PLANETARY SCIENCE

Bedrock formation at Meridiani Planum

Arising from: T. M. McCollom & B. M. Hynek *Nature* 438, 1129–1131 (2005)

The Mars Exploration Rover Opportunity discovered sulphate-rich sedimentary rocks at Meridiani Planum on Mars, which are interpreted by McCollom and Hynek[1] as altered volcanic rocks. However, their conclusions are derived from an incorrect representation of our depositional model[2,3], which is upheld by more recent Rover data[4–7]. We contend that all the available data still support an aeolian and aqueous sedimentary origin for Meridiani bedrock.

The McCollom and Hynek model[1] is based on their Fig. 1 (reproduced here as Fig. 1a), a ternary diagram of molar silicon and aluminium (Si + Al), magnesium, calcium and iron (Mg + Ca + Fe), and sulphur (S), which compares the molar chemical composition of Meridiani bedrocks with that of typical martian basalts. The apices of the shaded region are intended by McCollom and Hynek[1] to represent our model[2,3] of the components of the outcrop rock when it was first deposited: sulphates, haematite and the siliciclastic fraction. Because the data lie outside this region, they claim that our model is implausible. We would point out, however, that the nature of the siliciclastic fraction of the rock — that is, the portion that consists of neither sulphates nor haematite — is misrepresented in the shaded region in Fig.1a.

Although the sulphate and haematite apices are properly placed, the siliciclastic apex is not. We have consistently stated that the siliciclastic fraction is derived from chemical weathering of a basaltic precursor material[2,8] and not that it consists of basaltic clasts, as asserted by McCollom and Hynek[1]. We proposed that aluminosilicate minerals and a non-aluminous silicate, possibly free silica, make up much of the siliciclastic fraction[8]. We have also emphasized that the chemical alteration occurred before the material was incorporated into the outcrop[8].

After chemical alteration, the distribution of cations is likely to be different from those in basaltic clasts: the altered siliciclastic residues would be shifted towards the (Si+Al) corner of Fig. 1a, especially under acidic conditions when iron is particularly mobile[9,10]. In principle, our model is consistent with the siliciclastic material plotting all the way to the (Si + Al) corner (Fig. 1b). But the key point is that our model requires the alteration to be sufficient for the data points to lie within the shaded region.

McCollom and Hynek point out that the data fall on a mixing line between basalt and sulphur, and suggest that the rocks formed when sulphur was added to basalt in a volcanic environment. But the data available to them at the time were from a single small outcrop examined at the beginning of the mission[1,2]; more recent data[4] show a very different trend,

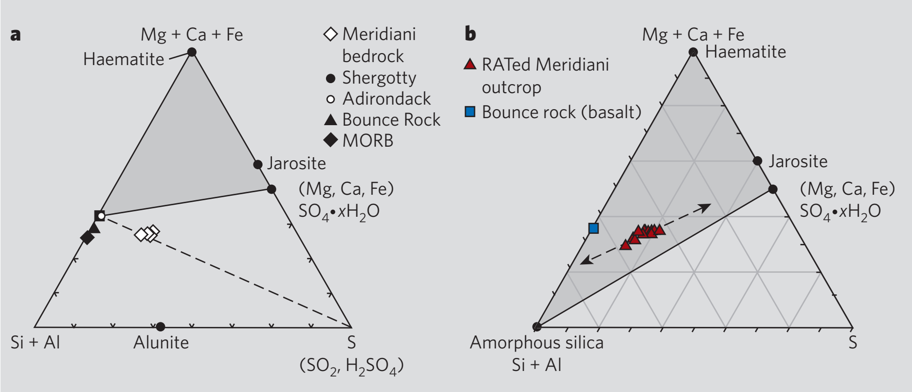

Figure 1 | Ternary diagrams of molar (Si + Al), (Mg + Ca + Fe) and sulphur. a, Ternary diagram taken from McCollom and Hynek[1]. The shaded region is intended to represent our depositional model, but has one apex plotted for basalt, rather than for the altered basalt we advocated[2–4,7–10]. b, Corrected diagram, in which the data points lie within the shaded region. In a, data points are shown only for a subset of our data that lie on a basalt–sulphur mixing line (dashed line). When all published data are included (b), a trend becomes evident that is inconsistent with that mixing line, but consistent with the mixing of altered basalt and sulphates plus haematite[4,7–9].

which can be explained instead by a mixture of altered basalt and another component consisting of sulphate salts and haematite (Fig. 1b).

Outcrop composition varies systematically with stratigraphic position: magnesium and sulphur co-vary and decrease with depth, whereas aluminium and silicon co-vary and increase with depth[4]. This variation is consistent with post-depositional interaction of the rocks with liquid water[4–6,10]. For a volcanic model, however, it would require both an implausible vertical compositional gradient within the primary volcanic deposits and sulphur enrichment that correlates strongly with primary basalt composition, contrary to expectations for the interaction of sulphur-laden vapours with basalt.

Geological observations[1,2,7] are also incompatible with a volcanic origin for Meridiani bedrock. The base surge deposits in Fig. 2b of ref. 1 are coarse-grained and poorly sorted, as are most base surge deposits. The rocks at Meridiani are uniformly fine-to-medium grained and are well sorted over the full area explored by the Rover[2,7]. The cross-stratification shown by McCollom and Hynek[1] is an order of magnitude larger than that found at Eagle crater, and does not show the festoon geometry (nested, truncated, concave-upward geometry) observed at Meridiani[7]. On Earth, centimetre-scale festoon cross-lamination is known to develop only in subaqueous flows[7].

Also, the broader stratigraphic context is neglected. Rocks at the Opportunity site form a 7-metre-thick set, subdivided into lower, middle and upper units, representing, respectively, aeolian dune (with internally complex cross-bed sets that are more than 2 m thick), aeolian sand sheet, and mixed aeolian sand sheet and interdune facies associations[7]. They form a 'wetting-upward' succession that records a progressive increase in the influence of groundwater and, ultimately, surface water in controlling depositional processes[7]. The aeolian mixing has naturally led to chemistry that is laterally homogeneous over scales large and small. We know of no setting on Earth where interaction of sulphur-laden vapours with basaltic materials has produced a large volume of well mixed sulphate-rich sand grains. Moreover, a base surge origin requires a volcanic source topographically higher than the deposits themselves, yet there is no evidence for volcanoes anywhere on the Meridiani plain[11].

S. W. Squyres[1], O. Aharonson[2], R. E. Arvidson[3], J. F. Bell III[1], P. R. Christensen[4], B. C. Clark[5], J. A. Crisp[6], W. Farrand[7], T. Glotch[2], M. P. Golombek[6], J. Grant[8], J. Grotzinger[2], K. E. Herkenhoff[9], J. R. Johnson[9], B. L. Jolliff[2], A. H. Knoll[10], S. M. McLennan[11], H. Y. McSween[12], J. M. Moore[13], J. W. Rice Jr[4], N. Tosca[11]
[1]Department of Astronomy, Cornell University, Ithaca, New York 14853, USA
e-mail: squyres@astro.cornell.edu
[2]Division of Geological and Planetary Science, California Institute of Technology, Pasadena, California 91125, USA
[3]Department of Earth and Planetary Sciences, Washington University, St Louis, Missouri 63130, USA
[4]Department of Geological Sciences, Arizona State University, Tempe, Arizona 85287, USA
[5]Lockheed Martin Corporation, Littleton, Colorado 80127, USA
[6]Jet Propulsion Laboratory, California Institute of

Technology, Pasadena, California 91109, USA
[7]Space Science Institute, Boulder, Colorado 80301, USA
[8]Center for Earth and Planetary Studies, Smithsonian Institution, Washington DC 20560, USA
[9]US Geological Survey, Flagstaff, Arizona 86001, USA
[10]Botanical Museum, Harvard University, Cambridge, Massachusetts 02138, USA
[11]Department of Geosciences, State University of New York, Stony Brook, New York 11794, USA
[12]Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, Tennessee 37996, USA
[13]NASA Ames Research Center, Moffett Field, California 94035, USA

1. McCollom, T. M. & Hynek, B. M. *Nature* **438,** 1129–1131 (2005).
2. Squyres, S. W. *et al. Science* **306,** 1709–1714 (2004).
3. Squyres, S. W. *et al. Science* **306,** 1698–1703 (2004).
4. Clark, B. C. *et al. Earth Planet. Sci. Lett.* **240,** 73–94 (2005).
5. McLennan, S. M. *et al. Earth Planet. Sci. Lett.* **240,** 95-121 (2005).
6. Tosca, N. J. *et al. Earth Planet. Sci. Lett.* **240,** 122–148 (2005).
7. Grotzinger, J. P. *et al. Earth Planet. Sci. Lett.* **240,** 11–72 (2005).
8. Squyres, S. W. & Knoll, A. H. *Earth Planet. Sci. Lett.* **240,** 1–10 (2005).
9. Nesbitt, H. W. & Wilson, R. E. *Am. J. Sci.* **292,** 740–777 (1992).
10. Tosca, N. J., McLennan, S. M., Lindsley, D. H. & Schoonen, M. A. A. *J. Geophys. Res.* **109,** E05003, doi:10.1029/2003JE002218 (2004).
11. Edgett, K. S. *Mars* **1,** 5–58 (2005).

doi:10.1038/nature05212

PLANETARY SCIENCE

McCollom & Hynek reply

Replying to: S. W. Squyres *et al. Nature* 443, doi:10.1038/nature05212 (2006)

Squyres *et al.*[1] contend that our proposed volcanic origin for Meridiani Planum[2] is inconsistent with more recently obtained data[3]. But although the new data reveal some variation in chemical composition, this variation is small (Fig. 1a) and mainly due to modest variations in magnesium and sulphur, with concentrations of the other elements remaining essentially constant[3]. In a volcanic model, this variation can be readily explained by mobilization of highly soluble magnesium sulphate salts during the later stages of alteration and diagenesis (Fig. 1a), as in the sedimentary/evaporite model in which sediments that were initially deposited with uniform composition are subsequently modified[3–5]. Although morphological features in the bedrock may be consistent with aeolian and fluvial origins[6], this interpretation is not unique, particularly as features with similar grain size, sorting and morphology are seen in base surge deposits[2,7–9]. Neither chemical nor morphological data therefore preclude a volcanic origin.

Squyres *et al.* claim[1] that their model is misrepresented in our Fig. 1 (ref. 2). However, the apices of the shaded triangle represent not the present composition of the mineral components, but the bulk composition of the potential primary chemical inputs in the sedimentary/evaporite model: a siliciclastic component, sulphate salts precipitated from evaporating groundwater, and iron that may have been mobilized to form haematite. In our Fig. 1 (ref. 2), the composition of the siliciclastic component was represented as basalt, consistent with their descriptions[3–5,10]. Although weathering of silicate minerals is discussed[4,5,10], the current mineralogical composition of silicates in the bedrock places no definitive constraints on the chemical composition of the original siliciclastic component; this is because it is inherently unclear whether the current minerals represent primary inputs or secondary alteration products. Consequently, the inferred presence of phyllosilicates and silica[4,5,10] cannot be used reliably to constrain the bulk chemical composition of the original siliciclastic input.

Squyres *et al.*[1] suggest that we should have placed one apex of the shaded triangle at the Si + Al end-member (their Fig. 1b), but this is valid only if one of the primary chemical inputs had a bulk composition consisting of just Si + Al. However, the Si:Al ratio is constant throughout Meridiani bedrock[3], and both the abundance of SiO_2 (48–53% by weight on a sulphur-free basis) and the Si:Al ratio (4.7–5.3) of the bedrocks are nearly identical to martian basalts[11] (48–51% by weight SiO_2; Si:Al, 3.5–7.2). There is thus no evidence for significant mobilization of Si or Al into the rocks, and Fig. 1b of Squyres *et al.*[1] does not accurately portray primary chemical inputs.

We agree that the current chemical composition of Meridiani bedrock can be accounted for by combining evaporitic and siliciclastic components[12]. However, this siliciclastic component would have to have been substantially depleted in divalent cations and enriched in Si+Al relative to basalt before it ever interacted with evaporating fluids, not just before it was incorporated into the current outcrop (Fig. 1b). This critical requirement is not discussed in descriptions of the sedimentary/evaporite scenario[3–5,10], nor has a plausible source for such a large amount of material with this composition been proposed. Furthermore, it would be necessary for evaporating groundwater to add divalent cations to the cation-depleted siliciclastic material in the right proportions to result in their basalt-like chemical compositions[12], which seems improbable. The sedimentary/evaporite scenario has significant shortcomings and alternative models[2,7] need to be considered.

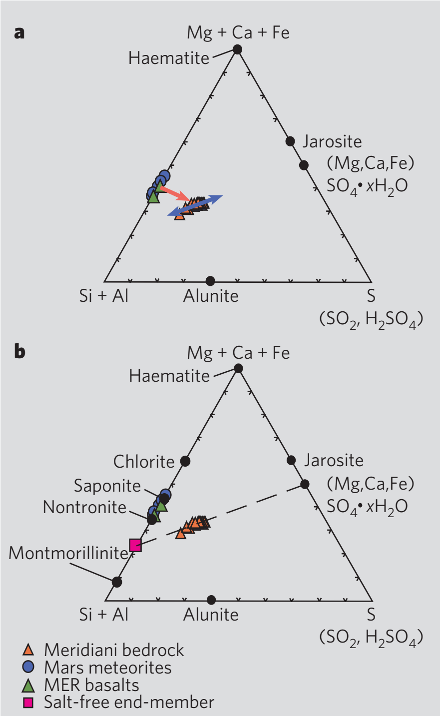

Figure 1 | Ternary diagrams showing relative molar abundances of major elements for Meridiani bedrock. Diagrams include data discussed by Squyres *et al.*[1] and typical martian basalts[2]. **a,** In a volcanic scenario[2], bedrock compositions are attributable to reaction of basaltic ash with sulphuric acid from volcanic vapours. Minor scattering among compositions can be accounted for by mobilization of magnesium sulphate salts in the later stages of alteration (arrows). **b,** In a sedimentary/evaporite scenario, extrapolation from bedrock compositions to remove sulphate salts would require the original siliciclastic component to be substantially depleted in divalent cations and enriched in Si + Al relative to martian basalt[12].

Thomas M. McCollom*†, Brian M. Hynek†
*Center for Astrobiology and †Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80309, USA
e-mail: mccollom@lasp.colorado.edu

1. Squyres, S. W. *et al. Nature* **443,** doi:10.1038/nature05212 (2006).
2. McCollom, T. M. & Hynek, B. M. *Nature* **438,** 1129–1131 (2005).
3. Clark, B. C. *et al. Earth Planet. Sci. Lett.* **240,** 73–94 (2005).
4. Squyres, S. W. & Knoll, A. H. *Earth Planet. Sci. Lett.* **240,** 1–10 (2005).
5. McLennan, S. M. *et al. Earth Planet. Sci. Lett.* **240,** 95–121 (2005).
6. Grotzinger, J. P. *et al. Earth Planet. Sci. Lett.* **240,** 11–72 (2005).
7. Knauth, L. P., Burt, D. M. & Wohletz, K. H. *Nature* **438,** 1123–1128 (2005).
8. Knauth, L. P., Burt, D. M. & Wohletz, K. H. *Lunar Planet. Sci. Conf. XXXVII abstr.* 1869 (2006).
9. Burt, D. M., Wohletz, K. H. & Sheridan, M. F. *Lunar Planet. Sci. Conf. XXXVII abstr.* 2295 (2006).
10. Squyres, S. W. *et al. Science* **306,** 1709–1714 (2004).
11. Lodders, K. *Meteor. Planet. Sci.* **33,** 183–190 (1998).
12. McCollom, T. M. & Hynek, B. M. *Lunar Planet. Sci. Conf. XXXVII abstr.* 2023 (2006).

doi:10.1038/nature05213