Palaeogeography, Palaeoclimatology, Palaeoecology 409 (2014) 280–289

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Air density of the Permian atmosphere: Constraints from lithified raindrop imprints

C. Glotzbach *, C. Brandes

Institut für Geologie, Leibniz Universität Hannover, Callinstraße 30, 30167 Hannover, Germany

ARTICLE INFO

Article history:
Received 20 January 2014
Received in revised form 19 May 2014
Accepted 23 May 2014
Available online 2 June 2014

Keywords:
Air density
Atmosphere
Raindrop impact
Permian
Northern Germany

ABSTRACT

In contrast to the composition of Earth's ancient atmosphere, the corresponding air density is almost unknown. A unique method to estimate the palaeo-atmospheric density is to use lithified raindrop imprints. The size of imprints is amongst other factors controlled by the air density, whereas large impacts form in a less dense atmosphere and vice versa. This basic relation was used to estimate the near sea-level atmospheric density of the Permian, a period characterised by an icehouse to greenhouse transition and an atmospheric composition comparable to the modern one. This makes the Permian an important analogue to better understand the current climate and environmental changes. In this study we analysed lithified raindrop imprints preserved in Permian terrestrial sandstone from the Flechting High, northern Germany. Following former applications, we experimentally determined the relation between raindrop momentum and imprint dimension to estimate the palaeo-air density. The maximum bound of the Permian air density is ~2.3 kg/m^3, assuming that the maximum measured imprint area of 68 ± 1.5 mm^2 was formed by the largest naturally occurring raindrop with a diameter of 6.8 mm. Although we cannot rule out an air density comparable to the present day (~1.2 kg/m^3), more realistic estimates of maximum raindrop diameters for a rainfall rate of 100 mm/h are between >3.2 and >4.3 mm, yielding air density estimates of 0.3 and 0.85 kg/m^3, approximately one-fourth to three-quarters of the present-day value. This approach is based on a few largest observed imprints, and does take the complete raindrop imprint distribution into account. The imprint distribution primarily depends on the drop size distribution of the rainfall event that causes the imprints, which follow a defined function. In this study we present a novel method to further constrain the palaeo-air density estimation by comparing the observed distribution of lithified raindrop imprints with modelled imprint distributions for different rainfall rates and drop size distribution functions. We observed significant differences; theoretical imprint distributions are in general shifted towards smaller imprints, which we interpret as a higher probability of larger imprints to be preserved. Above a threshold imprint area of 10 mm^2, observed and modelled distributions match each other, suggesting that a major fraction (~50%) of raindrops did not generate recognisable imprints in the analysed substrate. Unfortunately no unique rainfall rate fits the observed imprint distribution, but instead pairs of rainfall rates and air densities yield reasonable fits. Palaeo-air density estimates therefore depend on an unknown rainfall rate. Assuming that lithified imprints formed by a rain event with a rainfall rate of <100 mm/h (<50 mm/h) result in an upper estimate of the Permian atmospheric air density of ~1.1 kg/m^3 (~0.9 kg/m^3). These results corroborate estimates based on the maximum observed imprint area and realistic maximum raindrop diameters, suggesting that the Permian atmospheric air density was comparable or slightly lower than the present-day density.

1. Introduction

The Permian period was a time of global environmental change; episodic glaciations occurred during the Early Permian icehouse climate (e.g., Fielding et al., 2008), followed by a transition to a greenhouse climate with local extreme temperatures of up to 73 °C as recorded by ephemeral lake halite (Zambito and Benison, 2013). Together with similarities in the atmospheric composition, this makes the Permian period an important analogue to better understand the current environmental changes resulting from the anthropogenic rise in atmospheric CO$_2$ (e.g., Gastaldo et al., 1996). In contrast to the composition of the Permian atmosphere (e.g., Mora et al., 1996; Berner, 1999), the corresponding air density is unknown, making a direct comparison of the present-day situation with that during Permian times difficult. Understanding the Permian climate change, especially the sensitivity to changes in the CO$_2$ concentration (e.g., Gibbs et al., 2002), requires an estimate of the palaeo-air density. Air density proxies used in previous studies are the size distribution of lithified basalt vesicularity (e.g., Sahagian and Maus, 1994) and raindrop imprints (e.g., Som et al., 2012).

---

* Corresponding author. Tel.: +49 511 7622289.
E-mail address: glotzbach@geowi.uni-hannover.de (C. Glotzbach).

http://dx.doi.org/10.1016/j.palaeo.2014.05.024

The latter approach has been proposed already in 1851 by Sir Charles Lyell, who compared modern rain impacts with lithified impact structures in clastic rocks of Carboniferous and Triassic age and concluded that the density of the ancient atmosphere was similar to the modern one (Lyell, 1851). The momentum of raindrops and the substrate, in which they impact, are the main parameters controlling the size of raindrop imprints (e.g., Ghadiri, 2004). Raindrops reach their terminal velocity after falling for ~12 m (e.g., Gunn and Kinzer, 1949), and thus the momentum of raindrops depends on drop dimension and air density (Fig. 1). Based on this methodology, Som et al. (2012) experimentally determined the relation between impact dimension and the momentum of impacting drop for a fresh ash substrate as an analogue for a 2.7 Ga old tuff. From this relation they concluded that ground-level air density was less than 2.3 kg/m^3 (present-day value of 1.2 kg/m^3), and most likely air-density was below 1.3 kg/m^3. Kavanagh (2013) reviewed the uncertainties and reliability of this approach through application to present-day natural raindrop imprints and found that for low-intensity rain events (rainfall rate $\leq$2 mm/h) the maximum density value could be up to a magnitude above the true value.

Inspired by these studies, we applied a similar approach, to estimate the palaeo-air density of the Permian atmosphere. We measured lithified raindrop imprints preserved in Permian terrestrial mud- and sandstone from outcrops in the Flechting High in northern Germany. The substrate and raindrop size dependence of raindrop imprints was investigated through experiments with water droplets of defined volume falling with their terminal velocity on a sand/mud substrate with a composition similar to the Permian sediment. The resulting experimental relation between raindrop momentum and imprint dimension was used to estimate the palaeo-air density of the Permian atmosphere. The derived upper limit for the Permian air density is ~2.3 kg/m^3, whereas a value similar of less than the present-day value is much more likely. In addition, we investigated for the first time the possibility to use the complete distribution of measured imprint area to estimate the unknown rainfall rate, and therefore better constrain the derived palaeo-air density. Results reveal a clear discrepancy between theoretical and observed imprint distributions, which we interpret as a higher probability of larger imprints to be preserved. Taking this preservational bias into account and assuming a rainfall rate of $<$100 mm/h result in an upper estimate of the Permian air density of ~1.1 kg/m^3.

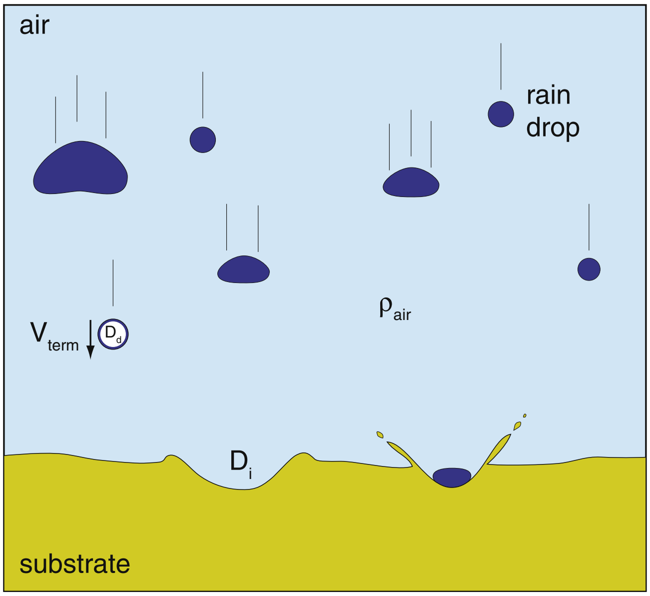

Fig. 1. Formation of imprints from falling raindrops on an unconsolidated substrate. The imprint dimension (D_i) depends on the substrate characteristics and the terminal velocity (V_{term}) of the falling raindrop. The latter depend on raindrop dimension (D_d) and air density (ρ_{air}).

2. Geological setting and palaeo-environment

During the Permian period a continuous belt of continents was located from the South Pole to high northern latitudes forming the supercontinent Pangaea (e.g., Scotese and Langford, 1995). The Late Carboniferous and Early Permian climate was characterised by episodic glaciations of the South Pole region in Gondwana (e.g., Fielding et al., 2008), whereas climate changed from an icehouse to a greenhouse state during the Permian period. The Carboniferous–Permian atmospheric composition was extreme; O_2 concentrations reached their maximum in Earth's history with values up to 25% or even above 30% (Berner, 1999), and the pCO_2 was close to present atmospheric levels (e.g., Mora et al., 1996), with higher-frequency variations that correlate to major glaciations (e.g., Royer, 2006; Montañez et al., 2007). Because of these climate similarities, the Permian can serve as an analogue to better understand the current environmental changes resulting from the anthropogenic rise in atmospheric CO_2 (e.g., Gastaldo et al., 1996).

We measured lithified raindrop imprints in Permian (so-called Rotliegend) terrestrial mud-sandstone layers from the Flechting High in northern Germany (Fig. 2A, B). The Flechting High trends NW-SE, is 90 km long and exposes Carboniferous to Permian rocks (Ziegler, 1990). It was uplifted from depth of several kilometres (>5 km) in the Late Cretaceous (Otto, 2003; Kley and Voigt, 2008; Fischer et al., 2012) along the SW-ward dipping Haldensleben fault (Schretzenmayr, 1993). The studied outcrop is located at the southwestern margin of the Flechting High (Schwentesius quarry: 52.24015°N, 11.30626°E), close to Bebertal village (Fig. 2A, B).

The sampled Permian sediments were deposited in a rift basin under semi-arid conditions at ~10 to 20°N (e.g., Ziegler et al., 1997). The succession exposed in the Schwentesius quarry is 15 m thick and belongs to the Parchim Formation of the Havel Subgroup (Schneider and Gebhardt, 1993) with a depositional age of ~265 Ma (Fig. 2C) (Menning et al., 2005). Marine intercalations indicate near-sea level (<100 m.a.s.l.) palaeo-elevations (Gast, 1993; Legler et al., 2005). The sampled succession is dominated by medium-grained and minor fine- and coarse-grained sandstones with thin layers of mudstone, mainly deposited under aeolian conditions with alluvial influence (Fig. 3) (Kleditzsch and Kurze, 1993; Irmen, 1999; Fischer et al., 2007). The sedimentary rocks are quartz-rich and derived from Lower to Upper Palaeozoic strata of the proximal Variscan hinterland (e.g., McCann, 1998). The raindrop imprints are concentrated below prominent deflation surfaces and are preserved in small-scale shallow channels, which rapidly dried out leaving behind a fine mud layer with decimetre-scale mud cracks (Figs. 3–5). We measured raindrop imprints on one of these surfaces in fine- to coarse-grained sandstones, which cover the mud cracks. Except for numerous raindrop imprints, we could not find any indices for plant imprints and animal tracks, although there is a high preservation probability (Fig. 5). Therefore lithified raindrop imprints are very likely caused by original sized raindrops fallen with their terminal velocity unaffected by a vegetative canopy.

3. Imprint characteristics

During fieldwork in summer 2013, lithified raindrop imprints were present just on a single layer at the transition from fluvial to aeolian deposits. Imprints are originally formed on a thin mud layer with large mud cracks within coarse-grained sandstone (Figs. 3–5). In the field we identified 453 individual raindrop imprints preserved on a superposed sandstone layer as positive epirelief deposited on a surface with large mud cracks, which most likely belong to the same rain event (Fig. 5A–C). The preserved raindrop imprints are circular or slightly elliptic with well-developed rims (Fig. 5A–C). Imprints are evenly distributed with no preferential occurrence of areas with large or small imprints. The imprint density is ~0.1 imprint per cm^2 and thus overlapping of imprints is rare, implying that the rain event that caused them was of short duration and/or of light to moderate intensity. The