Discussion by Jonathan Laronne

A variety of evidence has been available during the past decade that water was available on Mars, with even more convincing confirmation from the very recent months that at select locations it presently runs on the surface. Your paper is also based on several types of evidence, the most crucial is one of relatively close-up and very interesting photographs (Figures 28.2a–d) of a rock formation that has an obvious granular makeup and an appearance of a clastic deposit. In this photograph the particles are only slightly rounded, hence restating your words, if a meander is a meander, is this sufficiently convincing to ensure that it is fluvial gravel?

Discussion by Gordon Grant

Have you looked at the Froude numbers for your Martian rivers, not in a deterministic way, but as a check on your flow estimates? I would be suspicious, for example, if your results suggested supercritical flow where your channel dimensions are at least reasonably constrained.

Discussion by Mike Miles and Colin Thorne

Chinn and Mason (2015) summarize long-term hydrology data for the Onyx River, Antarctica – see our discussion of Session 16, Shaw and Healy (1980), and Head and Marchant (2014). Our analysis of these data indicates the 2-year return period daily and instantaneous flows (taken as representing bankfull discharge) are 2 and 3 m^3/s, respectively. Measurements on GoogleEarth indicate bankfull widths (in single-thread reaches) varying between 6 and 13 m. Figure 28.10 suggests that bankfull discharge in the Onyx River should be larger, ranging between 4 and 14 m^3/s. As Antarctic stream banks lack vegetation, which is known to result in wider channels when other bank properties are held constant, this is not unexpected.

This cursory analysis suggests that the hydraulic geometry relationships for unvegetated, high-latitude streams should be further investigated as possible analogues for ancient Martian streams and the effects of ice-rich permafrost on streambank stability (Church and Miles, 1982) and channel geometry should be better defined. Perhaps we should arrange a joint field trip to some polar streams (though probably on Earth rather than Mars!)?

References

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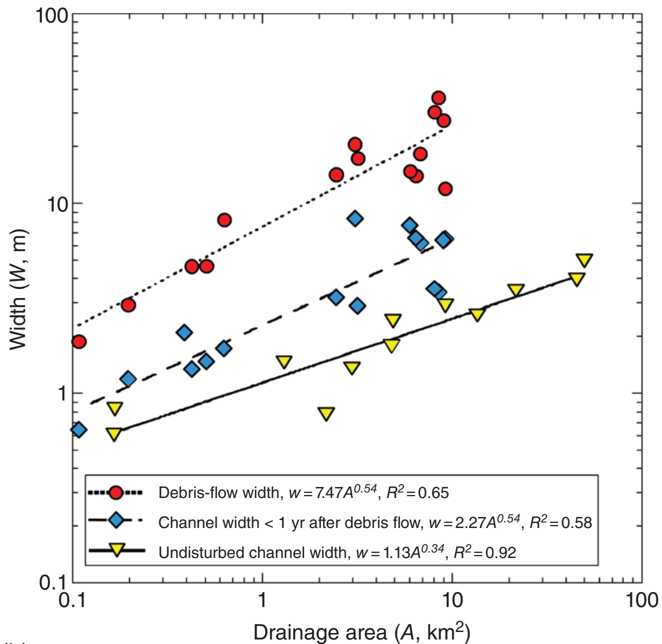
Discussion by John Buffington

Hydraulic geometry offers robust scaling of channels across many orders of magnitude in natural rivers, irrigation canals, and laboratory channels (Ferguson 1986). Although the authors' analysis focuses

(a)



(b)

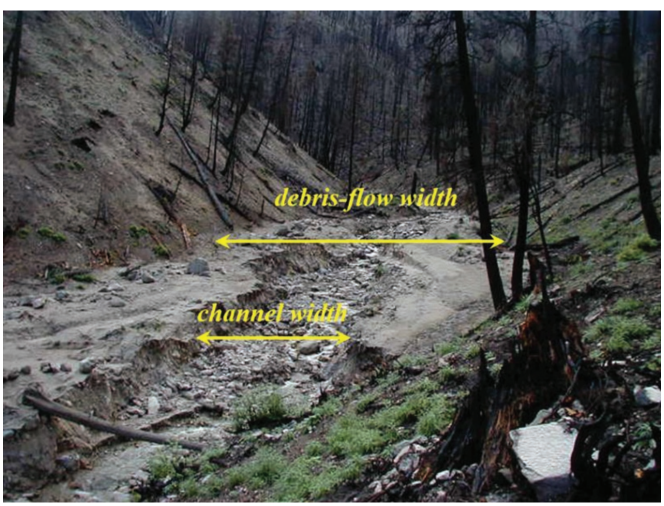


Figure 28.15 (a) Width as a function of drainage area for (i) post-fire debris flows (circles), (ii) channels carved into the debris-flow deposits via a mixture of hyperconcentrated and fluvial flows within the first year following disturbance (diamonds), and (iii) undisturbed fluvial channels in neighboring basins (inverted triangles). The study sites are mountain streams in confined, alluvial valleys (plane-bed, step-pool, and cascade morphologies, with gravel to boulder beds, and channel slopes > 1%) in the upper Boise River, central Idaho, USA. Debris flows were triggered by intense thunderstorms on bare, hydrophobic soils following fire. Subsequent thunderstorm and snowmelt runoff incised channels into the debris-flow deposits via hyperconcentrated and fluvial flows for bare, unvegetated banks. Undisturbed channels are produced by predominantly snowmelt runoff, with banks well-vegetated by shrubs and conifers, resulting in smaller channel widths for a given drainage area. (b) Photograph illustrating debris-flow width and width of channel subsequently carved into the debris-flow deposit.

on fluvial deposits, it is worth noting that hydraulic geometry relations can be developed for a variety of fluids, which may have relevance for some Martian channels given that differences in gravity and atmospheric conditions (pressure, temperature, and, thus, viscosity) may cause channel hydraulics and flow rheology (Froude and Reynolds numbers) to differ from those on Earth. Data from mountain rivers in Idaho provide an example of how channel width responds to differences in erosional processes, flow rheology, runoff characteristics, and degree of riparian vegetation within a given physiographic region (similar topography, geology, and climate) following fire disturbance (Figure 28.15). In all cases, the exponent of the hydraulic geometry equation is within the range typically observed for terrestrial alluvial and bedrock rivers (0.3–0.6; Montgomery and Gran 2001; Wohl 2004) but systematic differences in width are evident. The debris-flow widths are event-based responses and the post-debris-flow channel widths are transient responses following disturbance, both of which differ from the long-term bankfull conditions examined by the authors, but they nonetheless provide some sense of scaling for different formative processes across a range of rheological and environmental conditions.

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Reply by the Authors

The discussions touch on three important issues in the paper. (i) Are gravel deposits observed during the *Curiosity* mission convincingly of fluvial origin? (ii) Are the derived hydraulic expressions sensible, and, specifically, do they predict flows to be subcritical rather than supercritical in most circumstances? (iii) What is the significance of the specific power law relationship of bankfull discharge versus bankfull width (Equation (28.21)) and what processes might influence the relationship on Mars?

Jonathan Laronne comments that the gravels visible in our figures appear to be only slightly rounded and might this challenge the interpretation of their fluvial origin. For the outcrops shown in Figure 28.2 (and a nearby exposure), Williams *et al.* (2014) measured 535 gravels and concluded that the majority of the pebbles are subrounded to rounded (based on the qualitative Powers' roundness indices). Yingst *et al.* (2013) demonstrated that roundness measured at the outcrops shown in our Figure 28.2 was much greater than that found in previous missions on Mars. Williams *et al.* (2014) suggested the rounding required a minimum of several kilometers of transport, but was likely more given the reduced abrasion rates of less intense collisions of bedload transport on Mars. Szabo *et al.* (2015) employ other measures to document rounding of gravels observed by the *Curiosity* rover and conclude that rounding due to fluvial transport likely developed over distances of tens of kilometers by fluvial processes. Grotzinger *et al.* (2015) provide outcrop description, placing conglomerates in a fluvial deltaic system propagating from Gale Crater wall towards the center of the crater. Collectively these analyses argue strongly that these are fluvially transported gravels.

Gordon Grant suggests we review the Froude number implications of our derived hydraulic relationships, with the expectation that if the calculations predict falsely supercritical conditions it should be a concern. We calculated the Froude number by using Equations (28.12) and (28.8) (which are based on a threshold shear stress concept) and compared that to the Froude number *Fr* calculated from the observed bankfull velocity and depth values reported in Li *et al.* (2014). The regression yielded $Fr_{observed} = 0.97\ Fr_{\mathrm{predicted}} + 0.02$, so a close comparison, but with considerable variance yielding only an R^2 of 0.38. None of the predictions exceeded a *Fr* number of 1.0 and only four of the observed values did. The *Fr* values calculated from Equations (28.17) and (28.15), expressions that use an empirical relationship for the bankfull shear velocity, showed essentially no correlation with observed *Fr* and predicted 24 of the rivers would have supercritical flows at bankfull. Hence, the performance is poorer but does not excessively overpredict supercritical conditions. The *Fr* derived from Equations (28.12) and (28.8) is independent of gravity (the gravity term in the velocity expression cancels the gravity term in the *Fr*) and thus the incidence of supercritical flow is not expected to be higher on Mars. The *Fr* derived from the empirical shear velocity relationship indicates that *Fr* is also only weakly dependent on gravity.

Colin Thorne and Mike Miles ask why the exponent in the plot of bankfull discharge versus bankfull width is not closer to the inverse of the common exponent of 0.5 when width is plotted against discharge. The least squares approach used in regressions typically leads to exponents that are not the inverse of each other when the variables are reversed. Also, many have reported discharge–width relationships in regional surveys, and Wharton (1995) summarized findings in his table 1. His value of 1.97 for British rivers is an exception. For the nine large data sets from western US rivers used in analyses by Osterkamp and Hedman (1977; cited in Wharton 1995), the exponents for the nine studies ranged from 1.4 to 1.97, but with six lying between 1.60 and 1.71, i.e. very similar to values reported in Equations 28.19 through 28.21. Many factors influence channel width, which Osterkamp and Hedman (1997), for example, explicitly explore empirically, and as John Buffington illustrates in his discussion of this paper. Our approach was to combine two recent data summaries with additional data from sources not included in these two summaries that represented smaller, steeper, and coarser bedded rivers. The data are all based on field measurements, including bankfull discharge. The streambed material ranged from sand to boulders and we purposely sought a wide range of conditions given the large uncertainty of Martian conditions. The data field is biased towards US rivers and to channels between 2 and 100 m wide. The largest rivers are lowland tropical sand-bedded rivers. The slope of the correlation reported in Figure 28.10 with a 95% confidence interval is 1.66 ± 0.04. Note that for the largest channel widths the data density is smaller and the range about the regression is about a factor of two. For the high data density the range about the regression is about 10. The width range for a given discharge is much less. The data from small Antarctic streams reported by Miles and Thorne fall within the data field shown in Figure 28.10. The range of variance of data, assuming measurements are accurate, reflect the varying factors that influence channel width for a given discharge, e.g., bank strength, sediment supply, bed grain size, flow dynamics, and process dominance. A conservative application of Equation 28.21 to Mars would be to assume that for a given calculated discharge the range could be a factor of ten larger or smaller. Despite this large uncertainty, such data provide key hydroclimatological information of the history of Mars.

Reference

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