Supplement S5
Tumba-Funda and Balombo Boulders (Bimbe, Gale Crater, Mars) Sedimentological Details

Extraformational sediment recycling on Mars

Kenneth S. Edgett, Steven G. Banham, Kristen A. Bennett, Lauren A. Edgar, Christopher S. Edwards, Alberto G. Fairén, Christopher M. Fedo, Deirdra M. Fey, James B. Garvin, John P. Grotzinger, Sanjeev Gupta, Marie J. Henderson, Christopher H. House, Nicolas Mangold, Scott M. McLennan, Horton E. Newsom, Scott K. Rowland, Kirsten L. Siebach, Lucy Thompson, Scott J. VanBommel, Roger C. Wiens, Rebecca M. E. Williams, and R. Aileen Yingst

TUMBA-FUNDA AND BALOMBO BOULDERS (BIMBE, GALE CRATER, MARS) SEDIMENTOLOGICAL DETAILS

Note that some of the figures identified here are in the main text of "Extraformational sediment recycling on Mars".

Sedimentology

Observations

The Tumba-Funda and Balombo boulders are weakly stratified (**Fig. S5-1 and Figs. 6D, 7B, 9A, in main paper**) and exhibit pebble-rich layers. Some pebbles are arranged in clusters. Overall, the fabric is disorganized and shows little evidence of preferential clast orientation (e.g., imbrication). Pebbles stand in relief on each boulder; some protrude on windward surfaces (**Fig. 9A in main paper**), and some on the boulder tops have streamlined tails on their aeolian lee sides (e.g., **Fig. 9A in main paper**). Grain size distribution analysis (**Fig. S5-1**)—using the approach of Banham et al. (2018)—shows that the Tumba-Funda boulder is a poorly sorted, clast-supported pebble conglomerate with a sandy matrix. The primary grain size of the matrix is coarse sand; the framework grains are mostly fine to medium pebbles (**Fig. S5-1C**). The shape of the coarser fraction is size-dependent, fine pebbles are tabular to semi-spherical and rounded to well rounded; larger clasts are mostly sub-angular and have a low sphericity (**Fig. S5-1B**). No fractures or veins are observed in the Tumba-Funda or Balombo boulders. Recessive, pebble-sized white features are present in the Tumba-Funda boulder (**Fig. 8 in main paper**) but not in the Balombo boulder (**Fig 9A in main paper**).

Interpretations

Although the conglomeratic boulders at Bimbe are float rocks (Wiens et al., 2020), their internal sedimentary structures and textures permit interpretation of their original sedimentary depositional processes and settings. The presence of grains of up to very coarse pebble size, and the evidence for rounding of these clasts, are characteristics consistent with aqueous transport and deposition. Like other conglomerates observed in Gale crater (Williams et al., 2013), their rounded clasts indicate abrasion associated with bedload transport. The poor sorting, polymodal grain size distribution, and disorganized fabric suggest rapid deposition with a limited capacity to sort grains. These clasts were likely deposited by sediment-charged stream-flood flows, terms that refer to episodic, high magnitude discharge conditions that transport and rapidly deposit grains of a range of sizes (e.g., Pierson and Scott, 1985; Went, 2005; Blair and McPherson, 2009). The absence of a preferred orientation among the larger clasts supports this view. The boulder surfaces have been subjected to recent aeolian erosion; pebbles protrude on the boulder sides and streamlined wind tails occur behind some of the protruding pebbles on their nearly planar top-surfaces.

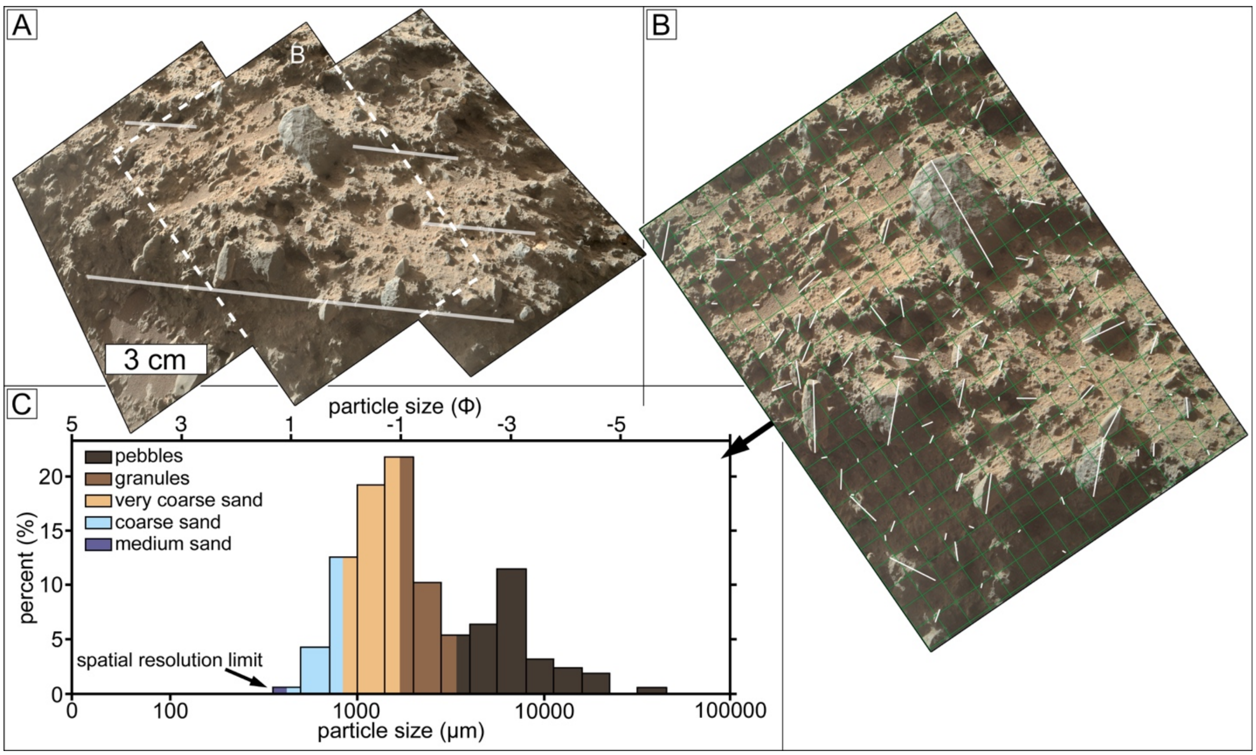

Figure S5-1. Tumba-Funda boulder granulometric properties and sedimentary structures. **(A)** MAHLI mosaic covering part of the Tumba-Funda boulder, showing weak stratification (white lines). Dashed box indicates the location of B. **(B)** Grain size point count measurements (white lines) via gridded (green) pattern used to produce plot C per method described by Banham et al. (2018). **(C)** Grain size distribution for the measured area. Image identifiers: **(A)** Portions of MAHLI focus merge products 1408MH0001630000502846R00, 1408MH0001630000502848R00, and 1408MH0001630000502850R00; **(B)** MAHLI focus merge product 1408MH0001630000502850R00. **(C)** Grain size measurement data are in **Table S5-1** (file Table_S5_1_TumbaFundaBoulder_GrainSizeMeasurements.xlsx).

Igneous and Impact Melt Rock Fragments

Neither the Tumba-Funda nor the Balombo boulder consists entirely of sedimentary rock fragments. Indeed, only a few examples are identified with certainty, including Tumba, Funda, the layered clast in **Figure 7D (in main paper)**, the sandstone pebble at Bolombo (**Fig. 9B in main paper**), and the features similar to Funda in the Tumba-Funda boulder (**Fig. 8 in main paper**). The pebbles and sands observed via the APXS 4-spot raster at Funda (**Supplement 3, Fig. S3-1**) are mafic siliciclastics. MAHLI images of the APXS raster area (**Supplement 3, Fig. S3-1**) provide the most detailed views of some of the other pebbles in the Tumba-Funda boulder (**Fig. S5-2**); these permit a few basic observations regarding the petrography of the siliciclastic pebbles.

Observations

Figure S5-2A shows some of the pebbles on the Tumba-Funda boulder near Funda. **Figure S5-2B** shows part of a ~7.4 x ~ 4.9 mm pebble that displays a porphyritic texture with light gray laths in a dark gray, aphanitic groundmass. **Figure S5-2C** shows a pebble that includes a ~2 mm light gray component protruding from dark gray, fine-grained material. The dark gray material contains smaller, lighter-toned, angular features; the top part of the light gray component has a vitreous luster. The pebble in **Figure S5-2D** (which could be two very similar, smaller pebbles) is (or are) dominated by light gray material containing darker gray components; the light gray material might be somewhat pink, but this is uncertain. The pebble in **Figure S5-2E** is in shadow; stretching the dynamic range of the original image shows that it is dark gray and contains lighter-gray, angular features (one is triangular) that are ~100–260 μm across.

Interpretations

The pebble in **Figure S5-2B** is interpreted to be igneous; it could either be a fragment derived from a lava flow or a shallow intrusive rock (less likely, it could be an impact melt but porphyritic textures in such rocks are generally unknown). Interpreting the pebble in **Figure S5-2C** is more challenging, as it could be a piece of a volcanic, shallow intrusive, or impact melt rock, or it could be an impact breccia. The light gray part of the pebble in **Figure S5-2C**, with its vitreous luster, might include quartz or some other high silica material. The light-toned, mottled pebble(s) in **Figure S5-2D** could be a cumulate igneous rock fragment(s) (i.e., plutoniclast(s)), but this is highly uncertain; it or they could otherwise be a fragment (or fragments) of a coarser-grained portion of a volcanic rock or impact melt; impact breccia is also an option. The dark gray pebble in **Figure S5-2E**, which contains small, angular, light gray objects, could be a porphyritic volcanic rock, a clast-bearing impact melt, or an impact breccia.

Interpretation of the rock type for each of the four pebbles highlighted in **Figure S5-2** is difficult in the absence of thin sections. They are not sedimentary lithoclasts, the one in **Figure S5-2B** is from a lava or shallow igneous intrusion, and the other three can be interpreted as igneous rock, impact melt rock, or impact breccia fragments. The source area for the clasts in this boulder would therefore have to include **(1)** sedimentary rocks to provide clasts such as Tumba and Funda, **(2)** extrusive or shallow intrusive igneous rocks—or pebbles in a preceding conglomerate or breccia derived initially from such rocks, and **(3)** other rock types derived from igneous or impact processes (extrusive igneous, intrusive igneous, impact melt, impact breccia)—or pebbles in a conglomerate or breccia initially derived from such rocks.

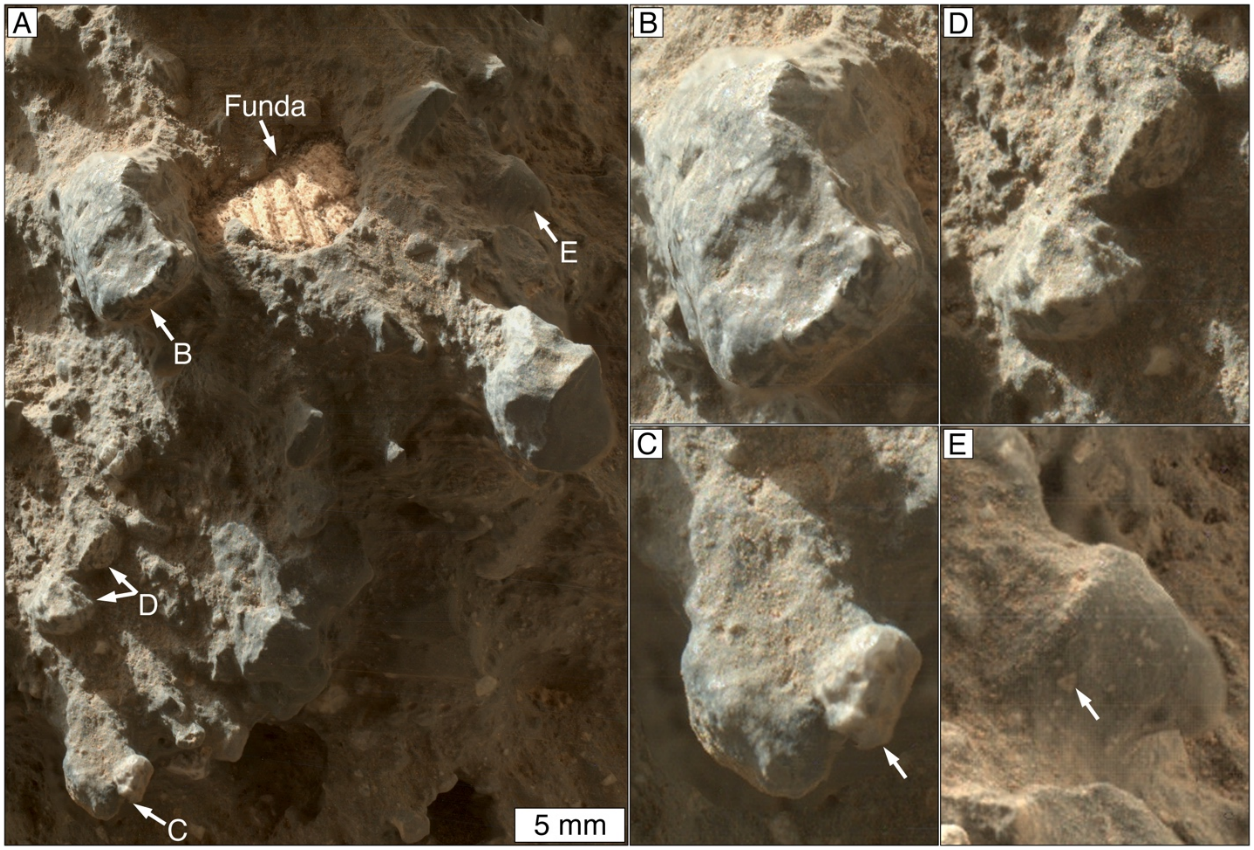

Figure S5-2. Examples of igneous and (perhaps) impact melt rock pebbles in the Tumba-Funda boulder. **(A)** Funda in context with a variety of protruding pebbles and granules; note scale. The locations of B–E are indicated. **(B)** Pebble containing light gray phenocrysts, probably plagioclase; interpreted to be an igneous extrusive or shallow intrusive rock fragment. **(C)** Gray pebble with white protrusion (arrow) and a vitreous luster. **(D)** Pebble or pebbles with light and dark gray mottling, with a hint of pink. **(E)** Gray pebble, in full shadow, containing angular fragments or phenocrysts; the arrow points to one that is triangular. The pebbles in C–E could be igneous or impact melt fragments or impact breccias. Image identifiers: **(A)** Mosaic of portions of MAHLI focus merge products 1411MH0005840000503002R00, 1411MH0005840000503010R00, 1411MH0005840000503006R00, and 1411MH0005840000503014R00. **(B)** Portion of MAHLI focus merge product 1411MH0005840000503006R00. **(C)** Portion of MAHLI focus merge product 1411MH0005840000503010R00. **(D)** Portion of MAHLI focus merge product 1411MH0005840000503010R00. **(E)** Portion of MAHLI focus merge product 1411MH0005840000503002R00.

REFERENCES CITED IN THIS SUPPLEMENT

Banham, S.G., Gupta, S., Rubin, D.M., Watkins, J.A., Sumner, D.Y., Edgett, K.S., Grotzinger, J.P., Lewis, K.W., Edgar, L.A., Stack-Morgan, K.M., Barnes, R., Bell, J.F. III, Day, M.D., Ewing, R.C., Lapôtre, M.G.A., Stein, N.T., Rivera-Hernández, F., and Vasavada, A.R., 2018, Ancient Martian aeolian processes and palaeomorphology reconstructed from the Stimson formation on the lower slope of Aeolis Mons, Gale crater, Mars: Sedimentology, v. 65, p. 993–1042, https://doi.org/10.1111/sed.12469.

Blair, T.C., and McPherson, J.G., 2009, Processes and forms of alluvial fans, Chapter 14 *in* Parsons A.J., and Abrahams A.D., eds., Geomorphology of Desert Environments: Dordrecht, Netherlands, Springer, p. 413–467, https://doi.org/10.1007/978-1-4020-5719-9_14.

Pierson, T.C., and Scott, K.M., 1985, Downstream dilution of a lahar: Transition from debris flow to hyperconcentrated streamflow: Water Resources Research, v. 21, p. 1511–1524, https://doi.org/10.1029/WR021i010p01511.

Went, D.J., 2005, Pre-vegetation alluvial fan facies and processes: an example from the Cambro-Ordovician Rozel Conglomerate Formation, Jersey, Channel Islands: Sedimentology, v. 52, p. 693–713, https://doi.org/10.1111/j.1365-3091.2005.00716.x.

Wiens, R.C., Edgett, K.S., Stack, K.M., Dietrich, W.E., Bryk, A.B., Mangold, N., Bedford, C., Gasda, P., Fairén, A., Thompson, L., Johnson, J., Gasnault, O., Clegg, S., Cousin, A., Forni, O., Frydenvang, J., Lanza, N., Maurice, S., Newsom, H., Ollila, A., Payré, V., Rivera-Hernández, F., and Vasavada, A., 2020, Origin and composition of three heterolithic boulder- and cobble-bearing deposits overlying the Murray and Stimson formations, Gale crater, Mars: Icarus, v. 350, 113897, https://doi.org/10.1016/j.icarus.2020.113897.

Williams, R.M.E., Grotzinger, J.P., Dietrich, W.E., Gupta, S., Sumner, D.Y., Wiens, R.C., Mangold, N., Malin, M.C., Edgett, K.S., Maurice, S., Forni, O., Gasnault, O., Ollila, A., Newsom, H.E., Dromart, G., Palucis, M.C., Yingst, R.A., Anderson, R.B., Herkenhoff, K.E., Le Mouélic, S., Goetz, W., Madsen, M.B., Koefoed, A., Jensen, J.K., Bridges, J.C., Schwenzer, S.P., Lewis, K.W., Stack, K.M., Rubin, D., Kah, L.C., Bell, J.F. III, Farmer, J.D., Sullivan, R., Van Beek, T., Blaney, D.L., Pariser, O., Deen, R.G., and the MSL Science Team, 2013, Martian fluvial conglomerates at Gale crater: Science, v. 340, p. 1068–1072, https://doi.org/10.1126/science.1237317.