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GR focus review

Permian and Triassic greenhouse crises

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ABSTRACT

Paleoclimatic time series from Permian and Triassic paleosols reveal transient episodes of unusually warm and wet conditions, interrupting long periods of cool and dry conditions usual for calcareous red paleosols. Some of these paleoclimatic events are known from stomatal index of fossil *Lepidopteris* leaves to have been episodes of elevated global atmospheric CO_2. The magnitude of 19 known Permian and Triassic greenhouse crises varied considerably, and they offer new evidence for the relationship between paleoclimate and atmospheric CO_2 levels. These greenhouse crises also had marked effects on global lowland vegetation, introducing frost-sensitive tropical lycopsids to high latitudes and drought-tolerant conifers to low latitude lowlands. Greenhouse events punctuate phases in plant evolution (*Ottokaria–Callipteris*, *Plumsteadia–Rufloria*, *Lidgettonia–Tatarina*, *Pleuromeia*, and *Dicroidium–Scytophyllum* floras). Greenhouse events also punctuate the evolution of reptilian dynasties (successive pelycosaur, dinocephalian, dicynodont, rhynchosaur and dinosaur faunas) and respiratory adaptations (such as enlarged bony secondary palate). Greenhouse crises of the Late and Middle Permian were the most severe known, and suggest a role for atmospheric pollution with CH_4 and CO_2 in those mass extinction events, probably from thermogenic cracking of coals by intrusive feeder dikes of flood basalts. Because of formalities in boundary definition these mass extinctions are neither "end-Permian" nor "end-Guadalupian", but upper Changhsingian and mid-Capitanian, respectively.

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1. Introduction

By the year 2100, atmospheric CO_2 partial pressures are predicted to triple, from pre-industrial levels of 280 ppm to some 856 ppm (+70/−101 ppm: using emission scenario A2, very heterogeneous world with continued population growth of Solomon et al., 2007). Such changes are unprecedented in Quaternary records (Lüthi et al., 2008), and are best tested by proxies for atmospheric CO_2 deeper in geological time (Royer, 2006). The Permian and Triassic periods offer an array of greenhouse crises (Retallack, 2005a, 2009a), including the largest known Phanerozoic CO_2 levels coincident with the largest known Phanerozoic mass extinction (Retallack and Jahren, 2008). Furthermore, high resolution sequences of paleosols now show that many Permian and Triassic greenhouse crises were geologically abrupt transients (Retallack, 2009a), in some cases on time scales comparable with the current greenhouse crisis driven by fossil fuel consumption (Solomon et al., 2007). Lacustrine deposits yield fossil leaf stomatal index evidence for Early Triassic CO_2 plummeting from 3860 to 305,

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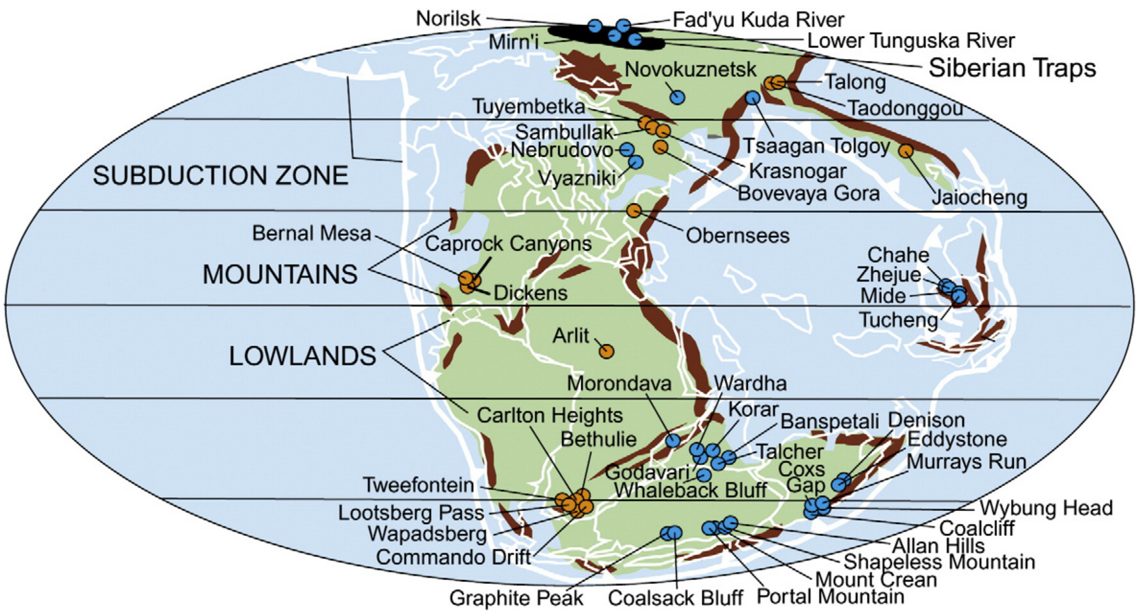

Fig. 1. Late Permian map of the world showing non-marine Permian–Triassic boundary sections of calcareous red beds (Table 1) and of coal measures (Table 2). Marine boundary sections are too numerous to be depicted at this map scale (91 sites are listed by Korte and Kozur, 2010).

then 417 and 3510 ppm, all within only 130,000 years (Retallack et al., 2011). Isotopic proxies for Late Permian atmospheric methane reveal dramatic fluctuations (−5‰ $\delta^{13}C_{org}$) within as few as 800 annual varves (Retallack and Jahren, 2008). Permian–Triassic greenhouse crises were abrupt and often brutal. Gases such as methane from thermogenic cracking of coal by large intrusive precursors to Siberian trap lavas have been suggested as causes of these Late Permian and Early Triassic greenhouse crises (Retallack and Jahren, 2008; Grasby et al., 2011). Also likely were massive volcanic emissions of HCl (Sobolev et al., 2011) and Hg (Sanei et al., 2012). Other kill mechanisms include degassing of H_2S, CH_4 or CO_2 from an anoxic and acidified ocean (Grice et al., 2005; Kump et al., 2005; Şengör and Atayman, 2009), release of marine and permafrost methane clathrate or gas (Heydari and Hassandzadeh, 2003; Ryskin, 2003), or impact of large asteroids or comets (Becker et al., 2001, 2004). Such events were not restricted to the Late Permian and Early Triassic: Emeishan flood basalts may coincide with mid-Capitanian mass extinction (Retallack and Jahren, 2008; Retallack et al., 2011) and Wrangellia flood basalts may coincide with early Carnian biotic overturn (Dal Corso et al., 2012).

This review concerns not such theories (ably reviewed by Korte et al., 2010), but rather empirical evidence for timing and duration of Permian and Triassic CO_2 greenhouses from non-marine rock sequences (Fig. 1), primarily paleosols of calcareous red beds (Table 1) and peaty wetlands (Table 2). The marine record of atmospheric CO_2 and paleoclimate is muted and imprecise (Rothman, 2002; Berner, 2006), and has been reviewed elsewhere (Korte and Kozur, 2010). Much work on the Permian–Triassic boundary has focused on coal measure sequences with well-preserved fossil pollen and leaves (Kazarinova, 1979; Wright and Askin, 1987; Sadovnikov and Orlova, 1990; Retallack, 1995, 1999; Morante, 1996; Wang, 1996; Krull and Retallack, 2000; de Wit et al., 2002; Sarkar et al., 2003; Retallack et al., 2005, 2006, 2007; Lindström and McLoughlin, 2007; Johnson et al., 2008; Sadovnikov, 2008, 2011; Krassilov and Karasev, 2009; Mogutcheva and Krugovykh, 2009; Davies et al., 2010; Mogutcheva and Naugolnykh, 2010). This paper instead emphasizes ongoing studies of calcareous red beds (Retallack et al., 2003; Retallack, 2005a; Coney et al., 2007; Szurlies, 2007; Taylor et al., 2009; Inosemtsev and Targulian, 2010; Tabor et al., 2011; Thomas et al., 2011; Benton et al., 2012; Newell et al., 2012), with their distinctive aridland paleosols (Aridosols, Alfisols, and Vertisols) and fossil vertebrates (Figs. 2–3). There have been difficulties understanding the Permian–Triassic transition in calcareous red beds because plant fossils are rare to lacking (Gastaldo et al., 2005), and

Table 1
Calcareous red bed Permian–Triassic boundary sections.

Locality	GPS position	Permian formations	Triassic formations	References
Arlit, Niger	N7.251954 E17.717555	Moradi Formation	Telqua Formation	Tabor et al., 2011
Bernal Mesa, New Mexico, USA	N35.39339 W105.29997	Bernal Fm.	Anton Chico Fm.	Retallack, 2005a
Bethulie, South Africa	S30.415899 E26.262209	Balfour Fm.	Katberg Sandstone	Retallack et al., 2003
Bovevaya Gora, Russia	N51.304616 E54.907964	Kulchumovskaya	Kopanskaya Svita	Taylor et al., 2009
Cap Rock Canyons, Texas, USA	N34.45346 W101.081580	Alibates Fm.	Dewey Lake Fm.	Retallack, 2005a
Carlton Heights, South Africa	S31.295033 E24.915155	Balfour Fm.	Katberg Sandstone	Retallack et al., 2003
Commando Drift, South Africa	S32.169550 E26.0533317	Balfour Fm.	Katberg Sandstone	Coney et al., 2007
Dickens, Texas, USA	N33.62552 W100.81791	Alibates Fm.	Dewey Lake Fm.	Retallack, 2005a
Lootsberg Pass, South Africa	S31.852132 E24.873138	Balfour Fm.	Katberg Sandstone	Retallack et al., 2003
Obernsees, Germany	N49.914927 E11.374448	Bröckelschiefer	Geinhausen Fm.	Szurlies, 2007
Sambullak, Russia	N51.877001 E56.207016	Kulchumovskaya	Kopanskaya Svita	Taylor et al., 2009
Taodonggou, NW China	N43.260342 E88.978817	Guodeking Fm.	Jiucaiyuan Fm.	Thomas et al., 2011
Tarlong, NW China	N43.263978 E89.036817	Guodeking Fm.	Jiucaiyuan Fm.	Thomas et al., 2011
Tuyembetka, Russia	N51.918510 E56.337648	Kulchumovskaya	Kopanskaya Svita	Taylor et al., 2009
Tweefontein, South Africa	S31.798666 E24.79219	Balfour Fm.	Katberg Sandstone	Ward et al., 2005
Wapadsberg, South Africa	S31.923139 E24.923139	Balfour Fm.	Katberg Sandstone	Ward et al., 2005