Bedrock formation at Meridiani Planum


The Mars Exploration Rover Opportunity discovered sulphate-rich sedimentary rocks at Meridiani Planum on Mars, which are interpreted by McCollom and Hynek1 as altered volcanic rocks. However, their conclusions are derived from an incorrect representation of our depositional model2,3, which is upheld by more recent Rover data4-7. We contend that all the available data still support an aeolian and aqueous sedimentary origin for Meridiani bedrock.

The McCollom and Hynek model1 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 Hynek1 to represent our model2,3 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 material3,5 and not that it consists of basaltic clasts, as asserted by McCollom and Hynek1. We proposed that alumino-silicate minerals and a non-aluminous silicate, possibly free silica, make up much of the siliciclastic fraction3. We have also emphasized that the chemical alteration occurred before the material was incorporated into the outcrop4.

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 mobile4,9,10. 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 mission1; more recent data9 show a very different trend, 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 depth5. This variation is consistent with post-depositional interaction of the rocks with liquid water5,6,9,10. 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 observations3,7 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 Rover2,7. The cross-stratification shown by McCollom and Hynek1 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 Meridiani7. On Earth, centimetre-scale festoon cross-lamination is known to develop only in subsurface flows2.

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 associations9. They form a ‘wetting-upward’ succession that records a progressive increase in the influence of groundwater and, ultimately, surface water in controlling depositional processes7. 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 plain11.


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Squyres et al.1 contend that our proposed volcanic origin for Meridiani Planum is inconsistent with more recently obtained data.1 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. 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.2–5. 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 the base surge deposits.7–9. Neither chemical nor morphological data therefore preclude a volcanic origin. Squyres et al. claim 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 silica4,5,10 cannot be used reliably to constrain the bulk chemical composition of the original siliciclastic input. Squyres et al. 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 bedrock1, and both the abundance of SiO₂ (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 basalts12–14 (48–51% by weight SiO₂; 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. 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. However, this siliciclastic component would have to be 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 scenario1–3,10,11 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 basal-like chemical compositions,12 which seems improbable. The sedimentary/ evaporite scenario has significant shortcomings and alternative models2,7 need to be considered.

**McCollom & Hynek reply**


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**Figure 1** Ternary diagrams showing relative molar abundances of major elements for Meridiani bedrock. Diagrams include data discussed by Squyres et al. and typical martian basalts. **a**, In a volcanic scenario, 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 shortcomings and alternative models2,7 need to be considered.

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