SEDIMENT COMPACTION ON MARS AND ITS EFFECT ON LAYER ORIENTATION.

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Introduction: Compaction, or the progressive loss of porosity of a loaded sediment, influences many geological phenomena such as fluid flow, diagenesis and faulting. Quantifying the effect of compaction is thus essential to understanding the history of a sedimentary basin. For example, [1] argue that compaction may account for layer tilting in the sediment mount in Gale crater (154 km diameter, 5.4S°S, 137.8°E). Determining the cause of the layer tilting may be important in reconstructing paleofluvial processes in Gale. Here, we model the compaction of sediment infill in Gale and Gunjur (27 km diameter, 0.2°S, 146.7°E) and compare its effects on layer orientation to measured layer dips and faulting.

Data: The Gunjur data is in the form of 120 radial depth profiles measured from a CTX DTM. The Gale layer dip measurements were produced by layer tracing on eight HiRISE DTMs. The first six came from [2]; the other two were traced by Jonathan Sneed in 2015. Contra [1], outward dips at Gale have been independently confirmed (e.g., [3-5]).

Method: To determine the effect of compaction on sediment thickness, we make the following assumptions:

(1) present-day compaction represents maximum pressure during sediment's lifetime (no rebound after erosion)

(2) porosity decays exponentially with depth [6], taking the form $\phi = \phi_0 \times e^{-cz}$ with ϕ_0 and c values taken from [7] and [8] and adjusted for Martian gravity ($c_{Mars} = c_{Earth} \div 9.81 \times 3.71$).

Lithology	Sand	Shale [7]	Shale [8]
c_{Mars} (m^{-1})	0.1021	0.1929	0.3139
ϕ_0	0.49	0.63	0.70

Table 1. Compaction parameters used for calculations

(3) height is uniquely determined by porosity.

(4) the basal surface is noncompactible (e.g., basalt).

To find the original height of a compacted sediment column, we integrate porosity over z, which gives us:

$$z_{uncompacted} = \frac{z + \frac{\phi_0}{c} \times (e^{-cz} - 1)}{1 - \phi_0}$$

To obtain the compacted height of a sediment column, we use simple numeric iteration to converge towards the height that would produce the original column height upon decompaction.

Two adjacent columns of different thicknesses will compact to different extents, and the resulting slope naturally translates to layer tilting.

Gunjur crater. In the case of Gunjur crater, we focus on determining whether compaction-induced subsidence could cause concentric faulting around the crater rim and peak. To do this, we calculate sediment thickness and compaction along the radial profiles and interpolate a grid in order to create a horizontal gradient map, which we then compare with the geomorphological map of the basin.

Gale layer orientation. For Gale, we evaluate the hypothesis of [1] in 1D: we study the effect of compaction on layer tilting in a cross-section from the peak to the rim of the crater, assuming axisymmetry. We examine the effect of different grain lithology as well as different basal surface shape. The possible basal surfaces are taken from pristine Martian craters, scaled appropriately using formulas from [9], as well as a section of Gale itself taken from its southern side, where we assume either little sedimentation or near-total erosion has occurred.

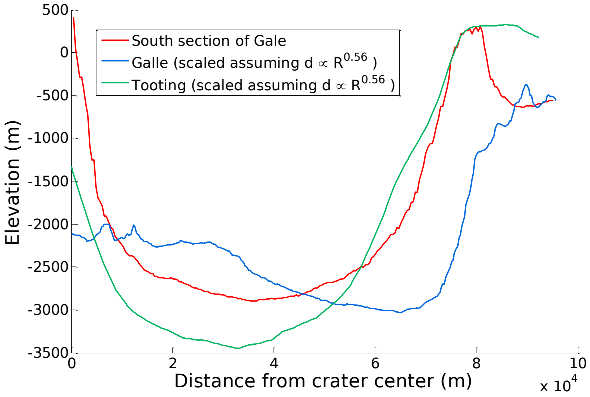

Fig. 1. Basal surface comparison with scaling parameters from [9].

We try multiple possibilities for the shape of the infill, using Chebyshev polynomials [10] to model its surface. Our model is restricted to even-degree polynomials up to degree 4.

We then calculate the layer dips produced in the measurement locations for all plausible values of $\{k_0, k_2, k_4\}$ and the mean square error between the calculated and measured layer dips, which have been projected on the radial axis. The lowest mean square errors occur for extraordinarily large sediment thicknesses. Therefore, we have focused on reducing the thickness of the sediment infill rather than the mean square error on the dip. The radial projection means that any azimuthal variation in the geological processes causing the dipping is not taken into account, but instead introduces further error to the data. Perfect agreement is thus not to be expected.

Results and discussion: At Gunjur, gradients in compaction are maximal near the outer edge of the sediment fill and near the central peak, consistent with the locations of observed circumferential graben. The next step is to compare the strains predicted by the compaction model with graben offsets measured from HiRISE DTMs.

The Chebyshev modeling of the infill in Gale produces a variety of results. We find a smaller error with Galle as a basal surface as opposed to Tooting or the southern part of Gale itself; most likely this is due to its slight outward slope, as the measured dips are also directed outwards. This is consistent with the theory that Gale, like Galle, contains a central ring which is concealed within Mount Sharp [11].

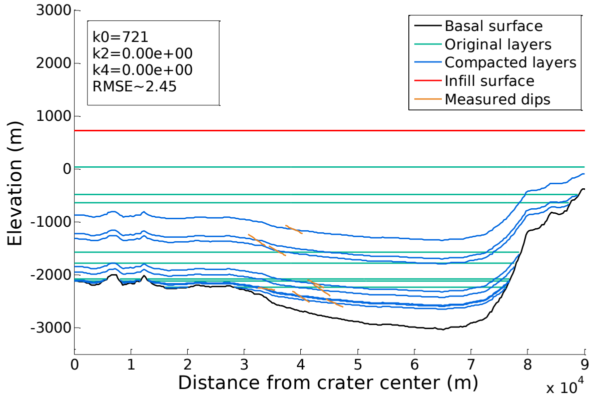

Fig. 2. Gale best-fit scenario with flat infill, using shale lithology and Galle as basal surface.

We can see in Fig. 2 that due to the near-horizontality of the basal surface, a flat sediment infill will not cause significant layer tilting in the locations where it has been measured. This disparity is slightly mitigated by the tilt of the basal surface itself in the case of Galle, but not sufficiently.

Generating a more rugged infill surface gives far more promising results. A model with only a nonzero k_2 (thick around the rim, thins out towards crater peak) is geologically easier to explain with a sediment source located outside the crater rim, but a sediment load of dozens of kilometers is not physically plausible. However, an infill modeled with k_2 and k_4 is reduced to a more realistic thickness towards the rim (see Fig. 3).

It is more difficult to find a formative geological process for the torus shape generated in this case. However, ‘lumpy’ sediment mounds do occur, for example in Nicholson crater, which may be explained by aeolian processes [12].

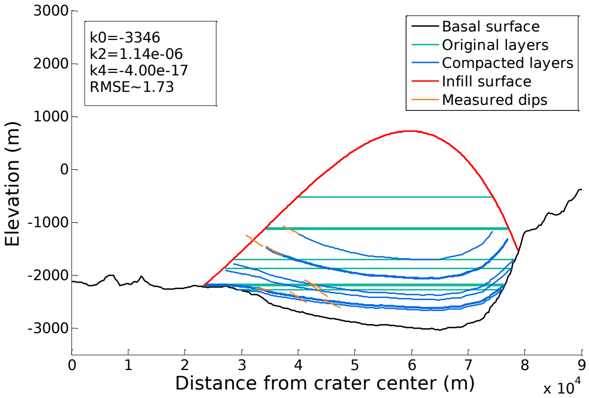

Fig. 3. Gale best-fit scenario with convex infill determined by 4th-degree Chebyshev polynomial, using shale lithology and Galle as basal surface.

Shale produces the lowest MSE and smallest sediment thickness [7,8].

In summary, compaction in Gale can only produce the observed outward sign of layer tilting if the basal surface has a central ring, or if the sediment load is torus-shaped and extraordinarily thick (dozens of kilometers). Excluding extraordinarily thick paleo-sediment thicknesses, compaction in Gale can approximately match the measured tilt if (i) the basal surface is shaped like a central ring, (ii) the infill compacted like shale, (iii) the sediment load was torus-shaped.

Continued exploration of the Gale sediment mound, and identification of fluvial paleoflow directions, will allow us to conclude more decisively on whether the dips are driven by compaction: if previously horizontal layers are tilted due to sediment subsidence, fluvial deposits directed "uphill" on modern topography are likely.

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