 2–10 years (Revelle and Suess, 1957; Levin et al., 1992). The Sydney Basin however, has a thick (4.5 km), Permian to Middle Triassic succession (Figs. 2 and 3) and fossil plants and soils as proxies for atmospheric CO_2 and paleoclimate (Retallack, 1980, 1997a,b, 1999a,b). Furthermore, the Sydney Basin was then at high paleolatitude (Blakey, 2008), and it is at high latitudes where effects of current global warming attributed to rising atmospheric CO_2 are most pronounced (Alley et al., 2007).

The centrepiece of our work is a local record of carbon isotopic composition ($\delta^{13}C$) of organic matter (Fig. 3), supplementing earlier records (Compston, 1960; Philip and Saxby, 1979; Morante, 1996; Birgenheier et al., 2010), as a guide to estimating variations in carbon

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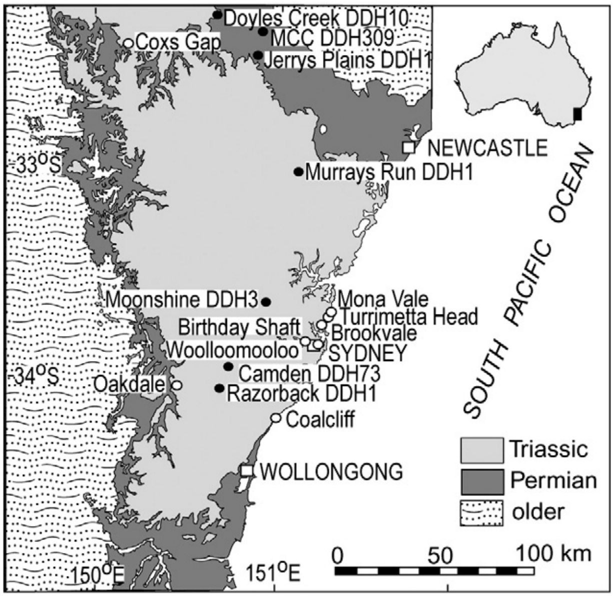

Fig. 1. Geological map of Permian and Triassic rocks of the Sydney Basin, Australia (simplified after Mayne et al., 1974). Localities shown are drillhole cores used for carbon isotope analysis (closed symbols), and localities for fossil plants used for stomatal index studies (open symbols).

sequestration and burial (Jahren et al., 2001), and as a tool for assessing international correlation of the greenhouse crises (Retallack et al., 2006). These new isotopic data complement newly compiled paleoclimatic data of comparable temporal resolution: (1), diversity of spores of lycopsids, which were plants of tropical affinities within these temperate floras (Retallack et al., 2006); (2), measurements of plant leafy shoot size as guides to incursions of frost-sensitive plants (Greenwood and Wing, 1995), and (3), chemical weathering indices of paleosols as guides to mean annual precipitation and temperature (Sheldon and Tabor, 2009). Only five of nine paleoclimatic perturbations identified by these proxies are supported by new estimates from stomatal index of Late Permian and Early Triassic atmospheric CO_2 levels, in support of comparable data from elsewhere in the world (Retallack, 2001a, 2002, 2009). Only four of the paleoclimatic perturbations are supported by appearance of poikilothermic–ectothermic large temnospondyls, because, like cuticular preservation required for studies of stomatal index (Retallack, 2002), large temnospondyls known from the Sydney Basin required exceptional preservation in black shales (Feistmantel, 1890; Woodward, 1890, 1908, 1931; Mitchell, 1924, 1925; Wade, 1935). Our study also includes locality details of U–Pb SHRIMP ages of zircons (Carr et al., 2003) used to reconcile advances in dating of Permian and Triassic rocks in Australia (Metcalfe et al., 2008) and in stratotype sections of China (Mundil et al., 2004; Lehrmann et al., 2006; Wignall et al., 2009).

2. Geological setting

The Sydney Basin, Permian–Triassic succession is largely outwash from the New England volcanic arc to the northeast, onlapping the older Lachlan Fold Belt to the southwest (Figs. 2 and 3; Mayne et al., 1974). This thick sequence includes numerous volcanic ashes, dated from zircons by $^{206}Pb/^{238}U$ geochronology using the SHRIMP instrument at the Australian National University Research School of Earth Sciences. Recent dates by Carr et al. (2003) (Table 1) using the SL13 standard are added to comparable published SHRIMP dates from the same laboratory (Gulson et al., 1990; Roberts et al., 1996) to develop a comprehensive local set of geochronological tie points (Fig. 4; Table 2). The SHRIMP age of Sri Lanka alluvial zircon standard SL13 was found by Black et al. (2003) to be 9% older than an IDTIMS age of the same standard (577.4 ± 1.2 versus 572 ± 0.4 Ma, respectively). This difference cannot be used for recalibration because of heterogeneity of the SL13 standard (Compston, 2001), as also indicated by broad errors (ca. ±2 Ma 2σ). Nevertheless, our analyses are within error of recent redating of biostratigraphic boundaries of the Late Permian and Early Triassic (Mundil et al., 2004; Lehrmann et al., 2006; Ovtcharova et al., 2006), and about 2 Ma older than in the time scale of Gradstein et al. (2004).

Other constraints come from a few recognized paleomagnetic reversals found in volcanic lava flows (Fig. 4; Table 2). A complete magnetostratigraphy for the Sydney Basin is not available (Facer, 1981; Theveniaut et al., 1994), because of problems with Cretaceous paleomagnetic overprinting of sedimentary rocks (Foster and Archbold, 2001). The internationally correlated top of the long Kiaman paleomagnetic reversal is dated elsewhere at 265.5 Ma (Steiner, 2006), but has its type section in the top of the Dapto Latite flow 67 m below the Woonona Coal, near Kiama, in the coastal southern Sydney basin (Irving and Parry, 1963; Bowman, 1970; Facer, 1981). Unfortunately this level cannot be accurately correlated with the northern Hunter Valley (Figs. 1 and 3), because the Dapto Flow is part of an anomalously thick local stratovolcano (Raam, 1969; Retallack, 1999a), unrelated to local sequence stratigraphy (Arditto, 1991; Herbert, 1997a) or tephrostratigraphy (Kramer et al., 2001; Grevenitz et al., 2003).

The various radiometric and paleomagnetic tie points, which can be fixed to a specific meter level in a Camden–Murrays Run–Muswellbrook composite section (Fig. 4), either directly within the cores, or by sequence-stratigraphic correlation (Arditto, 1991; Herbert, 1997a,b) or tephrostratigraphy (Kramer et al., 2001; Grevenitz et al., 2003) are listed in Table 2. These are the basis for the age models shown in Fig. 5. The datum (0 m) for the composite section is the collar of Murrays Run bore hole, which has depths as positive numbers, so that section stratigraphically above that level has negative meter levels. The two Permian–Early Triassic age models (Muswellbrook and Murrays Run) are broadly similar, but Middle Triassic rocks (in Camden–Razorback sections) accumulated at a slower rate. The basal Hawkesbury Sandstone is a fluvial deposit with a source terrane in the southwest, where it eroded down into underlying units (Herbert, 1997b). Age models proposed here (Fig. 5) confirm that it is disconformable over the central Sydney Basin as well, at a time of reduced sedimentation rate.

Permian marine fossils of the Sydney Basin are endemic Gondwanan forms (Foster and Archbold, 2001), but a few cosmopolitan ammonoids and foraminifera allow correlation with international timescales. An Artinskian age was assumed by Glenister and Furnish (1961) for two species of ammonoids: "*Neocrimites*" *meridionalis* (Elderslie Formation, 30 m above Greta Coal Measures in the Maitland Colliery shaft near Farley), and "*Uraloceras*" *pokolbinensis* (Farley Formation, 3 miles southwest of Farley). Leonova and Bogolovskaya (1990) reassigned "*N*." *meridionalis* to *Aricoceras*, a genus of late Artinskian to Wordian range (284.4–265.8 Ma in time scale of Gradstein et al., 2004). Schiappa et al. (2005) excluded "*Uraloceras*" *pokolbinensis* from the genus, and regard it as *Epijuresanites*, a genus of Kungurian (275.6–270.6 Ma) range (Popov, 2005; Leonova, 2007). In addition, the Mulbring Siltstone has yielded the Wordian (268.0–265.8 Ma) foraminiferan *Pseudonodosaria borealis* (Foster and Archbold, 2001).

Biostratigraphic control for the Triassic part of the section comes from Australian palynological zones (Foster and Archbold, 2001), which are now correlated internationally using conodonts in the Perth Basin, Western Australia. The upper *Protohaploxypinus microcorpus* palynozone, for example, has yielded the late Changsingian conodont *Neospathodus jolfensis*, and the lower *Lunatisporites pellucidus* palynozone has yielded the Dienerian–Smithian conodont *Neospathodus dieneri* (Metcalfe et al., 2008). Latest Permian and earliest Triassic rocks in the Sydney Basin are also confirmed by new radiometric