FORMATION OF INVERTED FLUVIAL DEPOSITS ON EARTH AND MARS. A. T. Hayden[1], M. P. Lamb[1], W. W. Fischer[1], R. C. Ewing[2], B. J. McElroy[3], [1]California Institute of Technology, Pasadena, CA 91125, [2]Texas A&M University, College Station, TX 77843, [3]University of Wyoming, Laramie, WY 82071. (ahayden@caltech.edu)

Introduction: Sinuous topographic ridges are common geomorphic features on Mars and are commonly interpreted as exhumed sedimentary deposits of river channels (i.e., inverted channels). They are useful for quantifying ancient martian surface hydrology due to their 1) detectability from orbit; 2) presence in areas lacking valley networks [1]; 3) locally high areal [2] and stratigraphic density [3] and range of morphologies [4, 5], especially in the Aeolis Dorsa region; and 4) presence in five of nine remaining potential landing sites for Mars 2020 (Eberswalde Crater, Holden Crater, Jezero Crater, Melas Chasma, Mawrth Valles) and two of three for ExoMars (Mawrth Valles, Aram Dorsa). However, reconstructing paleoenvironment and paleohydrology from ridge geometry is not straightforward and reconstructions of parameters as fundamental as flow direction can be unclear, as at a large branching ridge network in Aeolis Dorsa where modern slope and planform morphology indicate opposite flows [6, 7] (Fig. 1A,B). Terrestrial analogues have broadly aided interpretation (e.g., [8-10]), but we still lack well accepted methods for paleo-hydraulic reconstructions from ridge geometries.

Hypotheses: We investigated two hypotheses for ridge formation by studying the sedimentology and morphology of inverted channels in Jurassic (Morrison Fm.) and Cretaceous (Cedar Mountain Fm.) outcrops in Utah, and in Aeolis Dorsa on Mars. We evaluated a *topographic inversion hypothesis*, in which ridge and ridge network geometry accurately reflect paleo-river channel and network geometry [11, 12], and a *deposit inversion hypothesis*, in which ridges represent fluvial channel-belt deposits with geometries differing significantly from the parent river channels [7]. The deposit inversion hypothesis predicts 1) vertical and lateral channel aggradation; 2) ridge intersections (Fig. 1) at distinct stratigraphic levels; 3) deposition over significant amounts of time; and 4) ridge dimensions exceeding paleochannel dimensions. The topographic inversion hypothesis predicts absence of each trait.

Methods: We recorded 34 stratigraphic sections and measured ridge geometry on 19 ridges at our 4 field sites (38.87, -110.20; 38.56, -110.85; 39.135,-110.925; 39.125,-110.917).

Sedimentology: Sandstone and conglomerate units were described by median grain diameter (D_{50}) and cross-bedding style and thickness while mudstone units were described by color, grain size, and carbonate nodule abundance. To reconstruct paleoflow directions we measured dip directions for dune and ripple cross-sets, and for bankfull paleoflow depths (d) we measured height of dune sets ($d = 9\ h_{duneset}$) and complete bar sets ($d = h_{barset}$).

Remote sensing: We measured caprock thickness, breadth, and relief of the ridges manually from a combination of publicly available data (1 m/px air photos and 5 m/px DEMs available online from the Utah Geologic Survey; 0.5 m/px imagery in Google Earth), and UAV air photos and DEMs (<20 cm/px) reconstructed from photogrammetry performed on the UAV photos in Agisoft PhotoScan.

Paleohyhdraulic reconstructions: We used classic empirical relationships from measured grain size and reconstructed depth to reconstruct paleochannel width, slope, flow velocity, and discharge. Channel width (w) was related to depth and median grain diameter [13]. Slope (s) was found by relating bankfull Shields stress τ^* to particle Reynolds Number [14]. Flow velocity (u) was found by its relationship with bed shear velocity (u^*) and a friction factor (C_f) [15]. Conservation of mass then gave the discharge $Q=whu$. We compared these reconstructions to a paleohydraulic reconstruction using the ridge geometry following the common topographic inversion model by assuming that caprock breadth, thickness, and slope are equal to the paleochannel width, depth and slope [e.g., 5, 10].

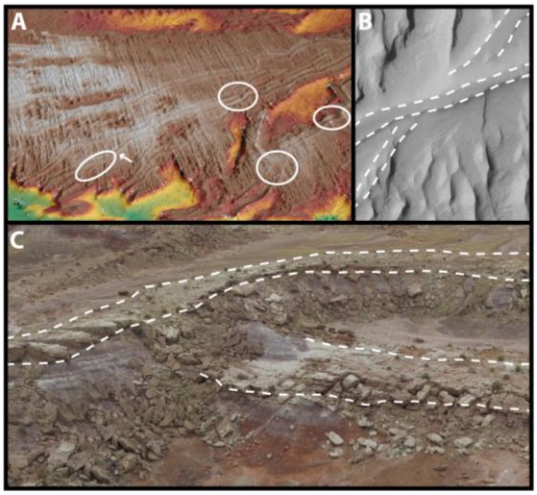

Fig. 1: Ridges in all images ~50 meters wide. A) Branching ridge network in Aeolis Dorsa (151.5E, 6.0S; CTX: P03_002279_1737_XI_06S208W) where slopes indicate a tributary network (white = high elevation, green = low), morphology indicates distributary; circles indicate ridge intersections. B) Ridge intersection at distinct stratigraphic levels; ridges outlined; location by arrow in (A) (HiRISE: PSP_002279_1735). C) Ferron Creek South field site with ridge intersection at separate stratigraphic levels.

Results: *1. Ridges were capped by thick (5-15m), narrow (<100m), multi-storied sandstones and conglomerates.* Caprocks comprised sandstone and conglomerate with abundant dune- and bar-scale cross-stratification indicative of fluvial channel aggradation and lateral migration. Similar bodies with smaller thickness and breadth did not form caprocks. Material below caprocks was largely carbonate-nodule-rich mudstone with a few thin sheets of fine sandstone—interpreted as soil and floodplain river sediments.

2. Ridges intersect at distinct stratigraphic levels. Most ridge intersections identified in satellite imagery were found in the field to be intersections of caprocks at distinct stratigraphic levels (e.g., Fig. 1C).

3. Deposits developed over thousands to millions of years. Quantitative time constraints were taken from the Ruby Ranch Member. Consistent with previous studies, we identified abundant carbonate nodules and paleosols indicating individual paleosurfaces were broadly stable for at least 10 k.y. [16]. A maximum depositional time of 5 M.y. is taken by differencing ash dates bounding the Ruby Ranch Member [16, 17], which exhibits inverted channels throughout its full thickness at the Green River site (38.87, -110.2).

4. Ridge dimensions exceed paleochannel dimensions. Ridge breadth and thickness exceed paleochannel width and depth, in most cases by a factor of 2-5. Ridge slopes are greatly modified such that even if local stratal dips are removed, the downhill direction of many ridges is opposite the paleoflow direction; therefore magnitudes of ridge slope, which are found to all vary from 2-150 times larger than paleochannel slope, are unreliable. See figure 2.

5. Modern erosion degrades caprock breadth quickly through cliff retreat. Absent this rapid erosion, ridge breadth would exceed paleochannel width by a larger factor. Thickness does not degrade significantly.

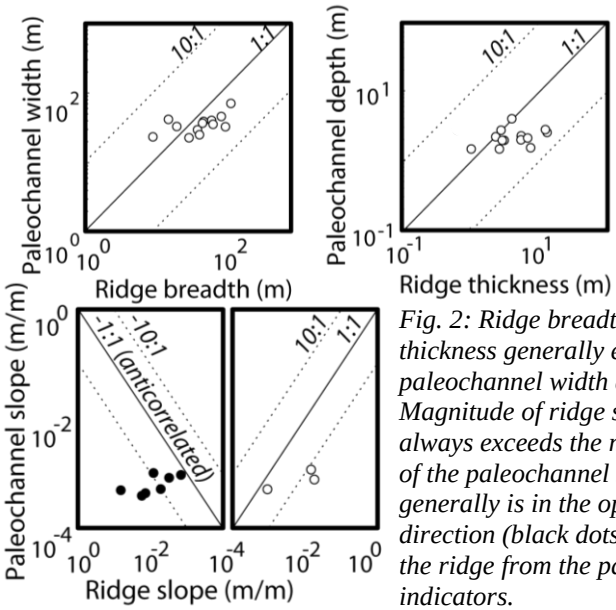

Fig. 2: Ridge breadth and thickness generally exceed paleochannel width and depth. Magnitude of ridge slope always exceeds the magnitude of the paleochannel slope, and generally is in the opposite direction (black dots) along the ridge from the paleoflow indicators.

Conclusions and Mars implications: The studied ridges meet all predictions of the deposit inversion hypothesis, including evidence of aggradation over significant time and ridge dimensions exceeding paleochannel dimensions. Most notably, discharges reconstructed from ridge geometry overestimate paleochannel reconstructions by a factor of 30-1,700. Evidence of sediment deposition over 10 k.y. – 5 M.y. indicates long durations of fluvial activity, rather than preservation of a single geomorphic surface.

Applying the findings to Mars, we predict that modern slopes are unreliable indicators of paleoflow directions due to denudation and tectonic influence (e.g., Fig. 1A). Second, we find ridge intersections at distinct stratigraphic levels, as predicted by deposit inversion (Fig. 1B). Third, existing reconstructions of paleochannel dimensions and discharge are potentially overestimated by several orders of magnitude. Fourth, inverted channels formed by deposit inversion represent significant durations of fluvial activity, especially when present in thick stratigraphic sections like the ≥400 meters preserved in Aeolis Dorsa [3]. Finally, discerning topographic versus deposit inversion is an important step in accurate paleohydraulic reconstruction from ridge geometry. Developing a reliable test for this distinction is key. In absence of such a test, assuming topographic inversion yields a maximum estimate of paleodischarge and a minimum estimate of duration of fluvial activity.

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