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PLANETARY SCIENCE

Pebbles on Mars

Douglas J. Jerolmack

Mars is a cold, dry place. Yet there is abundant evidence that fluvial (river) processes have carved the planet's surface; witness deep canyons, streamlined islands, and drainage networks. Most of these features formed more than 3 billion years ago, and a long line of research has led to the “warm and wet early Mars” hypothesis. The idea is that early Mars had a thicker atmosphere with an enhanced greenhouse effect that allowed stable liquid water and a hydrologic cycle to exist (1). The search for life on Mars, or at least conditions suitable for life, is predicated on this idea. Until now, no observations have unambiguously identified and characterized river-lain sediments, although the Mars Exploration Rovers turned up some evidence of a watery past (2). As the first major finding from the Mars Science Laboratory mission and its car-sized rover, Curiosity, Williams *et al.* (3) report on page

1068 of this issue the discovery of conglomerates on Mars—pebbles mixed with sand and turned to rock—resulting from ancient river deposits. The finding provides the clearest view yet on the nature of early martian rivers and should provide momentum for Curiosity's mission moving forward.

The most striking fluvial features on Mars are huge canyons (>1000 km long) eroded into bedrock. They have been associated with catastrophic outburst floods (1), but how large these floods were is hard to say; imagine trying to estimate the discharge of the Colorado River from the size of the Grand Canyon. Thus, we must look elsewhere to constrain ancient flows on Mars. All eroded channel material must be deposited somewhere. On Earth, river deltas and alluvial fans (collectively “fans”) form at the mouths of rivers debouching into oceans and basins, respectively. Their deposits consist of stacked river channels and floodplains whose history can be read by the trained eye. Until a decade ago, however, no such features had ever been observed on Mars. [One likely culprit for this absence of evidence is aeolian (wind) processes, which have had more than

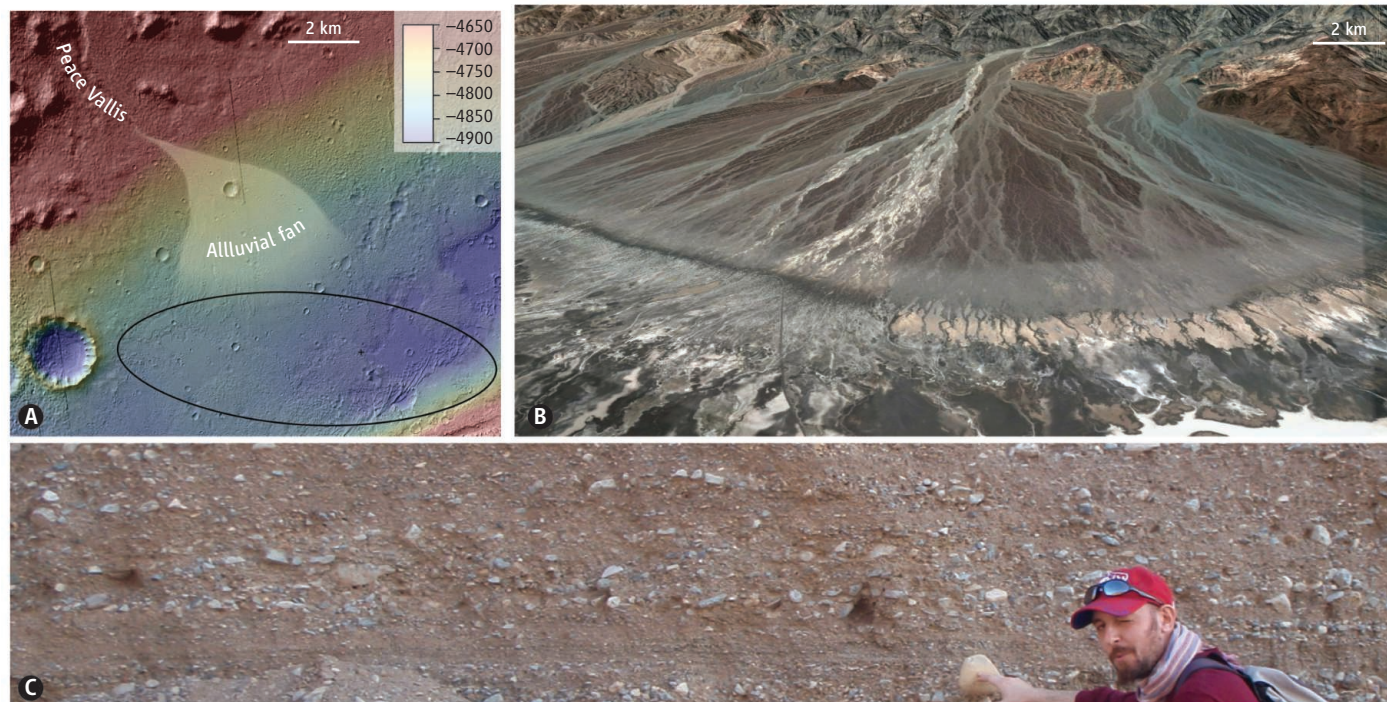
The observation of conglomerates by the Mars rover Curiosity provides the most definitive proof yet of ancient river flow.

3 billion years to erode or bury early martian fluvial features.]

The discovery from satellite images of the first putative river delta on Mars in 2003 (4) marked a turning point. The beautifully preserved depositional channels made it possible to measure the width, depth, and slope of the ancient river. Discharge estimates were rather pedestrian, comparable to medium-sized rivers on Earth (5, 6). This discovery was hailed as a smoking gun for the warm and wet early Mars hypothesis, and focused searching with better imagery has turned up dozens of fans (7). However, it has been pointed out that such deposits could form in decades and may have resulted from impulsive heating (e.g., crater formation or volcanic intrusions) rather than a globally warmer planet (6, 8).

Until now, the sediments composing martian fans were unknown, leaving some room for doubt regarding their formative processes. Curiosity was sent to Gale crater to explore the promising mountain of stacked sedimentary deposits at its center, informally called Mount Sharp and thought to be of lacustrine and fluvial origin (9). The conglomerates dis-

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Alluvial fans and associated deposits. (A) Topographic map draped on images showing the landing ellipse (oval) and landing site (cross) of Curiosity in Gale crater, Mars. (B) Google Earth perspective view of an alluvial fan in the Mojave

Desert, USA. (C) Alluvial fan deposits exposed in a river bank in New Mexico. Note the alternating gravel and sand sheets, similar to those described at Gale crater by Williams *et al.*

covered by Williams *et al.* lie on a relatively flat crater floor, several kilometers downslope from the eroded terminus of an alluvial fan (see the figure). The deposits are estimated to be older than 3.5 billion years. The rounded pebbles, mixed in alternating layers with sand-sized particles, are indicative of a free-flowing gravel stream. Additional support comes from the observation of imbricated clasts, pebbles arranged like a train of collapsed dominoes, which are strictly associated with fluvial transport.

On Earth such deposits are a common feature; the finding is a breakthrough for Mars, however, because (i) it is the first definitive in situ identification of river sediments; (ii) the rounding of the pebbles indicates abrasion during transport, suggesting that particles traveled at least several kilometers from their source area; and (iii) it allows quantitative reconstruction of ancient flows. Under reasonable assumptions associated with near-threshold fluvial transport, the formative river flow had depths in the range 0.03 to 0.9 m and velocities in the range 0.2 to 0.75 m/s. The main uncertainty is associated with river slope, which cannot be obtained directly from the deposits.

Williams *et al.* are conservative in their interpretation, but the nature of the sediments and their proximity to the fan terminus are consistent with deposition on an

alluvial fan. Noncohesive gravel streams on Earth typically exhibit critical flow, where fluid inertial and gravitational forces approximately balance (10), and dimensionless shear stresses are slightly in excess of the threshold of motion (11). A friction factor typical of gravel streams (0.01) would result in a slope of 1%, the same value as the adjacent alluvial fan. Corresponding flow depth and velocity would be 0.1 m and 0.6 m/s, respectively.

The finding of Williams *et al.* shows that martian rivers can be similar to terrestrial ones, all the way down to the grain scale; this suggests a depositional environment similar to the distal regions of typical alluvial fans observed in the American Southwest (12). As the authors point out, climate conditions must have been appreciably warmer and wetter at the time of sediment transport relative to modern conditions. Whether sediments were laid down over a long time in an arid region with intermittent rain (as in terrestrial deserts) or deposited more rapidly under a sustained outflow cannot be determined. Meanwhile, fresh challenges to the warm and wet early Mars hypothesis are emerging. Some point to new physical and chemical evidence that supports a cold and dry early Mars interrupted by brief bursts of wetness (13, 14); other recent work (15) suggests that Mount Sharp itself is composed primarily of aeolian rather than water-lain strata.

Skepticism about the warm and wet early Mars hypothesis will continue. This debate is healthy, however, and has encouraged formation of clear hypotheses and targeted missions. Our understanding of Earth's present and past climate comes from observations of the surface and subsurface across the globe, coupled with sophisticated modeling. It is becoming clear that the landscapes on Mars are almost as varied and complex as those on Earth. Thus, there is unlikely to be a smoking gun for a warm and wet early Mars. Rather, the case will be built from circumstantial evidence accumulated over decades of lander and satellite missions. Onward, Curiosity!

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CELL BIOLOGY

GATORs Take a Bite Out of mTOR

Reuben J. Shaw

Coupling nutrient availability to cellular growth is essential for all organisms. Across eukaryotes, the serine-threonine kinase called target of rapamycin (TOR; or mTOR in mammals) is a master regulator of cell growth. It is the catalytic subunit of two molecular complexes, mTORC1 and mTORC2. The mTORC1 complex is acutely sensitive to concentrations of both growth factors and nutrients, including glucose and amino acids (1). The mTORC1 signaling pathway in cells is hyperactivated in a broad spectrum of human cancers and in metabolic disease (2). On page 1100 in this issue, Bar-Peled *et al.* (3) identify a protein complex that negatively regulates mTORC1 and functions as

a tumor suppressor, pointing to new possible therapeutic strategies for cancer.

Genetic studies in the fly *Drosophila melanogaster* and in mammals identified the tuberous sclerosis complex (TSC) tumor suppressors as critical inhibitors of mTORC1 under conditions of low growth factors. The *TSC1* and *TSC2* genes are genetically inactivated in sporadic cancers in addition to the inherited disorder tuberous sclerosis (1). The *TSC2* protein encodes a guanosine triphosphatase (GTPase)-activating protein (GAP) that inactivates Rheb, a small GTPase that binds to and activates mTOR. In response to amino acid abundance, a different set of small GTPases, the Rag proteins, bind to and activate mTORC1 (4). When amino acid availability increases, Rag proteins translocate to the outer surface of the lysosome where they bind to Ragulator, a protein complex that loads RagA (or

A negative regulator of amino acid sensing by the mTOR signaling pathway is identified and discovered to be inactivated in cancers.

RagB) with GTP. In this state, Rag proteins can recruit mTORC1 to the lysosomal surface (5) where it becomes activated and can signal. Thus, when amino acid availability is low, mTORC1 does not translocate and remains inactive in the cytosol.

Given that the TSC complex serves to suppress mTORC1 by inhibiting Rheb, Bar-Peled *et al.* investigated whether negative regulators of Rag proteins exist as well. The authors identified a protein complex, which they call GAP activity toward Rags (GATOR), that acts upstream of the Rag proteins (see the figure). The eight proteins that comprise GATOR can be divided into two subcomplexes based on the affinity of protein-protein interactions and epistasis experiments that examined their effects on mTORC1. Inhibition of GATOR1 constituents [dishevelled, Egl-10 and pleckstrin (DEP) domain-containing 5 (DEPDC5); nitrogen permease

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