ALIGNMENT OF MARS ELONGATED CRATER AZIMUTHS WITH ORBIT PLANES REPRESENTING PALEO-EQUATORS.

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Introduction: Elongated craters can form from low angle impacts. The distinguishing morphological properties of elongated craters and their ejecta become more pronounced with decreasing impact angle, which allows ease of identification of craters formed by grazing impacts.

Following construction of an updated database of elongated craters on Mars and retrieval, via an ellipse-fitting algorithm, of best-fit parameters describing crater location and orientation [1], we determine the best-fit azimuth of craters and use this to retrieve the inclination of the orbit from which a possible grazing impactor originated.

The inclination of the parent orbit plane for each elongated crater is calculated using the best-fit azimuth and crater latitude. The azimuth for a given elongated crater is interpreted to coincide with the ground-projection of the orbit from which it originated, represented as a great circle at an inclination, *i*. For a fixed rotation axis, the azimuth (measured counter-clockwise from East) and latitude of mapped craters is a function of only the orbit inclination. The relationship is independent of longitude and the position of the ascending node (Figure 1). We exclude craters from our analysis whose state of degradation or geomorphology warranted further investigation before azimuth could be meaningfully retrieved, leaving 191 features from an initial 248 candidates in our database.

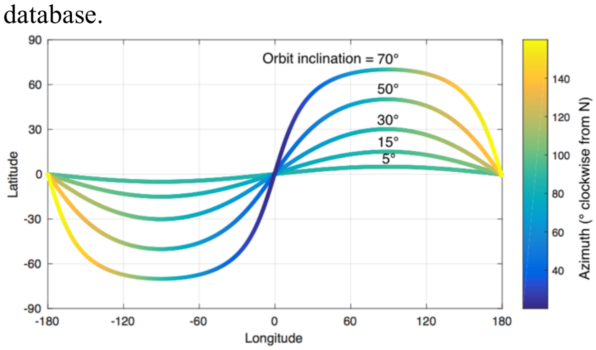

Figure 1: Relationship between orbit inclination, crater azimuth (bidirectional thus limited to the phase < 180 degrees) measured clockwise from north, and latitude. It can be seen that these quantities are not dependent on longitude and thus orbit inclination may be retrieved using only a 2D lookup table of azimuth and latitude.

Errors on azimuth are calculated by sub-sampling from vertices in mapped crater polygons over all permutations down to 50% of the mapped vertices, and calculating the 1-sigma on the distribution of deviations from the best-fit value retrieved using all vertices. The majority of analyzed craters show errors on retrieved azimuths < 0.2°, and all are < 1.8°.

We find that no elongated craters originated from orbits inclined within 10 degrees of the present day equator, but many have azimuths requiring their origin from high inclination orbits (Fig. 2) for Mars' present day rotation pole.

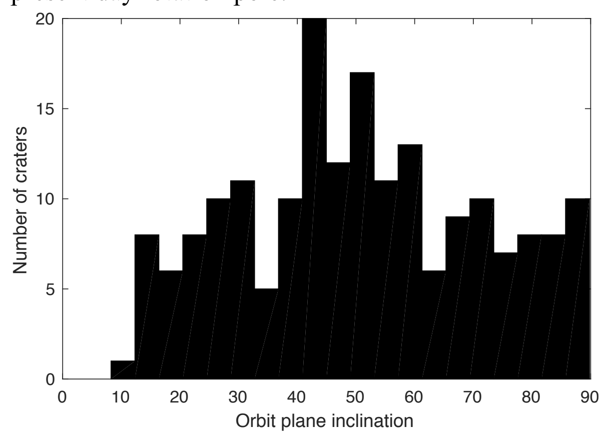

Figure 2: Distribution of retrieved orbit inclination for 191 elongated craters.

Decaying moonlet hypothesis: Moonlets from an equatorial debris disk caused by a giant impact (a mechanism by which Phobos and Deimos may have formed [2, 3]), may have had slowly decaying orbits leading to craters formed at low impact angles (< 5°). The absence of crater morphologies consistent with very low impact angles has been used to argue against the spiraling moonlet hypothesis for the formation of elongated craters [4], but the absence of comprehensive atmospheric entry and impact modelling for decaying moonlets leaves open the possibility that some only moderately elongated craters on Mars were formed by decaying moonlets in a thicker atmosphere. Indeed, the 12.5km spatial separation and apparent 3-3.7Ga age and cogenesis of double-oblique impact craters observed by [5] could be inconsistent with formation by a fast (i.e. non-moonlet) meteorite impactor unless a thicker atmosphere provided drag to increase impact angle during spiraling.

True Polar Wander: To investigate the decaying moonlet hypothesis true polar wander of Mars' rotation axis [6, 7, 8] is expected to be the predominant factor determining whether crater azimuths align with paleo-equators, above which moonlets in a quasi-stable debris disk could gradually decay. While obliquity cycles would indeed modify the relationship between latitude, azimuth and orbit plane inclination, a transient debris disk that lingered for several Ma would be expected to align with Mars' equator throughout obliquity variations. Tharsis formation provoked a shift in Mars' rotation pole [8, 9, 10], which helps explain dependence on longitude of latitude in global distribution of valley networks [7].

Alignment with paleo-equator: To investigate alignment of crater azimuths with paleo-equators, we place the Mars rotation pole at positions in a global geographic grid. For each position (each which produces its own coordinate reference system, CRS) we perform a coordinate transformation for elongated crater geographic parameters into the new CRS then retrieve the corresponding azimuths and orbit inclinations. We calculate the number of elongated craters in our database with orbit inclinations that are within azimuth-error of the paleo-equator for each rotation pole position (Figure 2). We calculate this with tolerances of within 1, 3 and 5 degrees in orbit inclination from the equator.

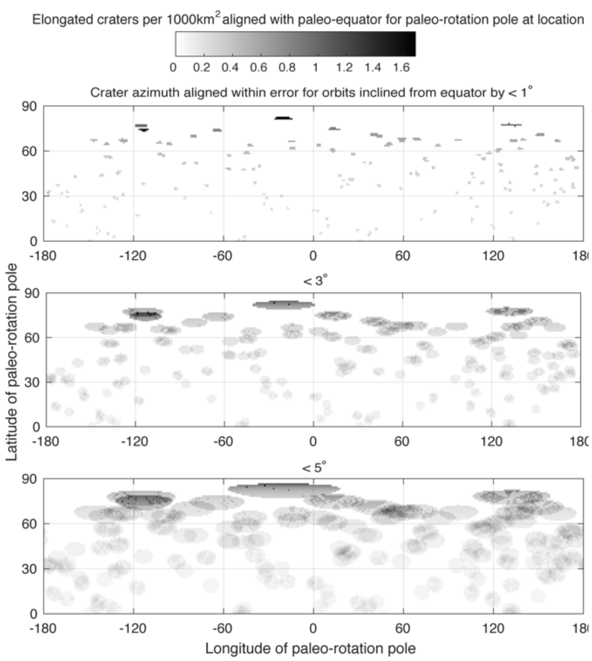

Figure 2: Craters 1000km^{-2} with azimuths originating from orbit planes aligned within 1, 3 and 5 degrees of Mars paleo-equators defined by paleo-rotation poles placed at the latitude and longitude.

Given that results are calculated on a latitude longitude grid, we divide by area per square degree (we use craters 1000km^{-2} for convenience) as a function of latitude to remove the latitude-area bias. This highlights the most likely signatures in the north polar region, around the present day rotation pole.

Discussion: We find several polar areas where Mars rotation pole would have needed to be for our mapped craters to align with its paleo-equator. Preliminary results indicate one notable coincidence; a group of craters that align with a hypothetical paleo-rotation pole located at ~100-130 W°, ~70-75 N°, coincident with the location of a paleo-rotation pole predicted by [7] using the present-day distribution of valley networks.

Further analysis of such correlations, including consideration of elongated crater ages as well the effects of atmospheric drag should yield a clearer picture of whether any groups of elongated craters on Mars originated from a debris disk formed by a giant impact.

References: **[1]** Sefton-Nash et al., (2017) EPSC Abstracts, Vol. 11, EPSC2017-286. **[2]** Rosenblatt, P. et al (2016) *Nature Geoscience* 9, p. 581-583. **[3]** Craddock, R. A. (2011) *Icarus* 211(2), p. 1150-1161. **[4]** Bottke, W. F. et al (2000) *Icarus* 145, p. 108—121. **[5**] Chappelow, J. E., and Herrick, R. R. Icarus 197 (2008) 452–457. **[6]** Schultz and Lutz (1988), *Icarus* 73, p. 91-141. **[7]** Bouley, S. et al. (2016), *Nature* 531, p. 344-347. **[8]** Keane, J. T. and Matsuyama, I. (2017) EPSC Abstracts, Vol. 11, EPSC2017-415. **[9]** Matsuyama, I. and M. Manga., *J. Geophys. Res.* 115 (2010), E12020. **[10]** Sprenke, K. F. et al. (2005), *Icarus*, 174, 486–489.