



*International Association of Geomorphologists
Working Group on Planetary Geomorphology*

Recommended Reading List for Mars Rock Breakdown Studies

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Rock breakdown refers to the cumulative effects of weathering and erosion on surface materials. For Mars, a rich array of literature exists describing the morphology and physical properties of landing site rocks. Additionally, studies of the weathering environment—e.g. the climate and availability of salts—provide important constraints on operating processes. Geochemical measurements of Mars surface, both at the landing sites and from orbit, provide insight into the timing and nature of chemical alteration. Finally, several Earth laboratory and analog studies, in particular those addressing the effects of wind and chemical alteration, provide additional information on the morphologies, mechanisms and chemistry of Martian rock breakdown.

General-overview

- Bishop, J. L., Murchie, S. L., Pieters, C. M., and Zent, A. P. (2002). A model for formation of dust, soil, and rock coatings on Mars: Physical and chemical processes on the Martian surface. *Journal of Geophysical Research* **107**, doi:10.1029/2001JE001581.
- Christensen, P. R., and Moore, H. J. (1992). The Martian Surface Layer. In *Mars* (H. H. Kieffer, B. M. Jakosky, C. W. Snyder, and M. S. Matthews, Eds.), p. 686-729. The University of Arizona, Tucson, Arizona.
- Garvin, J. B., Mouginiis-Mark, P. J., and Head III, J. W. (1981). Characterisation of rock populations on planetary surfaces: Techniques and preliminary analysis of Mars and Venus. *The Moon and the Planets* **24**, 355-387.
- Golombek, M. P., Grant, J. A., Crumpler, L. S., *et al.* (2006). Erosion rates at the Mars Exploration Rover landing sites and long-term climate change on Mars. *Journal of Geophysical Research* **111** E12S10, doi:10.1029/2006JE002754.
- Gooding, J. L., Arvidson, R. E., and Zolotov, M. Y. (1992). Physical And Chemical Weathering. In *Mars*. (H. H. Kieffer, B. M. Jakosky, C. W. Snyder, and M. S. Matthews, Eds.), p. 626-651. The University of Arizona, Tucson, Arizona

Surface geology and geomorphology – insight from landed missions

Viking Landers

- Arvidson, R. E., Gooding, J. L., and Moore, H. J. (1989). The Martian surface as imaged, sampled, and analyzed by the Viking landers. *Rev. Geophys.* **27**, 39-60.
- Binder, A. B., Arvidson, R. E., Guinness, E. A., *et al.* (1977). The geology of the Viking Lander 1 site. *Journal of Geophysical Research* **82**, 4439-4451.
- Mutch, T. A., Arvidson, R. E., Binder, A. B., *et al.* (1977). The geology of the Viking Lander 2 site. *Journal of Geophysical Research* **82**, 4452-4467.
- Sharp, R. P., and Malin, M. C. (1984). Surface Geology from Viking Landers on Mars: A Second Look. *Geological Society of America Bulletin* **95**, 1398-1412



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Pathfinder Rover

- Basilevsky, A. T., Markiewicz, W. J., Thomas, N., and Keller, H. U. *et al.*, (1999a). Morphologies of rock within and near the Rock Garden at the Mars Pathfinder landing site. *Journal of Geophysical Research* **104**, 8617-8636.
- Basilevsky, A. T., Markiewicz, W. J., Thomas, N., *et al.* (1999b). Morphology of the APXS-analyzed rocks at the Mars Pathfinder site. *Solar System Research* **33**, 170-186.
- Golombek, M. P., Anderson, R. C., Barnes, J. R., *et al.* (1999). Overview of the Mars Pathfinder Mission: Launch through landing, surface operations, data sets, and science results. *Journal of Geophysical Research* **104**, 8523-8553.
- Golombek, M. P., Cook, R. A., Economou, T., *et al.* (1997). Overview of the Mars Pathfinder Mission and Assessment of Landing Site Predictions. *Science* **278**, 1743.
- McSween, H. Y., Jr., Murchie, S. L., Crisp, J. A., *et al.* (1999). Chemical, multispectral, and textural constraints on the composition and origin of rocks at the Mars Pathfinder landing site. *Journal of Geophysical Research* **104**, 8679-8715.
- RoverTeam. (1997). Characterization of the Martian surface deposits by the Mars Pathfinder Rover, Sojourner. *Science* **278**, 1765-1767.
- Smith, P. H., Bell III, J. F., Bridges, N. T., *et al.* (1997). Results from the Mars Pathfinder camera. *Science* **278**, 1758-1765.

Mars Exploration Rovers-Spirit (Gusev Crater)

- Arvidson, R. E., Anderson, R. C., Bartlett, P., *et al.* (2004). Localization and Physical Properties Experiments Conducted by Spirit at Gusev Crater. *Science* **305**, 821-824.
- Cabrol, N. A., Farmer, J. D., Grin, E. A., *et al.* (2006). Aqueous processes at Gusev crater inferred from physical properties of rocks and soils along the Spirit traverse. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2005JE002490.
- Ferguson, R. L., Christensen, P. R., Bell, J. F., *et al.* (2006). Physical properties of the Mars Exploration Rover landing sites as inferred from Mini-TES derived thermal inertia. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2005JE002583.
- Golombek, M. P., Crumpler, L. S., Grant, J. A., *et al.* (2006). Geology of the Gusev cratered plains from the Spirit rover traverse. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2005JE002503.
- Grant, J. A., Arvidson, R., Bell, J. F., III, *et al.* (2004). Surficial Deposits at Gusev Crater Along Spirit Rover Traverses. *Science* **305**, 807-810.
- Herkenhoff, K. E., Squyres, S. W., Arvidson, R., *et al.* (2004). Textures of the Soils and Rocks at Gusev Crater from Spirit's Microscopic Imager. *Science* **305**, 824-826.
- McSween, H. Y., Arvidson, R. E., Bell, J. F., III, *et al.* (2004). Basaltic Rocks Analyzed by the Spirit Rover in Gusev Crater. *Science* **305**, 842-845.



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- McSween, H. Y., Wyatt, M. B., Gellert, R., *et al.* (2006). Characterization and petrologic interpretation of olivine-rich basalts at Gusev Crater, Mars. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2005JE002477.
- Morris, R. V., Klingelhofer, G., Bernhardt, B., *et al.* (2004). Mineralogy at Gusev Crater from the Mossbauer Spectrometer on the Spirit Rover. *Science* **305**, 833-836.
- Ruff, S. W., Christensen, P. R., Blaney, D. L., *et al.* (2006). The rocks of Gusev Crater as viewed by the Mini-TES instrument. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2006JE002747.
- Squyres, S. W., Arvidson, R. E., Blaney, D. L., *et al.* (2006). Rocks of the Columbia Hills. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2005JE002562.

Mars Exploration Rovers-Opportunity (Meridiani)

- Arvidson, R. E., Anderson, R. C., Bartlett, P., *et al.* (2004). Localization and Physical Properties Experiments Conducted by Opportunity at Meridiani Planum. *Science* **306**, 1730-1733.
- Grotzinger, J. P., Arvidson, R. E., Bell III, J. F., *et al.* (2005). Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns formation, Meridiani Planum, Mars. *Earth and Planetary Science Letters* **240**, 11-72.
- Morris, R. V., Klingelhofer, G., Schroder, C., and *al.*, e. (2006). Mössbauer mineralogy of rock, soil, and dust at Meridiani Planum, Mars: Opportunity's journey across sulfate-rich outcrop, basaltic sand and dust, and hematite lag deposits. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2006JE002791.
- Squyres, S. W., Grotzinger, J. P., Arvidson, R. E., *et al.* (2004). In-situ evidence for an ancient aqueous environment at Meridiani Planum. **306** 1709-1714.

General rock breakdown

- Thomas, M., Clarke, J. D. A., and Pain, C. F. (2005). Weathering, erosion and landscape processes on Mars identified from recent rover imagery, and possible Earth analogues. *Australian Journal of Earth Sciences* **52**, 365-378.

The weathering environment: climate and water availability

Large-scale climate patterns

- Forget, F., Haberle, R. M., Montmessin, F., *et al.* (2006). Formation of glaciers on Mars by atmospheric precipitation at high obliquity. *Science* **311**, 368-371.
- Haberle, R. M., McKay, C. P., Schaeffer, J., *et al.* (2001). On the possibility of liquid water on present-day Mars. *Journal of Geophysical Research (Planets)* **106**, 23,317-23,326.
- Jakosky, B. M., Haberle, R. M., and Arvidson, R. E. (2005). The Changing Picture of Volatiles and Climate on Mars. *Science* **310**, 1439-1440, 10.1126/science.1118031.



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- Owen, T. (1992). The composition and early history of the atmosphere of Mars. In *Mars*. (H. H. Kieffer, B. M. Jakosky, C. W. Snyder, and M. S. Matthews, Eds.), p. 818-834. The University of Arizona, Tucson, Arizona.
- Richardson, M. I., and Mischna, M. A. (2005). Long-term evolution of transient liquid water on Mars. *Journal of Geophysical Research (Planets)* **110**, 03003.
- Zurek, R. W. (1992). Comparative Aspects Of The Climate Of Mars: An Introduction To The Current Atmosphere. In *Mars*. (H. H. Kieffer, B. M. Jakosky, C. W. Snyder, and M. S. Matthews, Eds.), p. 799-817. The University of Arizona, Tucson, Arizona

Small-scale climate: weather at the landing sites

- Schofield, J. T., Barnes, J. R., Crisp, D., *et al.* (1997). The Mars Pathfinder atmospheric structure investigation/meteorology (ASI/MET) experiment. *Science* **278**, 1752-1758.
- Smith, M. D., Pearl, J. C., Conrath, B. J., and Christensen, P. R. (2001). One Martian year of atmospheric observations by the Thermal Emission Spectrometer. *Geophysical Research Letters* **28**, 4263-4266.
- Spanovich, N., Smith, M. D., Smith, P. H., *et al.* (2006). Surface and near-surface atmospheric temperatures for the Mars Exploration Rover landing sites. *Icarus* **180**, 314-320

Water availability

- Baker, V. R., Strom, R. G., Gulick, V. C., *et al.* (1991). Ancient oceans, ice sheets and the hydrological cycle on Mars. *Nature* **352**, 589--594.
- Carr, M. H. (1979). Formation of Martian flood features by release of water from confined aquifers. *Journal of Geophysical Research* **84**, 2995-3007.
- Malin, M. C., and Edgett, K. (2003). Evidence for persistent flow and aqueous sedimentation on early Mars. *Science* **302**, 1931-1934.
- Malin, M. C., and Edgett, K. S. (2000). Evidence for Recent Groundwater Seepage and Surface Runoff on Mars. *Science* **288**, 2330.
- Schorghofer N. and O. Aharonson, Stability and exchange of subsurface ice on Mars, *Journal of Geophysical Research*, 110, E05003, doi:10.1029/2004JE002350, 2005
- Squyers, S. W., Clifford, S. M., Kuzmin, R. O., *et al.* (1992). Ice In The Martian Regolith. In *Mars*. (H. H. Kieffer, B. M. Jakosky, C. W. Snyder, and M. S. Matthews, Eds.), p. 523-554. The University of Arizona, Tucson, Arizona



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Weathering processes: physical

Aeolian

- Arvidson, R. E., Guinness, E. A., and Lee, D. S. (1979). Differential aeolian redistribution rates on Mars. *Nature* **278**, 533-535.
- Bridges, N. T., Greeley, R., Haldemann, A. F. C., *et al.* (1999). Ventifacts at the Pathfinder landing site. *Journal of Geophysical Research* **104**, 8595-8615.
- Greeley, R., Arvidson, R. E., Barlett, P. W., *et al.* (2006). Gusev crater: Wind-related features and processes observed by the Mars Exploration Rover Spirit. *Journal of Geophysical Research (Planets)* **111**.
- Greeley, R., and Iversen, J. D. (1985). *Wind as a geological process on Earth, Mars, Venus and Titan*. Cambridge University Press, Cambridge.
- Greeley, R., Leach, R. N., Williams, S. H., *et al.* (1982). Rate of wind abrasion on Mars. *Journal of Geophysical Research (Planets)* **87**, 10,009-10,024.
- Greeley, R., Squyres, S. W., Arvidson, R. E., *et al.* (2004). Wind-Related Processes Detected by the Spirit Rover at Gusev Crater, Mars. *Science* **305**, 810-813.
- Kraft, M. D., and Greeley, R. (1999). Aeolian Abrasion and the Preservation of Rock Coatings at the Mars Pathfinder Landing Site. Lunar and Planetary Institute Conference Abstracts. p. 1686.

Flood/fluvial

- Baker, V. R., and Milton, D. J. (1974). Erosion by catastrophic floods on Mars and Earth. *Icarus* **23**, 27-41.

Freeze-thaw, wet-dry

- Mohlmann, D. T. F. (2003). Unfrozen subsurface water on Mars: presence and implications. *International Journal of Astrobiology* **2**, 213-216.

Glacial

- Head, J. W., and Marchant, D. R. (2003). Cold-based mountain glaciers on Mars: Western Arsia Mons. *Geology* **31**, 641-644

Salts and salt weathering

- Brass, G. W. (1980). Stability of brines on Mars. *Icarus* **42**, 20-28.
- Chavdarian, G. V., and Sumner, D. Y. (2006). Cracks and fins in sulfate sand: Evidence for recent mineral-atmospheric water cycling in Meridani Planum outcrops? *Geology* **34**, 229-232.
- Clark, B. C., and Van Hart, D. C. (1981). The salts of Mars. *Icarus* **45**, 370-378.
- Malin, M. C. (1974). Salt weathering on Mars. *Journal of Geophysical Research (Planets)* **79**, 3917-3931.
- Wang, A., Haskin, L., Squyres, S. W., *et al.* (2006). Sulfate deposition in subsurface regolith in Gusev crater, Mars. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2005JE002513.



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Yen, A. S., Gellert, R., Schroder, C., *et al.* (2005). An integrated view of the chemistry and mineralogy of martian soils. *Nature* **436**, 49-54.

Thermal insolation

Leask, H. J., and Wilson, L. (2003). Heating and cooling of rocks on Mars: consequences for weathering. *In LPSC XXXIV* abst. 1320.

Weathering processes: chemical

- Bibring, J.-P., Langevin, Y., Mustard, J. F., *et al.* (2006). Global Mineralogical and Aqueous Mars History Derived from OMEGA/Mars Express Data *Science* **312**, 400-404. 10.1126/science.1122659.
- Chevrier, V., and Mathe, P. E. (2007). Mineralogy and evolution of the surface of Mars: A review. *Planetary and Space Science* **55**, 289-314
- Christensen, P. R., Morris, R. V., Lane, M. D., *et al.* (2001). Global mapping of Martian hematite mineral deposits: Remnants of water-driven processes on early Mars. *Journal of Geophysical Research (Planets)* **106**, 23,873-23,885.
- Clark, B. C., Morris, R. V., McLennan, S. M., *et al.* (2005). Chemistry and mineralogy of outcrops at Meridiani Planum. *Earth and Planetary Science Letters* **240**, 73-94.
- Gendrin, A., Mangold, N., Bibring, J.-P., *et al.* (2005). Sulfates in Martian Layered Terrains: The OMEGA/Mars Express View. *Science* **307**, 1587-1591.
- Haskin, L. A., Wang, A., Jolliff, B. L., *et al.* (2005). Water alteration of rocks and soils on Mars at the Spirit rover site in Gusev crater. *Nature* **436**, 66-69.
- Hurowitz, J. A., McLennan, S. M., Tosca, N. J., *et al.* (2006). In situ and experimental evidence for acidic weathering of rocks and soils on Mars. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2005JE002515.
- McLennan, S. M., Bell III, J. F., Calvin, W. M., *et al.* (2005). Provenance and diagenesis of the evaporite-bearing Burns formation, Meridiani Planum, Mars. *Earth and Planetary Science Letters* **240**, 95-121.
- Ming, D. W., Mittlefehldt, D. W., Morris, R. V., *et al.* (2006). Geochemical and mineralogical indicators for aqueous processes in the Columbia Hills of Gusev crater. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2005JE002560.
- Morris, R. V., Golden, D. C., Bell, J. F., III, *et al.* (2000). Mineralogy, composition, and alteration of Mars Pathfinder rocks and soils: Evidence from multispectral, elemental, and magnetic data on terrestrial analogue, SNC meteorite, and Pathfinder samples. *Journal of Geophysical Research* **105**, 1757.
- Poulet, F., Bibring, J.-P., Mustard, J. F., *et al.* (2005). Phyllosilicates on Mars and implications for early martian climate. *Nature* **438**, 623-627.
- Tosca, N. J., McLennan, S. M., Clark, B. C., *et al.* (2005). Geochemical modeling of evaporation processes on Mars: insights from the sedimentary record at Meridiani Planum. *Earth and Planetary Science Letters* **240**, 122-148.
- Tosca, N. J., and McLennan, S. M. (2006). Chemical divides and evaporate mineral assemblages on Mars. *Earth and Planetary Science Letters* **241**, 21.31.



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Wang, A., Korotev, R. L., Jolliff, B. L., *et al.*, (2006). Evidence of phyllosilicates in Wooly Patch, an altered rock encountered at West Spur, Columbia Hills, by the Spirit rover in Gusev crater. *Journal of Geophysical Research (Planets)* **111**, doi:10.1029/2005JE002516.

Laboratory

Chemical weathering

- Chevrier, V., Rochette, P., Mathe, P.-E., and Grauby, O. (2004). Weathering of iron-rich phases in simulated Martian atmospheres. *Geology* **32**, 1033-1036.
- Golden, D. C., Ming, D. W., Morris, R. V., and Mertzman, S. A. (2005). Laboratory simulated acid-sulfate weathering of basaltic minerals: implications for formation of sulfates at Meridiani Planum and Gusev Crater. *Journal of Geophysical Research (Planets)* **110**.
- Moore, J. M., and Bullock, M. A. (1999). Experimental studies of Mars-analog brines. *Journal of Geophysical Research (Planets)* **104**, 21,925-21,934.
- Tosca, N. J., McLennan, S. M., Lindsley, D. H., and Schoonen, M. A. A. (2004). Acid-sulfate weathering of synthetic Martian basalt: The acid fog model revisited. *Journal of Geophysical Research* **109**, 10.1029/2003JE002218.
- Vaniman, D. T., Bish, D. L., Chipera, S. J., *et al.* (2004). Magnesium sulphate salts and the history of water on Mars. *Nature* **431**, 663-665.

Physical weathering

- Bridges, N. T., Laity, J. E., Greeley, R., *et al.* (2004). Insights on rock abrasion and ventifact formation from laboratory and field analog studies with applications to Mars. *Planetary and Space Science* **52**, 199-213

Earth analogue

- Allen, C. C., and Conca, J.-L. (1991). Weathering of basaltic rocks under cold, arid conditions - Antarctica and Mars. Proceedings of the 21st Lunar and Planetary Sciences Conference, Houston.
- Allen, C. C., Gooding, J. L., Jercinovic, M., and Keil, K. (1981). Altered basaltic glass: A terrestrial analog to the soil of Mars. *Icarus* **45**, 347-369.
- Bell III, J. F., and Morris, R. V. (1993). Thermally altered palagonitic tephra - A spectral and process analog to the soil and dust of Mars. *Journal of Geophysical Research (Planets)* **98**, 3373-3385.
- Bishop, J., Schiffman, P., Southard, R. J., *et al.* (2003). Constraints on Martian Surface Material from a Study of Volcanic Alteration in Iceland and Hawaii. Sixth International Conference on Mars. p. 3009.
- Gibson, E. K., Wentworth, S. J., and McKay, D. S. (1983). Chemical weathering and diagenesis of a cold desert soil from Wright Valley, Antarctica: An analog of Martian weathering processes. LPSC XIII. pp. A912-A928.



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Greeley, R., Bridges, N. T., Kuzmin, R. O., and Laity, J. E. (2002). Terrestrial analogs to wind-related features at the Viking and Pathfinder landing sites on Mars. *Journal of Geophysical Research (Planets)* **107**.

Rice, J. W., and Edgett, K. S. (1997). Catastrophic flood sediments in the Chryse Basin, Mars, and Quincy basin, Washington: Application of sandar facies model. *Journal of Geophysical Research* **102**, 4185-4200.
