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Multi-Gyr History of Mars' CO_2-Dominated Atmosphere: New Data and a New Synthesis

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1. Introduction. Changes in Martian atmospheric pressure over time are an important control on Mars' climate evolution. Most constraints for Martian atmospheric pressure over time are indirect. A direct method uses minimum crater size to estimate an upper limit on atmospheric pressure [1,2]. Thin planetary atmospheres allow small objects to reach the surface at high velocities, forming hypervelocity impact craters [3]. This method is useful for constraining atmospheric pressure during deposition/alteration of ancient sedimentary rocks on Mars with evidence for surface liquid water, as demonstrated by [2] for channel deposits in Aeolis Dorsa. However, finding paleopressure estimates for sites of multiple ages gives us better temporal coverage of paleopressure evolution. Here we report paleopressure data for 2 new sites.

2. Integrating New Paleopressure Results. The Mawrth phyllosilicates are the oldest known hydrously altered sedimentary rocks in the Solar System (4-3.8 Ga [4]), and suggest surface temperatures >273K [5]. The phyllosilicates overlie an even more ancient (>4 Gyr) paleosurface [4] with a high density of preserved exhumed ancient craters. This paleosurface may record a signal of changing impactor population over time. Our Meridiani Planum site (~3.8 Ga [7]) features sedimentary units indicative of the presence of surface liquid water during their deposition (e.g. [8]). We use HiRISE orthoimages, anaglyphs, and digital terrain models (DTMs) to identify exhumed ancient craters at our 2 sites and compare the size-frequency distribution of measured crater populations to predictions from an atmosphere- impactor interaction model [9] for atmospheres of different pressures [2]. Assuming pressure to be constant over the duration of crater population accumulation, our new paleopressure limits are <(1.9±0.1) bar at/before 4 Ga (Mawrth paleosurf.), and <(1.5±0.1) bar at ~3.8 Ga (Mawrth Phyllosilicates and Meridiani) (Fig. 1).

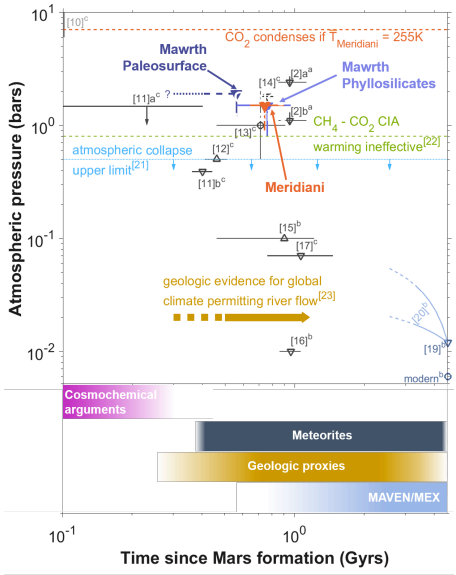

Fig 1 - Updated paleopressure constraints for Mars. Numbers correspond to reference list. Superscripts: a – constraints from exhumed ancient craters, b remote sensing, c - all other methods. [17]c (since superceded by experimental results, see [18]), modern b - annual mean modern atmospheric pressure. Modern MAVEN O loss rates [20]b (assumed all due to CO2) extrapolated backwards in time. Colored bars - approximate temporal extent of methods for constraining paleopressure. Upward/downward facing triangles indicate lower/upper bounds. Circles – estimates of absolute atmospheric pressure/direct measurements.

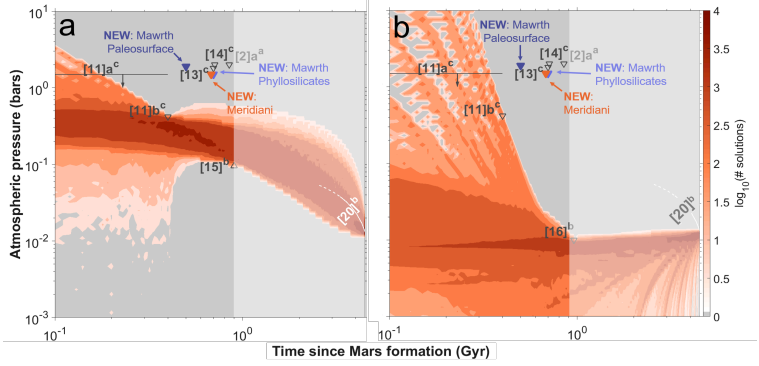

Fig 2- Paleopressure histories allowed by existing data. Solution density plots of pressure histories for 10,000 combinations of k_1–k_4. Grey areas do not match data. log_{10}(# solutions) = all solutions pass through point. a) lowest constraint at~3.8 Ga is 6^b b) 8^b. Constraints as for Fig 1. Washed out region - no paleopressure estimates exist 3.6 Ga - present, solutions not well constrained.

3. Bridging direct measurements, meteorites and modelling: Detailed Mars atmospheric evolution models rely on balancing fluxes from processes such as impact delivery/erosion, outgassing, and loss to space, for which many assumptions are necessary. We used a basic 2-component model starting at present day annual mean atmospheric pressure (including CO_2 in ice caps as estimated from SHARAD data [19][b]) and measured MAVEN/MEX O loss rates [20][b]. Our paleopressure upper limits are 2 points among many others that come from meteorite isotope data [11,12], rover sedimentology [15,16], and modelling results [11,12,13,14,17]. To integrate our results with existing knowledge, we built a basic, 2-component, process-agnostic model for Mars' paleopressure evolution constrained by existing data. We gather sources and sinks into 1 term, expressed as either a powerlaw ($\Delta P_{source/sink} = k_{1/3}t^{(-k_{2/4})}$) or an exponential ($\Delta P_{source/sink} = k_{1/3}\exp(-t/k_{2/4})$) with free parameters k_1, k_2 (sinks), k_3 & k_4 (sources). Parameters $\{k_1, k_2, \ldots k_4\}$ are found using upper limits of existing paleopressure estimates (excluding [12][a], [13][c] & [2][b] – Fig 1) as hard constraints on permitted pressure histories. Our model is sensitive to the lowest implemented pressure constraint ([15][b] or [16][b]; Fig 2). However, most solutions cluster around initial atmospheric pressures <1 bar irrespective of the minimum paleopressure constraint. This is consistent with upper limits on atmospheric pressure from atmospheric evolution models based on ALH84001 isotope data ([11][a]).

4. Climate implications from ~4–3.8 Ga: It is possible for atmospheric pressure to vary on both short and long timescales through atmospheric collapse through condensation into CO_2 ice sheets at pressures <0.5 bar (e.g [21]) and 100 Myr-timescale processes such as outgassing, impact erosion/delivery of volatiles, atmospheric escape to space, and carbonate formation [24]. Additionally, small craters are preferentially obliterated by sedimentation due to their reduced topographic expression, are less likely to be exposed by erosional cuts through a cratered volume [25], and are more likely to be missed in crater counts due to insufficient DTM/anaglyph resolution. It is possible to reproduce our measured CSFDs by modifying CSFDs for time-varying atmospheric pressure to preferentially remove small craters, provided that the minimum atmospheric pressure is less than our upper limits. To reproduce the number of 15.6-22.1m diameter craters at our Meridiani site, a minimum of 50kyrs must be spent at pressures <<0.1 bar. Therefore, our results suggest 3 end-member paleopressure histories from ~4-3.8 Ga (Fig 3). ① Maximum pressure <0.5 bar with episodes of condensation of CO_2 into ice caps, ② pressure persistently below our upper estimates, ③ pressure changes of several bar due to changes in atmospheric sources/sinks.

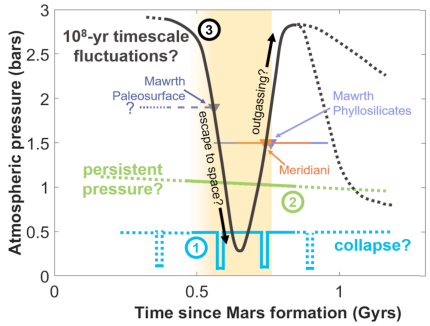

Fig 3 – Schematic illustration of 3 possible end-member cases for Mars' atmospheric pressure history for ~4-3.8 Ga (yellow area). Dotted lines: pressure not directly constrained.

More paleopressure estimates are needed. For example, there are few paleopressure constraints 3.6 to <<1 Ga (Fig 1). More precise chronologies for climate-altering events such as the end of the Martian dynamo and the growth of Tharsis, would constrain the feasibility of scenario #3. Additionally, improved absolute dating of sedimentary deposits would reduce the uncertainty on the ages of our sites and better constrain the intervals in which Mars had rivers.

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