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Using raindrops to constrain past atmospheric density

Lucas Kavanagh[a,b,*], Colin Goldblatt[a]

[a] University of Victoria, Bob Wright Centre, 3800 Finnerty Road, Victoria, British Columbia, V8P 5C2, Canada
[b] McGill University, Adams Building, 3450 University Street, Montreal, Quebec, H3A OE8, Canada

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ABSTRACT

There exists a dearth of constraints on the physical properties of the early Earth atmosphere. The Som palaeopycnometry method estimates an upper limit on ancient atmospheric density based on the size of lithified raindrop imprints preserved in ancient strata, with the assumption that the largest imprint was made by the largest possible raindrop. Using this technique Som et al. (2012) proposed a constraint on Archean atmospheric density of less than 2.3 $kg\,m^{-3}$. Applying this method to modern raindrop imprints, the upper bound on surface density produced is 0.9 $kg\,m^{-3}$, lower than the actual value of 1.2 $kg\,m^{-3}$, refuting the method. We propose several changes to the method, the most important of which is increasing the maximum possible drop size from 6.8 to 10 mm to be consistent with new large datasets of raindrop observations. With these changes, our upper bound on modern surface density becomes 2.7 $kg\,m^{-3}$, a valid limit. The upper bound on Archean atmospheric density is then revised to 11.1 $kg\,m^{-3}$. In general, we find that raindrop imprint size distribution depends much more strongly on rainfall rate than atmospheric density, which translates into large errors. At best, the precision of raindrop palaeopycnometry will be a factor of a few to an order of magnitude.

1. Introduction

The mass of the Archean atmosphere, and hence surface pressure, has generally been regarded as unconstrained. The bulk atmospheric composition of Earth today is 78% di-nitrogen, 21% dioxygen and 1% argon. Previous constraints on Archean atmospheric composition are geochemically based, relating to individual constituents. Oxygen is best constrained; it was only a trace gas during the Archean (e.g. Holland, 1984; Farquhar et al., 2000). Nitrogen may have been up to three times present level, given the size of the bulk silicate Earth nitrogen inventory (Goldblatt et al., 2009). Palaeosol constraints indicate that carbon dioxide was a minor species through the Proterozoic (Sheldon, 2006), but this is presently unconstrained during the Archean; very high levels (tens of bars) are possible in theory, given the size of the oxidized geologic carbon inventory.

Historically, a qualitative physical constraint on the density of atmosphere was proposed by Lyell (1851). He noted that the size distribution of lithified Phanerozoic raindrop imprints was qualitatively similar to modern imprints, implying a similar atmospheric density. Given that carbon dioxide is constrained to be a minor species during the Phanerozoic (e.g. Royer, 2006), the mean molecular weight of the atmosphere would be similar to today's and pressure would thus have been similar.

Recently, Som et al. (2012) proposed a quantitative method to use such raindrop imprints as a palaeopycnometer (measure of past density) and applied this to Neoarchean fossil imprints thought to have formed at sea level. Their method relies solely on the largest preserved raindrop imprint, taken to be caused by some theoretical maximum raindrop size, yielding a hard upper bound on density, or a "likely" largest raindrop, yielding a "likely" upper bound on density. This method uses an empirical transfer function to relate imprint crater diameter to drop momentum and, with an assumed drop size, recovered terminal velocity and hence atmospheric density. The proposed values are a hard upper bound of 2.3 $kg\,m^{-3}$ or a "likely" upper bound of 1.3 $kg\,m^{-3}$, compared to modern mean surface density of 1.2 $kg\,m^{-3}$. For a given atmospheric mass (surface pressure), density depends on temperature and mean molecular weight; assuming modern mean surface temperature and a di-nitrogen bulk composition gives hard and "likely" upper bounds on pressure of 2000 hPa and 1100 hPa, whereas modern sea-level pressure is 1000 hPa. Likely temperature variation gives a 10% uncertainty. A carbon dioxide bulk composition would reduce pressure by a third. The Som method has also been applied to samples of Permian age by Glotzbach and Brandes (2014) who proposed an upper bound on density during that period of 2.3 $kg\,m^{-3}$.

* Corresponding author. Tel.: +1 514 834 4003.
E-mail addresses: lucas.kavanagh@mcgill.ca (L. Kavanagh), czg@uvic.ca (C. Goldblatt).

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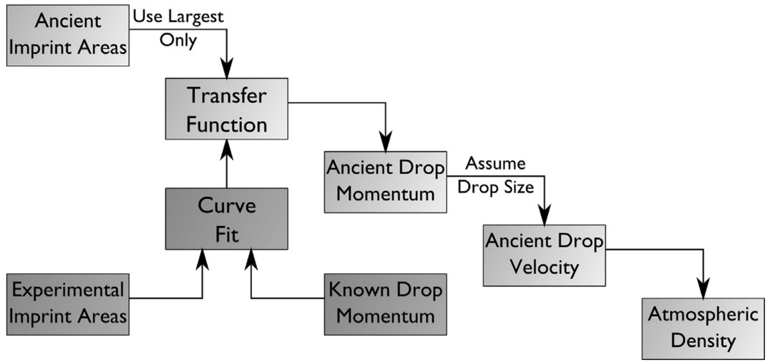

Fig. 1. A flowchart outlining the basics of the Som method. The light gray boxes represent the path that data collected in the field takes, the dark gray boxes represent the calibration of the transfer function.

The purpose of this paper is to critically analyze the quantitative method introduced by Som et al. (2012) and give our resulting re-interpretation of the Archean data. The structure of the paper is as follows: in Section 2, we describe the Som method, in Section 3 we present our analysis of it and propose revisions, in Section 4 we test the original and revised method with modern raindrop imprints, followed by discussion and conclusions.

2. An outline of the Som palaeobarometry method

In order to present a coherent analysis, we begin by reviewing the Som method and the theoretical basis for it. The method (summarized in Fig. 1) is split into two key procedures: an experimental calibration to relate crater area to the momentum of the drop responsible (Fig. 1, orange path) and the procedure for calculating atmospheric density from the drop momentum inferred from preserved raindrop imprint (Fig. 1, green path).

2.1. Theoretical basis

The dominant forces of a falling raindrop are gravity acting downwards and air resistance (drag), acting upwards. When these are balanced, the raindrop has reached terminal velocity. Experimentally, the largest drops reach this after falling for 12 m; smaller drops will achieve this sooner (Gunn and Kinzer, 1949).

A common misconception is that raindrops are shaped like teardrops. High-speed photography by Matthews and Mason (1965) shows the lifecycle of raindrops (Fig. 2). They begin spherical, but soon develop a flat bottom due to air resistance. Deformation continues, causing the drop to inflate and form a parachute of water, supported by a thick rim at its base. This inverted bag continues to grow until the external aerodynamic forces are greater than the surface tension and hydrostatic pressure of the drop. At this point the top breaks and the entire drop shatters into smaller droplets of varying size (Villermaux and Bossa, 2009). A fundamental consequence of this evolution of droplet shape is the existence of a maximum droplet size (Clift et al., 1978), which is relied on heavily in the Som method. We will show later that size of this assumed maximum is of critical importance.

The life of a raindrop ends suddenly when it impacts the substrate below. If the substrate can be deformed easily, the impacting drop will form a crater. The formation of a crater depends upon the mass and velocity of the impacting drop and the properties of the sediment (shear strength, water content and compaction) (Ghadiri, 2004).

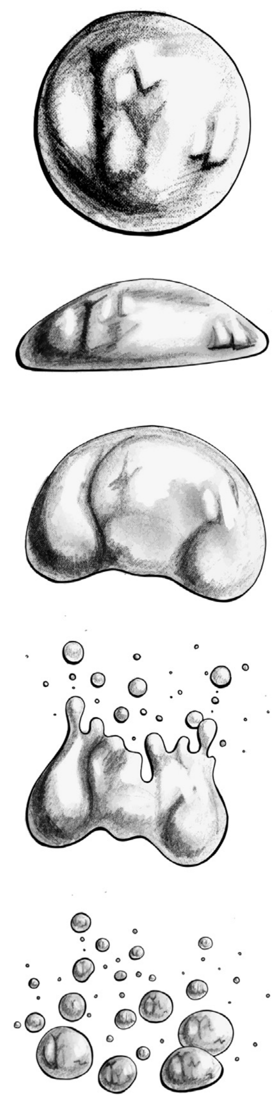

Fig. 2. A series of sketches by Kelsey Hemphill showing the breakup process of raindrops, based on photographs by Villermaux and Bossa (2009).

2.2. Calibration

Som et al. (2012) defined a dimensionless momentum term (J) of falling drops,

$$J = \frac{V_t m_d}{\eta A_d} \tag{1}$$