The Rocks of the Columbia Hills

Steven W. Squyres[1], Raymond E. Arvidson[2], Diana L. Blaney[3], Benton C. Clark[4], Larry Crumpler[5], William H. Farrand[6], Stephen Gorevan[7], Kenneth E. Herkenhoff[8], Joel Hurowitz[9], Alastair Kusack[7], Harry Y. McSween[10], Douglas W. Ming[11], Richard V. Morris[11], Steven W. Ruff[12], Alian Wang[2], and Albert Yen[3]

[1] Dept. of Astronomy, Space Sciences Bldg. Cornell University, Ithaca, NY 14853

[2] Dept. Earth and Planetary Sciences, Washington University, St. Louis, MO 63130

[3] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

[4] Lockheed Martin Corporation, Littleton, CO 80127

[5] New Mexico Museum of Natural History and Science, Albuquerque, NM 87104

[6] Space Science Institute, Boulder, CO 80301

[7] Honeybee Robotics, New York, NY 10012

[8] U.S. Geological Survey, Flagstaff, AZ 86001

[9] Dept. of Geosciences, State University of New York, Stony Brook, NY 11794

[10] Dept. of Earth and Planetary Sciences, Univ. of Tennessee, Knoxville Tennessee 37996

[11] NASA Johnson Space Center, Houston, TX 77058

[12] Dept. of Geological Sciences, Arizona State University, Tempe, AZ 85287

Abstract

The Mars Exploration Rover Spirit has identified five distinct rock types in the Columbia Hills of Gusev crater. *Clovis Class* rock is a poorly-sorted clastic rock that has undergone substantial aqueous alteration. We interpret it to be aqueously-altered ejecta deposits formed by impacts into basaltic materials. *Wishstone Class* rock is also a poorly-sorted clastic rock that has a distinctive chemical composition that is high in Ti and P and low in Cr. Wishstone Class rock may be pyroclastic in origin. *Peace Class* rock is a sedimentary material composed of ultramafic sand grains cemented by significant quantities of Mg- and Ca-sulfates. Peace Class rock may have formed when water briefly saturated the ultramafic sands, and evaporated to allow precipitation of the sulfates. *Watchtower Class* rocks are similar chemically to Wishstone Class rocks, and have undergone widely varying degrees of near-isochemical aqueous alteration. They may also be ejecta deposits, formed by impacts into Wishstone-rich materials and altered by small amounts of water. *Backstay Class* rocks are basalt/trachybasalt lavas that were emplaced in the Columbia Hills after the other rock classes were, either as impact ejecta or by localized volcanic activity. The geologic record preserved in the rocks of the Columbia Hills reveals a period very early in martian history in which volcanic materials were widespread, impact was a dominant process, and water was commonly present.

1 Introduction

For the first 155 martian days, or "sols", of its mission, the Mars Exploration Rover Spirit traversed across plains on the floor of Gusev crater [*Squyres et al*., 2004*a, Arvidson et al.,* 2005]. These plains are littered with angular blocks of impact ejecta [*Grant et al*., 2004], which were found by Spirit to be composed of olivine-rich basalt [*McSween et al*., 2004, 2005]. Study of the rocks and soils of the Gusev plains revealed evidence for transport of trace amounts of water within the soil, and for minor associated aqueous alteration of rock surfaces and precipitation of salts in soils and rock fractures [*Haskin et al*., 2005]. However, a primary conclusion drawn from the comparatively fresh nature of the Gusev plains basalts is that there has been little substantial aqueous activity in Gusev crater since the basalts were emplaced in Hesperian times [*Golombek et al*., 2005].

Circumstances changed when Spirit reached the Columbia Hills on Sol 156 of its mission. The Columbia Hills are composed of ancient materials, perhaps Noachian in age, that are surrounded and embayed by the younger Gusev plains basalts. Husband Hill, one of the highest summits in the range, rises to an elevation of about 90 meters above the plains (more than 110 meters above the landing site). Spirit first encountered Husband Hill at the base of its West Spur, a buttress that projects westward from the main mass of the hill. Over a period of many months, we commanded Spirit to ascend Husband Hill, first climbing the West Spur and then traversing across the northwest flank of the hill to Cumberland Ridge, the hill's northern summit ridge. As of this writing (in the summer of 2005), Spirit is approaching the summit of Husband Hill. The full traverse of Spirit to

date, both across the Gusev plains and up into the Columbia Hills, together with an overview of key scientific results, is described by *Arvidson et al.* [2005].

The Gusev plains where Spirit landed were marked by flat topography and apparently homogeneous rock composition. Since arriving in the Columbia Hills, however, Spirit has encountered a remarkably diverse set of lithologies. The rocks of the Columbia Hills are ancient, and in their diverse lithologies they preserve a rich record of geologic processes and environmental conditions early in martian history. In other papers in this volume, properties of Columbia Hills rocks that can be inferred from individual instruments on Spirit's payload are described in detail [*Farrand et al.*, 2005; *Ruff et al.*, 2005; *Herkenhoff et al.*, 2005; *Ming et al.*, 2005; *Morris et al.*, 2005; *Gellert et al.*, 2005]. In this paper we integrate these observations to provide detailed descriptions of all the major rock types encountered to date by Spirit in the Columbia Hills, and to draw inferences about their petrogenesis.

2 Rock Classification

We present here a simple rock classification scheme for the rocks of Gusev crater that is based on major-element geochemistry as measured by the APXS instrument [*Rieder et al.*, 2003]. This approach follows the classification convention for terrestrial volcanic rocks [*e.g.*, *Le Bas et al.*, 1986]. Although not all rocks at Gusev are volcanic, most appear to have a significant volcanic component. Each geochemically-defined class is named for a prominent rock or outcrop of that class that Spirit encountered during its traverse. To date, six distinct rock classes have been identified at Gusev crater. In order of discovery, they are:

- Adirondack Class
- Clovis Class
- Wishstone Class
- Peace Class
- Watchtower Class
- Backstay Class

Adirondack Class rocks denote the relatively unweathered olivine-rich basalts that dominate the plains on the floor of Gusev crater, and that are occasionally found as loose ejecta blocks within the Columbia Hills. All rocks that were examined in detail during the first 155 sols of the Spirit mission were of Adirondack Class. Because Adirondack Class rocks are described in detail elsewhere [*McSween et al*., 2004, 2005], we do not discuss them further here. All of the other rock classes have been found only in the Columbia Hills. Figure 1 shows the average major-element chemistry of the five classes in the Columbia Hills, each ratioed to Adirondack Class. The chemical differences among the classes are substantial, reflecting the lithologic diversity and geologic complexity of the Columbia Hills.

This classification scheme accommodates every rock that has been observed to date by Spirit in sufficient detail to determine its elemental composition. Because the classification scheme is based on major-element geochemistry, we only attempt to assign a rock to a class with certainty if we have obtained APXS data for that rock on a spot that has been abraded or brushed well by the Rock Abrasion Tool (RAT) [*Gorevan et al*., 2003] . Rocks for which reliable APXS analyses are not available, for whatever reason, are classified as "Other", although in many instances we have sufficient data to provisionally assign them to some class.

In each of the sections below, we describe the main attributes of each of the classes of rocks in the Columbia Hills, and their implications for the origin and evolution of the martian crust at this location. The rock classes are discussed in the order in which they were discovered. Figures 3-5 in *Arvidson et al*. [2005] show where and when along Spirit's traverse the rocks discussed below were found.

3 Clovis Class

3.1 Geographic Distribution: Clovis Class rocks dominate the West Spur of Husband Hill. All rocks, including both outcrop and float, that were observed on the West Spur in sufficient detail to permit classification were of Clovis Class. Moreover, no rocks of Clovis Class have been found elsewhere on Husband Hill to date, including the northwest flank and Cumberland Ridge. Rocks and outcrops of known or probable Clovis Class include Wooly Patch, Clovis, Ebenezer, Tetl, Uchben, and Lutefisk.

3.2 Geochemistry: Clovis Class rocks are closer in their bulk composition to the Adirondack Class basalts of the Gusev plains than are most other rocks in the Columbia Hills (Fig. 1). The concentrations of Si, Ti, Al and Fe in Clovis Class rocks are not notably different from those in Adirondack Class basalts, although Fe is somewhat lower. There is some significant rock-to-rock variability in the Fe and Al concentrations of Clovis Class rocks, and where Al variations are observed they correlate well with Si variations, suggesting that aluminosilicates may be present. Wooly Patch has higher Al content than the other rocks in its class, and *Wang et al*. [2005] have suggested that Wooly Patch may contain phyllosilicates.

An important distinction between Clovis Class and Adirondack Class rocks is that Clovis Class rocks are significantly enriched in S, Cl and Br [*Ming et al.*, 2005], suggesting that these elements were added during alteration of these rocks. The S, Cl and Br enrichments are evident even in deep RAT holes (the RAT was used to grind to a depth of ~9 mm in the Clovis outcrop), demonstrating that their enrichment is not a surface phenomenon. Sulfur is strongly correlated with Ca in Clovis Class rocks, suggesting that much of the S is present in Ca-sulfate. Sulfur also correlates with Na and K, but not with Mg. Chlorine correlates well with Mg, suggesting the presence of Mg-chlorides.

Clovis Class rocks are also substantially enriched in Ni (up to ~730 ppm) relative to Adirondack Class basalts. The Ni content of Clovis Class rocks is higher than expected for igneous rocks, and may reflect a meteoritic contribution to Clovis Class materials.

3.3 Mineralogy: Despite their relatively uniform chemistry, Clovis Class rocks exhibit substantial variability in Fe mineralogy that may reflect variability in the nature and degree of the alteration they have experienced. Comparison of Mössbauer Spectrometer [*Klingelhöfer et al.*, 2003] data from Clovis and Wooly Patch provides a case in point [*Morris et al., 2005*]. Clovis is the most oxidized of all the Clovis Class rocks, with Fe^{3+}/Fe_{Total} ~0.84, while Wooly Patch is the least oxidized, with Fe^{3+}/Fe_{Total} ~0.56. Clovis is rich in Fe oxides and oxyhydroxides, with 37% of its Fe in goethite, 19% in hematite, and 1% in magnetite. Wooly Patch has 6% of its Fe in goethite, 14% in goethite, and 15% in magnetite. Wooly Patch has 37% of its Fe in pyroxene, more than twice the value for Clovis, reflecting the lesser oxidation of Wooly Patch.

Fitting of the Mini-TES [*Christensen et al.*, 2003] spectra of Clovis Class rocks suggests a composition dominated (~33%) by a basaltic glass component [*Ruff et al.*, 2005]. Primary igneous silicates are only found in minor amounts, with ~10% each of Na-rich plagioclase and pyroxene (both low and high Ca) in the best-fit models. Olivine is notably absent in these models. A sulfate component of ~10-20% abundance is required for a good fit. Calcium- and Mg-sulfates, both hydrous and anhydrous, are permissible. Goethite of ~5-10% abundance is also a necessary component to produce the best fits. Some secondary minerals, including serpentine, zeolites, and trioctahedral smectites are permissible components, and could be present collectively at up to ~20% abundance.

The Mini-TES data can also be fit well by set of spectra of glassy materials from Hawaii that range from fresh to palagonitized, in combination with sulfates and oxides (including goethite).

Because Clovis Class rocks are clearly altered, normative mineralogy computed from geochemistry cannot be expected to provide an accurate representation of the actual minerals present in the rock. Norm calculations for altered rocks can be useful, however, as a "sanity check" for models of alteration; for example, exotic or implausible normative mineralogy can be a sign that rocks have experienced alteration processes that were non-isochemical. *Ming et al.* [2005] have performed CIPW norm calculations for Clovis Class rocks on a S-, Cl- and Br-free basis. The derived normative mineralogies fall into two groups, one that has >7% normative diopside, and another that has <5% normative diopside or normative corundum. Clovis itself is a member of the high normative

diopside group. Rocks in the low normative diopside group include Ebenezer, Uchben, and Wooly Patch. Ebenezer, Lutefisk and Wooly Patch are corundum-normative.

Spectral mixture analysis performed by *Farrand et al*. [2005] using 13-filter Pancam [*Bell et al*., 2003] images have shown that Clovis Class rocks form a distinct spectral "endmember" that can be distinguished from some other rock types at Gusev crater on the basis of their vis-NIR spectral properties. These properties can be helpful in inferring whether rocks that were not investigated using Spirit's *in-situ* instruments belong to the Clovis Class.

3.4 Morphology and Texture: Clovis Class materials exhibit substantial variety in morphology at outcrop scale (Fig. 2). Some rocks, such as Clovis and Wooly Patch (Figs. 2a, b), are massive, with little evident structure other than widely spaced and irregular fractures. Others, however, show distinctive structure. Notable among these is Tetl (Fig. 2c), one of several rocks on the West Spur that exhibit a fine-scale plane-parallel fabric. Individual planar elements are a few mm thick and spaced 6-8 mm apart. The structure of Tetl and other rocks like it is strongly suggestive of stratification, with alternating strata of resistant and less resistant material. Another nearby rock, Palenque (Fig. 2d), shows similar fine-scale planar structure in its lower portion, truncated unconformably and overlain by a more massive unit. (Palenque was not examined by any of the in-situ instruments on the payload, and is inferred to be of Clovis Class on the basis of its Mini-TES and Pancam spectral properties.)

At a fine scale, Microscopic Imager (MI) [*Herkenhoff et al*., 2003] images reveal Clovis Class materials to be poorly sorted clastic rocks. A good example is Lutefisk, shown in Fig. 3. Clasts are evident within Lutefisk with sizes ranging from the resolution

limit (~100 µm; pixel scale is 30 µm) to several mm. Large clasts appear to be relatively resistant to erosion; in fact, Pancam images show that the surfaces of many rocks across the West Spur are studded with raised clasts ranging from a few mm up to ~1 cm in size. Most large clasts in Pancam and MI images of West Spur rocks are angular, although some sectioned by the RAT in the rock Uchben appear subangular to rounded [*Herkenhoff et al.*, 2005].

3.5 Physical Properties: In order to assess the strength of the rocks encountered by Spirit, we consider a parameter called the specific grind energy, or SGE [*Gorevan et al.*, 2005]. SGE is a quantitative measure of the energy consumed by grinding into a rock with the Rock Abrasion Tool, and is calculated by dividing the energy expended during a grind by the volume of material removed. The computation is performed for just the last 0.25 mm of a grind to eliminate surface roughness effects and so that the value is as representative as possible of the bulk rock. Laboratory experiments have shown that SGE is moderately well correlated with the compressive yield strength of rocks [*Gorevan et al.*, 2003].

Specific grind energy values for Clovis Class rocks are substantially lower than SGE values for Adirondack Class rocks. Typical values for Adirondack Class rocks are 50-60 J mm^{-3}, comparable to values found in laboratory grind experiments for lightly-altered, massive basalts. In contrast, SGE values for Clovis Class rocks are only 4-9 J mm^{-3}, values more typical of weak terrestrial geologic materials like gypsum or poorly indurated limestone. The much weaker character of Clovis Class rocks is consistent with the notion that they have undergone substantial alteration.

3.6 Other Rocks of Probable Clovis Class: Spirit observed many rocks on the West Spur of Husband Hill that were probably of Clovis Class, but for which we did not obtain elemental chemical data of sufficient quality to make definitive classification possible. Of these, perhaps the most significant is Pot of Gold (Fig. 4). Pot of Gold was the first rock encountered by Spirit in the Columbia Hills. It is a small piece of float, with a morphology unlike any encountered by Spirit before or since. Like some other Clovis Class rocks, Pot of Gold contains a number of large clasts several mm in size. Unlike any other rock Spirit has observed, these clasts are at the ends of long, thin stalks of rock (Fig 4a). The resultant shape is extraordinarily irregular, which is why it was not possible to abrade Pot of Gold with the RAT completely and obtain definitive APXS chemistry. At fine scales, the surface of Pot of Gold is dominated by small pits with typical dimensions of a few tenths of a millimeter (Fig. 4b).

Attempts to brush and abrade Pot of Gold with the RAT did sever some of the stalks, and removed some of the rock's significant covering of soil. Post-RAT APXS measurements revealed a composition fairly similar to other Clovis Class rocks [*Ming et al.*, 2005]. This finding and the location of Pot of Gold on the West Spur lead us to suggest that Pot of Gold is probably a Clovis Class rock. Pot of Gold has an unusually high hematite content; 34% of the Fe in Pot of Gold is present in hematite [*Morris et al.*, 2005].

3.7 Origin and Evolution: Clovis Class materials are poorly sorted clastic rocks of basaltic bulk composition. The apparent fine-scale layering in some exposures may be indicative of deposition of particles in a fluid (water or air), and the poor sorting is indicative a high-energy environment or event that mixed clasts over a wide range of size

scales. The detection of a glass-like signature in Mini-TES spectra suggests that molten material was involved in the formation process. Taken together, these characteristics are consistent with emplacement of Clovis Class rocks by an explosive process, either pyroclastic volcanism or impact. Because there are no observations (*e.g*., graded bedding) that favor deposition in water, subaerial deposition is the most straightforward explanation.

The textural and morphologic properties of Clovis Class rocks are consistent with them being either tephra or impact ejecta. The high Ni content in the rocks favors the latter. (We assume in making this statement that ancient impactors on Mars, like most modern impactors on Earth, were Ni rich.) It is noteworthy that the Ni content of Clovis Class rocks is comparable to or higher than the Ni content of soils on the Gusev plains, which have been inferred to have a small but significant meteoritic component [*Yen et al*., 2005]; indeed the elemental chemistry of Clovis Class rocks is similar to that of Gusev soils in many respects. A straightforward explanation for Clovis Class rocks, then, could be that they represent the ejecta of impacts into ancient crustal material, perhaps regolith, that had meteoritic debris mixed into it by previous impact events.

After their formation, Clovis Class rocks were extensively altered. Primary basaltic mineralogy is not well displayed: olivine is absent or nearly absent, and the amount of Fe in pyroxene is highly variable [*Morris et al*., 2005]. The rocks are mechanically weak and heavily oxidized, and the presence of goethite clearly implicates water in the alteration process. The enrichments in S, Cl and Br suggest that aqueous processes led to precipitation of salts in these rocks, notably Ca-sulfates and lesser Mg-chlorides.

Potential alteration processes for these rocks include "acid fog" weathering [*Banin et al.*, 1997], and leaching and precipitation by S-, Cl-, and Br-laden acidic fluids. In this context, it may be noteworthy that some Clovis Class rocks are corundum normative [*Ming et al.*, 2005]. Because primary igneous rocks on Earth are rarely corundum normative, we infer that the corundum normative rocks of the Clovis Class probably had their original compositions changed by alteration processes. And because "acid fog" weathering should be nearly isochemical, it seems likely that aqueous fluids played a significant role in altering at least some Clovis Class rocks.

Ming et al. [2005] have developed two different models for the alteration mineralogy of Clovis Class rocks, reflecting the possibilities of moderate and extreme aqueous alteration. Fe is present in both models in nanophase oxides (np-Ox), goethite, hematite, as well as in residual pyroxene whose abundance depends on the degree of alteration. Significant alkali feldspar is present in the moderately-altered model, while secondary aluminosilicates dominate in the heavily-altered one. In both models, ~10% Ca-sulfate is present. These models reflect the significant remaining uncertainties in the mineralogy of Clovis Class rocks, but both are consistent with the view that the rocks are basaltic-composition impact ejecta that have undergone substantial aqueous alteration.

4 Wishstone Class

4.1 Geographic Distribution: Wishstone Class rocks were first found on the northwest flank of Husband Hill, after Spirit left the West Spur and began the climb toward Cumberland Ridge. The two best examples of Wishstone Class rocks investigated to date are Wishstone and Champagne. Both of these rocks are float; indeed, no outcrops

of Wishstone Class material have been found yet. As discussed below, Wishstone Class rocks have fairly distinctive surface textures and Mini-TES spectral properties. Based on the wide occurrence of rocks with these properties, we believe that Wishstone Class rocks dominate the float on the northwest flank of Husband Hill and are also common among the float on Cumberland Ridge.

4.2 Geochemistry: Wishstone Class rocks are strikingly different in their major element chemistry from rocks of both Adirondack and Clovis Class (Fig. 1). Iron is lower, and Al is significantly higher. Typical Al values are ~16 wt % Al_2O_3, which exceeds that of any martian meteorite and which leads to an Al/Si molar ratio for Wishstone Class rocks that is higher than for any other rock type observed to date in the Columbia Hills.

The most distinctive chemical characteristic of Wishstone Class rocks is that they are notably high in Ti and P, and low in Cr. Titanium is typically ~3 wt % TiO_2, and phosphorus is up to 5.2 wt. % P_2O_5. Chromium is so low that it is essentially not detected. This high-Ti, high-P, low-Cr "fingerprint" is a distinctive characteristic of a number of rocks and outcrops on Husband Hill (see below).

In contrast to Clovis Class rocks, which are highly altered, Wishstone Class rocks are not significantly enriched in S, Cl or Br. Wishstone Class rocks also show no enrichment in Ni. The Ni content of Wishstone Class rocks is substantially lower than that of Clovis Class rocks, and in fact is even lower than that of Adirondack Class rocks.

Element correlations provide some insight into mineralogy. Phosphorous is strongly correlated with Ca in Wishstone Class rocks, suggesting the presence of Ca-phosphate, possibly as apatite, whitlockite, or merrillite [*Ming et al*., 2005]. Na is

14

correlated with Al, suggesting the presence of Na aluminosilicates. The comparatively low degree of oxidation (see below) and its implication of only moderate alteration for Wishstone Class rocks suggests that these aluminosilicates may be primary (*e.g.*, feldspar).

How much of the P in Wishstone Class rocks is primary is an open question. The P_2O_5 content of Wishstone Class rocks is unusually high for igneous systems. On the other hand, we show below that Wishstone Class rocks have undergone only moderate alteration, and that the widely varying degree of alteration that has been experienced by Watchtower Class rocks has done little to change the P content of those rocks.

4.3 Mineralogy: Mössbauer data for Wishstone Class rocks suggest a less altered mineralogy than Clovis Class rocks, with 27% of Fe present in pyroxene and 23% present in olivine. Other Fe-bearing phases include np-Ox (18% of Fe), hematite (10%), magnetite (10%), and goethite (4%). Mössbauer data also show that ~9% of the Fe is present in ilmenite, consistent with the high Ti content of Wishstone Class rocks. The rocks are considerably less oxidized than Clovis Class rocks, with typical Fe^{3+}/Fe_{Total} values of 0.29-0.47 [*Morris et al*., 2005].

Mini-TES spectra of Wishstone Class rocks show a strong plagioclase signature, which is modeled in our spectral fitting procedure as labradorite [*Ruff et al*., 2005]. Mini-TES data also reveal smaller amounts of pyroxene and olivine (pyroxene > olivine), and minor phosphates.

Pancam 13-filter images of dust-free Wishstone Class rock surfaces display significant "900 nm" band depths (with a band minimum in the 934 nm band) and a relative reflectance maximum at 754 nm [*Farrand et al*., 2005]. These features set this

class of rocks apart from the Clovis Class, which exhibit a weaker long wavelength absorption and a relative reflectance maximum at shorter wavelengths. We take the significant long wavelength absorption in Wishstone Class rocks to be indicative of the presence of pyroxenes, with a contribution from olivine as well.

Normative mineralogy calculated from APXS data [*Ming et al.*, 2005] puts both Wishstone and Champagne in the low normative diopside group. The computed normative mineralogy is rich in plagioclase (~44% albite, ~10% anorthite). The calculation also yields ~17% olivine and 4-5% pyroxene. Overall, then, the various independent determinations of mineralogy are mutually consistent, and indicate that that Wishstone Class rocks are moderately altered rocks dominated by intermediate plagioclase, with substantial amounts of olivine and pyroxene and significant Fe oxides and oxyhydroxides, ilmenite, and Ca-phosphate.

4.4 Morphology and Texture: In Pancam images, Wishstone Class rocks have a distinctive fine-scale texture composed of densely-spaced knobs and pits (Fig. 5, particularly Fig. 5b). This texture contrasts markedly with the smooth surfaces of most Adirondack Class rocks, and also with Clovis Class rocks, which are primarily smooth but which have widely-spaced small knobs associated resistant coarse clasts. The distinctive texture of Wishstone Class rocks probably results from long-term abrasion by saltating grains, and reflects the existence of closely-spaced domains of varying hardness within the rock. To date, no layering has been observed in any Wishstone Class rocks.

MI images show that Wishstone Class rocks are composed of poorly-sorted clasts up to 1-2 mm in size embedded in a fine-grained matrix (Fig. 6). The clasts are irregularly shaped and in some instances are highly angular. In general appearance and in

16

some significant details, MI images of Wishstone Class rocks are strikingly similar to high-resolution images of ash-flow tuffs.

4.5 Physical Properties: Wishstone Class rocks are significantly stronger than Clovis Class rocks. The specific grind energy values for Wishstone and Champagne are 24 and 15 J mm^{-3}, respectively, several times larger than the values for rocks of Clovis Class. These higher values are in line with the less-altered character of Wishstone Class rocks.

4.6 Origin and Evolution: All of the compositional data for Wishstone Class materials provide a consistent picture of a rock that is rich in plagioclase, with lesser amounts of pyroxene and olivine and some Fe oxides and oxyhydroxides. The rock is strikingly high in Ti and P, and low in Cr; this distinctive chemical fingerprint, as we show below, is also important in Watchtower Class rocks. Titanium is present in ilmenite, and P appears to be present largely in Ca-phosphate.

Wishstone Class rocks are among the least altered materials found in the Columbia Hills. Evidence for this is provided by the comparatively low Fe^{3+}/Fe_{Total}, and by the generally good agreement between normative mineralogy and measured mineralogy. It is also significant that Wishstone Class rocks do not show a strong enrichment in S, Cl and Br, which are found in high concentrations in Clovis Class rocks and which we attribute there to precipitation from aqueous fluids.

The texture of Wishstone Class rocks, which is dominated by angular clasts, suggests an origin by some explosive process, either explosive volcanism or impact. The strong textural similarity of Wishstone Class rocks to ash-flow tuffs at MI scales is noteworthy, though it is plausible that impact-related flows could result in similar

17

textures at high enough atmospheric density and at appropriate distances from the impact point. In the case of Clovis Class rocks, the significant Ni enrichment leads us to favor an impact origin. Wishstone Class rocks show no such enrichment. The lack of Ni enrichment in Wishstone Class rocks and the strong visual similarity to ash-flow tuffs lead us to suggest that Wishstone Class rocks may be pyroclastic in origin, but we cannot rule out the possibility that they are impact deposits. In either case, they have undergone significantly less aqueous alteration since their formation than most other major rock types in the Columbia Hills.

5 Peace Class

5.1 Geographic Distribution: Peace Class materials have been uncommon to date. Only two exposures, both outcrops, have been found. Their names are Peace and Alligator, and both were found on the northwest flank of Husband Hill, several tens of meters west of the crest of Cumberland Ridge.

5.2 Geochemistry: Compared to other rocks at Gusev crater, Peace Class rocks are strikingly low in Al, Na and K (Fig. 1). The Al_2O_3 content of Peace is just 2.24 wt %, and the Al/Si molar ratio is the lowest of all materials examined by Spirit to date. The low Al content, along with the almost total lack of alkali elements, suggests that Peace Class rocks are low in feldspar. As pointed out by *Ming et al.* [2005], the major-element chemistry of Peace Class rocks shows some strong similarities to martian meteorites that are ultramafic cumulate lherzolites.

Peace Class rocks differ dramatically from SNC meteorites, and from any other rocks in Gusev crater, in their S content. The S content of Peace is 12.9 wt % SO_3, which is substantially higher than for any other rock type examined by Spirit. In fact, the only rocks on Mars known to contain more S than Peace Class rocks are the evaporitic rocks at Meridiani Planum studied by the rover Opportunity [*Squyres et al.*, 2004*b*]. Based on their high S content and on our experience with other martian materials at both MER landing sites, it is likely that Peace Class rocks contain a substantial quantity of sulfate salts.

The primary cations in the sulfates of Peace Class rocks can be inferred using element correlations. Although we are limited by the rarity of Peace Class rocks, there is a notable correlation of S with both Mg and Ca in the few measurements that have been made [*Ming et al.*, 2005]. It is likely, then, that Mg- and Ca-sulfates are dominant. Altogether, sulfate salts must make up about 16-17% of the Peace Class rocks investigated.

5.3 Mineralogy: Despite the high sulfate content of Peace Class rocks, other key aspects of the mineralogy resemble those of a lightly altered lherzolite. Mössbauer spectra show that 27% of Fe is present in olivine, and 30% in pyroxene [*Morris et al.*, 2005]. Only 15% of Fe is present in np-Ox, and the value of Fe^{3+}/Fe_{Total} is only about 0.35, both indicating a low degree of alteration. Interestingly, Mössbauer data show that 28% of the Fe in Peace Class rocks is present in magnetite, the highest value for any martian rock to date. Mössbauer spectra do not reveal any hematite, goethite, or Fe-sulfates.

Because of their very irregular surface textures (see below), Peace Class rocks present a challenging target for Mini-TES. Indentations in the rock tend to trap fine soil particles, masking the IR signature of the underlying rock, and the same indentations create small local blackbody cavities that reduce spectral contrast. However, Mini-TES observations of the cuttings produced by RAT abrasion in Peace Class rocks are noteworthy in that they have shown a distinct bound water feature at 6 µm [*Ruff et al.*, 2005]. This feature is probably attributable to water that is bound in the sulfate salts present in these rocks.

Pancam multispectral observations of Peace Class rocks are also affected by the loose soil coatings on these rocks, but 13-filter observations of the rock surface abraded by the RAT show a spectrum in the NIR that is very similar to that of Adirondack Class basalts [*Farrand et al.*, 2005]. At visible wavelengths, Peace has a negative 535 nm band depth, indicative of the general lack of crystalline Fe^{3+}-bearing materials.

Because of the very high SO_3 content of Peace Class rocks and its effect on cation partitioning, we do not consider the normative mineralogy of Peace Class rocks here.

5.4 Morphology and Texture: Pancam images show that the outcrops of Peace Class rock observed to date are finely layered (Figs. 7, 8). The two outcrops, Peace and Alligator, are about 12 meters apart. Peace is too fractured to determine structural attitude with confidence, but Alligator clearly dips gently to the northwest, with bedding that is nearly conformal with the local topography. No cross stratification is observed, although the small size of the outcrop and the paucity of well exposed bedding would make its recognition difficult.

Microscopic Imager images of Peace Class rocks are shown in Figure 8. The rocks are clastic, with individual clasts up to a few mm in size (Fig. 8a). Images obtained at a high angle to bedding (Figs. 8b, 8c) show that the rock is finely layered, with layers that in some instances are only several mm thick.

At the finest scale, the rock is dominated by a faintly-expressed granularity that has a characteristic size scale of a few tenths of a mm. This texture is particularly well expressed in Figure 8c, but it is present in all MI images of Peace Class rocks, and it may represent the dominant grain size of the primary basaltic clasts in the rock. While coarse clasts up to a few mm in size are present at some locations (*e.g.*, Fig. 8a), the pervasive nature of the fine granular texture suggests that the larger clasts may actually be cemented aggregates of smaller (fine to medium sand) grains.

Further evidence that the intrinsic grain size of the basaltic component of Peace Class rocks is in the range of hundreds of μm is provided by Fig. 9. Peace was subjected to a two-step grind with the Rock Abrasion Tool. The first step abraded away part of the rock's irregular surface and then brushed it, exposing a clean surface for MI imaging, while the second step abraded much deeper, exposing the interior of the rock for optimal APXS and Mössbauer investigation. Figure 9 shows the surface after the first grind, with the area that was actually abraded and brushed by the RAT outlined in red. A fine granular texture is seen, with typical grain sizes of 0.1-0.2 mm.

In exposures where layering is not evident (Fig. 8d), Peace Class rocks display a porous, almost spongy texture. The fine to medium sand-sized granular texture is clearly evident, and the grains appear to be bound together and encrusted with a cement.

5.5 Physical Properties: Only one Peace Class rock – Peace itself – has been abraded with the Rock Abrasion Tool. Peace is the weakest rock investigated by Spirit at Gusev crater, with a specific grind energy of only about 2 J mm^{-3}. This value is substantially lower than even the SGE of highly altered Clovis Class rocks. The only rocks with comparable SGE values investigated by either rover have been lightly-cemented sulfate-rich sedimentary rocks at Meridiani Planum [*Squyres et al.*, 2004*b*].

5.6 Origin and Evolution: Peace Class rocks have little in common with the other major rock types of the Columbia Hills. They have two components. One is ultramafic sand. Its mineralogy, however, is different from any known SNC, with an unusually high concentration of magnetite. The ultramafic component has undergone less alteration than most other materials in the Columbia Hills, with a low value of Fe^{3+}/Fe_{Total} and little evidence for alteration minerals.

The other component of Peace Class rocks is sulfate salt. Microscopic Imager images revealing grain cementation and the very low strength of the rock suggest that the sulfates form a cement that loosely binds the ultramafic grains together. We therefore interpret Peace Class rocks to be ultramafic sandstones cemented by Mg- and Ca-sulfates. The substantial quantity of SO_3 suggests that the sulfates were precipitated from water, perhaps in an evaporative process.

The presence of sand-sized grains that have suffered little aqueous alteration in a cement that was precipitated from water suggests that the exposure of the grains to water during the aqueous episode was very limited. The cement may be essentially a sulfate caliche, deposited by a quantity of water that was modest enough not to lead to pervasive aqueous alteration of the ultramafic sand grains. The preservation of olivine also suggests

22

that the water, unlike martian groundwater at some other locations, may not have been highly acidic [*e.g., Squyres et al.*, 2004*b, Haskin et al.,* 2005*, Hurowitz et al.,* 2005].

The origin of the layering in Peace Class rocks is enigmatic, and could result from deposition in either air or water. The presence of coarse clasts that may be cemented aggregates (*e.g*., Figs. 8a, 8b) suggests that the layering may have developed as a result of eolian or aqueous reworking that took place after initial precipitation of the sulfate cement.

6 Watchtower Class

6.1 Geographic Distribution: Watchtower Class rocks have been found to date only on Cumberland Ridge, where they form rugged and prominent outcrops. Some of these outcrops are stratified, and the materials there are of sufficient variety and thickness that they form the only true stratigraphic section investigated to date by Spirit at Gusev crater. We will describe the stratigraphy of this section in a subsequent publication, once we have determined structural attitudes with sufficient accuracy to reveal outcrop-to-outcrop stratigraphic correlations.

Like Peace and Alligator, the Watchtower Class rocks on Cumberland Ridge dip gently to the northwest, suggesting that Watchtower Class and Peace Class rocks may be part of a common stratigraphy. Although more structural work on this stratigraphy is required, we note briefly here that the Watchtower Class outcrops of Cumberland Ridge appear to lie stratigraphically lower than Peace and Alligator if the section is not inverted.

Major exposures of Watchtower Class material include Watchtower, Keystone, Paros, Pequod, and Keel, all of which lie on Cumberland Ridge.

6.2 Geochemistry: The elemental composition of Watchtower class rocks is similar to that of Wishstone Class rocks, with the same characteristic signature of high Ti, high P and low Cr (Fig. 1). Watchtower Class rocks differ from Wishstone Class rocks in that they are somewhat higher in Mg, S and Cl.

Watchtower Class rocks appear to show somewhat greater compositional diversity within the class than do some other rock types in the Columbia Hills. This apparent variability might result in part from the fact that only one Watchtower Class rock, Watchtower itself, was abraded by the RAT. The diamond-impregnated grind heads on the RAT wore away while Watchtower was being abraded, after many grinds on other rocks, and APXS measurements for all other Watchtower Class rocks were made on brushed rather than abraded surfaces. (See *Arvidson et al.*, 2005, for a detailed timeline.)

Recent work on element correlations by *Hurowitz et al.* [2006] has shown that much of the major element compositional variability evident for Watchtower Class rocks is consistent with mixing between two endmember rocks in varying relative proportions. One endmember has the approximate composition of Wishstone Class rocks, while the other endmember is richer in ferromagnesian elements (Mg, Fe, Mn, Cr, Ni, Zn) than Wishstone Class rocks. In all cases the Wishstone-like endmember dominates the mix, consistent with the broad similarity of Watchtower Class to Wishstone Class. The 2-component mixing relationship is not affected by the fact that some rocks have been abraded and brushed and others merely brushed; the relationships remain evident when

only brushed surfaces are examined and when possible surface contamination is taken into account..

6.3 Mineralogy: The mineralogy of Watchtower Class rocks is remarkably variable [*Morris et al.*, 2005]. Watchtower itself is heavily altered, with 39% of Fe present in np-Ox, 31% in hematite, and 12% in goethite. The value of Fe^{3+}/Fe_{Total} for Watchtower is 0.83, one of the highest values in the Columbia Hills. Paros, another Watchtower Class rock, is even more heavily altered, with 66% of Fe in np-Ox, and Fe^{3+}/Fe_{Total} ~0.94.

At the other end of the spectrum, the Watchtower Class rock Keystone has Fe^{3+}/Fe_{Total} of just ~0.43, 47% of Fe present in pyroxene, and only 17% of Fe present in np-Ox. Other rocks, such as Keel (Fe^{3+}/Fe_{Total} ~0.69) , are intermediate in their degree of alteration.

Mini-TES is able to distinguish moderately altered Watchtower Class rocks from highly altered ones [*Ruff et al.*, 2005], and this ability has allowed us to map the distribution of alteration within Watchtower Class outcrops. The distribution is remarkably heterogeneous, with substantial variations in alteration over less than 1 m of stratigraphic section and over lateral distances of ~10 m.

In Pancam multispectral images, many Watchtower Class rocks have a band minimum at 900 nm and a relative reflectance maximum at 754 nm. Some are unique among Columbia Hills rocks in having a positive slope from the 754 to the 1009 nm Pancam bands [*Farrand et al.*, 2005], probably because of the high hematite abundance in the most altered members of the class. Highly altered Watchtower Class rocks, like highly altered Clovis Class rocks, also have high 535 nm band depth values. *Farrand et*

al. [2005] have shown a strong correlation between 535 nm band depth and Mössbauer spectrometer observations of Fe^{3+}/Fe_{Total}.

Normative mineralogy of Watchtower Class rocks is broadly similar to that of Wishstone Class rocks, reflecting the geochemical similarity of the two classes [*Ming et al.*, 2005]. Because some Watchtower Class rocks are so heavily altered, however, such calculations cannot be expected to reveal much about the true mineralogy of the rocks.

6.4 Morphology and Texture: Watchtower Class rocks are texturally diverse. Watchtower itself (Fig. 10) is typical of the rocks on the west side of Larry's Lookout, a large outcrop on the crest of Cumberland Ridge. In Pancam images (Fig. 10a) Watchtower is similar in morphology to Wishstone Class rocks, with closely-spaced knobs and pits. In MI images (Fig. 10b), however, the rock exhibits only fine grains and little evident structure.

Not far from Larry's Lookout is Methuselah, another large outcrop of Watchtower Class rock. Keystone (Fig. 11) is typical of Methuselah, and is dramatically different in appearance from the rocks of Larry's Lookout. In Pancam images, Keystone is finely layered, with individual layers only 1-2 mm thick. Methuselah is a large outcrop, with Keystone-like fine layering throughout. We have examined it thoroughly for cross-stratification, but we have found none.

Figure 12 is a 4×6-frame Microscopic Imager mosaic of Keystone, the largest MI mosaic obtained to date by either Spirit or Opportunity. The rock is finely pitted on scales of a few tenths of a mm. Individual layers are etched into intricate relief, probably reflecting fine-scale variations in the degree of induration. In both the fine-scale pitting

and the complex relief Keystone is reminiscent of Pot of Gold, although it lacks Pot of Gold's distinctive large clasts on stalks.

Yet another surface texture is exhibited by Pequod (Fig. 13), a Watchtower Class rock on the eastern, stratigraphically lower side of Larry's Lookout. Pequod and many other rocks like it have a distinctive bulbous or globular texture. Individual rounded texture elements that are typically 1-4 mm in size, and they commonly appear merged or fused together along their boundaries. The most straightforward explanation for the globular texture is that the individual rounded texture elements are lapilli. The highly rounded, almost softened appearance of the rock may result from minor recrystallization or precipitation of cements associated with subsequent alteration. All instances of this texture are moderately to highly altered; for example, Pequod has a value for Fe^{3+}/Fe_{Total} of ~0.85.

6.5 Physical Properties: Only one Watchtower Class rock, Watchtower itself, has been abraded with the RAT, yielding a specific grind energy of 12.6 J mm^{-3}. This value is somewhat lower than that of Wishstone Class rocks, consistent with the fact that Watchtower is compositionally similar to Wishstone Class rocks, but more heavily altered.

6.6 Origin and Evolution: Watchtower Class rocks show considerable variety in appearance, with textures that range from massive to finely layered to globular. Layered examples like Keystone point to deposition in a fluid, either air or water. Globular textures like those in Pequod could be indicators of emplacement by an explosive mechanism, either volcanic or impact, if the spheroidal features are indeed lapilli.

Overall, however, it is difficult to determine how Watchtower Class rocks were deposited on the basis of their texture alone.

Additional information is provided by their chemistry. Their chemical similarity to Wishstone Class rocks hints at a genetic link. In particular, the fact that the chemistry of Watchtower Class rocks is matched well by simple linear mixing of an endmember similar to Wishstone with lesser amounts of another endmember that is richer in ferromagnesian material suggests that some mixing process may have been involved in formation of Watchtower Class rocks.

Watchtower Class rocks are like Clovis Class rocks in that most of their properties permit origin either by explosive volcanism or impact. In the case of Clovis Class rocks, we tentatively favor impact because of the high Ni content. Watchtower class rocks do not show a Ni enrichment, so that argument does not apply. However, the mixing arguments above suggest that impact again may be implicated, since impact provides a straightforward mixing mechanism. Accordingly, we conclude that Watchtower Class rocks may be fine-grained impact ejecta from one or more impacts into a material that was composed of Wishstone Class materials and a lesser quantity of another material richer in ferromagnesian elements. The layering in Keystone could have formed as fine-grained impact-generated debris settled in air or as part of a basal surge deposit. The globular features could indeed be lapilli formed in an air-suspended cloud of impact debris.

The substantial variability in the degree of alteration of Watchtower Class rocks is noteworthy, particularly because it occurs over such small length scales. Because the alteration is nearly isochemical, and because the rocks do not show substantial

enrichments in S, Cl and Br, we see no need to invoke interaction of Watchtower Class rocks with large amounts of liquid water. Instead, their near-isochemical alteration can be explained by interaction with H_2O at low water/rock ratios, in either the liquid or vapor state. Highly variable alteration over short length scales could perhaps result from short-lived local flows of hydrothermal fluids or vapors set up within a hot ejecta blanket immediately after its deposition [*e.g., Newsom, 1980*].

It is particularly interesting that Watchtower Class rocks show a large variation in degree of alteration, but very little variation in P content. Phosphorous could readily be introduced by some forms of aqueous alteration, but the widely varying degree of near-isochemical alteration suggests that this was not the case for Watchtower Class rocks. Instead, Watchtower Class rocks appear to have inherited their substantial phosphates from the Wishstone Class materials from which they formed. Whether the P in Wishstone Class rocks is primary or is in part a consequence of the modest alteration that Wishstone Class rocks have undergone is unclear. What is clear, however, is that the substantial alteration that some Watchtower Class rocks have experienced has done little to modify their P content.

7 Backstay Class

7.1 Geographic Distribution: To date, only one rock of this class – the rock Backstay – has been investigated in detail by Spirit. Backstay was found on the crest of Cumberland Ridge, not far from the Watchtower Class outcrops Jibsheet and Methuselah. Unlike these outcrops, however, Backstay is a piece of float whose provenance cannot be

determined. Mini-TES data (see below) suggest that many other pieces of Backstay Class float are also present in this area.

7.2 Geochemistry: Backstay is the rock in the Columbia Hills that is most like Adirondack Class rocks in its elemental chemistry (Fig. 1). It differs from Adirondack Class primarily in that it is higher in Ti, Al, K, and Na, and lower in Fe.

Unfortunately, the grinding teeth on Spirit's Rock Abrasion Tool were worn away before Backstay was encountered, so we have no APXS measurements in a RAT hole for this rock. Backstay was, however, brushed successfully by the RAT. We have found that brushing with the RAT is good at removing the loose coatings of dust and salt that are common on rocks at Gusev, especially when a rock surface is smooth like Backstay's. However, comparisons of brushed and abraded surfaces of other rock classes at the Spirit landing site have consistently shown subtle differences in chemistry, suggesting the operation of a surface alteration process [*Hurowitz et al.*, 2005]. Keeping these limitations in mind, we conclude that the elemental chemistry of Backstay is consistent with it being a relatively unaltered basalt/trachybasalt. There is no known SNC meteorite that provides a good compositional match to Backstay.

7.3 Mineralogy: Data from the Mössbauer Spectrometer show that 35% of the Fe in Backstay is present in olivine, 37% in pyroxene, 11% in magnetite, 3% in ilmenite (consistent with its relatively high Ti content), and 13% in np-Ox. This Fe mineralogy is similar to that of Adirondack Class rocks, although with less olivine and more np-Ox. It is plausible that much of the np-Ox detected by the Mössbauer is present in a thin weathering rind that could not be removed by brushing, but would have been removed by abrasion. Regardless of the np-Ox content, however, Fe^{3+}/Fe_{Total} is only 0.23,

considerably lower than anything else in the Columbia Hills and approaching that of Adirondack Class rock.

Backstay was initially identified as a unique rock on the basis of its Mini-TES spectrum. Figure 14a shows Mini-TES spectra of several basaltic rocks at Gusev crater, including two different spectra of Backstay that were obtained under different atmospheric conditions. Both spectra show features in the 10-12 µm region that are not exhibited by other rocks. As shown in Fig. 14b, these features are similar to features that are found in the basaltic SNC meteorite EET79001 [*Hamilton et al*., 1997], and that are attributable to the high pigeonite content of that meteorite. In fact, addition of plagioclase to EET79001 yields a spectrum that is very similar to that of Backstay [*Ruff et al*., 2005].

The normative mineralogy of Backstay agrees well with the Fe mineralogy measured by the Mössbauer, with ~57% feldspar, ~25% pyroxene, ~11% olivine, ~1% magnetite, and ~2% ilmenite. Again, this observation is consistent with the view that Backstay is a basalt/trachybasalt that has undergone little alteration.

7.4 Morphology and Texture: In its visual appearance in Pancam and MI images, Backstay is indistinguishable from Adirondack Class rocks (Fig. 15). In Pancam images the rock is smooth and faceted (Fig. 15a), evidently having undergone long-term abrasion by saltating particles. Near ground level is a small spike, several mm long, that may have developed where a resistant phenocryst protected rock behind it from erosion. Microscopic Imager images (Fig 15b) show a dark surface that is pitted at sub-mm scales; in Adirondack Class rocks this pitting has been attributed to preferential dissolution of olivine crystals under acidic surface conditions [*McSween et al*., 2005]. Several bright fractures are observed in Backstay. In Adirondack Class rocks such features are attributed

to filling of fractures by thin veins of precipitated salts [*McSween et al.*, 2004], but it is difficult to reach the same conclusion for the fractures in Backstay in the absence of a surface abraded by the RAT.

7.5 Physical Properties: Because the grinding teeth of Spirit's Rock Abrasion Tool wore away before Backstay was encountered, we have no data on the SGE of Backstay Class rocks. The relatively unaltered igneous mineralogy of Backstay and the visual similarity of Backstay to Adirondack Class rocks suggest that Backstay Class rocks may be strong relative to most other rock classes encountered in the Columbia Hills, but this is conjecture.

7.6 Origin and Evolution: Backstay is a loose piece of basalt/trachybasalt, similar to Adirondack Class rocks in its low degree of alteration but distinct from Adirondack Class rocks in its chemistry and mineralogy. Because it is much less altered than other rock types in the Columbia Hills, it may be younger than most Columbia Hills rocks, and perhaps more comparable in age to the plains rocks of Adirondack Class. The low degree of alteration suggests that Backstay may have been formed after the near-cessation of aqueous activity that preceded the emplacement of the Adirondack Class basalts on the plains [*Golombek et al.*, 2005].

How Backstay arrived at its position on Cumberland Ridge is unknown. Because it is a loose block, it certainly could have been transported there by impact, perhaps from a considerable distance. However, this idea is called into question by the distribution of other apparent Backstay Class rocks on Husband Hill. As noted above, Backstay Class rocks have a distinctive Mini-TES spectral signature, and several other rocks of probable Backstay Class have been found [*Ruff et al.*, 2005]. All of these are high on Husband

Hill, at elevations of 50 meters or more above the plains. No Backstay Class rocks have been found at lower elevations, despite the fact that we obtained Mini-TES spectra of many rocks there. There is no obvious reason why blocks transported from large distances by impact should be found only on the upper portions of the hill. While the distribution could be coincidental, it is also possible that bedrock that forms the source material for Backstay Class float is present somewhere high on Husband Hill, and that fragments of Backstay Class float have arrived at their current locations via downslope transport. If so, Backstay could represent an episode of igneous activity in the Columbia Hills that postdated formation of most of the rocks in the hills. Without any observations of Backstay Class bedrock, however, we cannot rule out the alternate possibility that it is an older rock that was somehow isolated from the aqueous alteration that affected other Columbia Hills rocks, and then transported to its current location. We are still searching for possible intrusions or other exposures of Backstay Class bedrock on the upper flanks of Husband Hill.

8 Discussion

As of this writing, Spirit has traversed about 800 meters in the Columbia Hills. Along the way it has identified five distinct, diverse rock types (Table 1). Backstay Class rocks are igneous rocks of probable volcanic origin. Wishstone Class rocks could be either impact ejecta or pyroclastic rocks; we tentatively favor a pyroclastic origin. We suspect that both Clovis Class and Watchtower Class rocks are impact ejecta, albeit of notably different composition. And Peace Class rocks, which are basaltic sandstones cemented by Ca- and Mg-sulfate salts, can properly be classified as sedimentary rocks.

All of these rocks show evidence of alteration, but to dramatically different degrees. Backstay Class rocks appear to have only a lightly-altered outer weathering rind, similar to that found on Adirondack Class rocks [*Hurowitz et al.*, 2005]. Wishstone Class rocks are moderately altered. Clovis Class rocks have undergone substantial non-isochemical alteration that we attribute largely to interaction with liquid water. Watchtower Class rocks have undergone widely varying degrees of near-isochemical alteration. And Peace Class rocks consist of lightly-altered ultramafic grains cemented by salts that probably formed via evaporation of liquid water.

Outcrops are few and far between in the Columbia Hills, making the underlying geologic relationships among these rock classes difficult to discern. We suspect that Backstay Class rocks are the youngest of the classes studied, based solely on their similarity to the Adirondack Class rocks of the Gusev plains that postdate the Columbia Hills. The only clear stratigraphic relationship in the hills is that the two outcrops of Peace Class rock lie stratigraphically higher than the Watchtower Class rocks on Cumberland Ridge, and even this inference could be incorrect if the stratigraphy is inverted. We cannot determine the ages of either Clovis Class or Wishstone Class rocks relative to the Watchtower/Peace section. The one thing we can say with confidence regarding age is that all of the rock classes found as bedrock in the Columbia Hills – Clovis, Peace and Watchtower – are older than Adirondack Class rock. And while Wishstone Class rocks have not been found in outcrop, their prevalence over much of Husband Hill and their close chemical relationship to Watchtower Class rocks suggest that they are older than Adirondack Class rocks as well.

Taken together, these observations paint an incomplete but still informative picture of geologic processes and environmental conditions on early Mars. At least three distinct geologic materials were present at this location. One was the Ni-enriched basaltic source material that was stirred by impacts and deposited to form Clovis Class rocks. The second was the Wishstone Class compositional endmember, which has a distinctive composition notably rich in Ti and P, and low in Cr. Wishstone Class rock could also be impact ejecta, but is plausibly interpreted as a pyroclastic deposit, perhaps an ash-flow tuff. The third material present was Peace Class sedimentary rock. This rock represents an interval of time in which magnetite-rich basaltic sand was transported to this region by wind or water, and saturated, perhaps briefly, with fluids that evaporated and left Ca- and Mg-sulfate salts behind. Watchtower Class rocks may also be impact ejecta, formed by one or more impacts into targets that were predominantly Watchtower Class rocks, but that also included other materials. After deposition of all these materials, Backstay Class rocks were emplaced, either as ejecta blocks from outside the hills or, perhaps, as shallow igneous intrusions or volcanic flows within the hills.

How are the materials of the Columbia Hills related to Gusev crater itself? Because they lie on the floor of Gusev crater, the rocks of the Columbia Hills probably postdate formation of the crater. It is hard to rule out the possibility that they predate formation of Gusev, though the good preservation of weak sedimentary materials like Peace Class rocks argues against this idea. In either case, they clearly predate the Adirondack Class rocks that subsequently covered much of the crater floor, and were uplifted to their current configuration before the low-lying portions of the crater floor were buried with Adirondack Class lava.

The depositional processes that emplaced the rocks probably included impact ejection (Clovis and Watchtower), possibly included explosive volcanism (Wishstone), and probably included wind or water (Peace). The process that uplifted them to their current configuration cannot be determined from the very incomplete geologic information at hand. It could have been tectonic, but the clear dominance of cratering during this part of martian history points to impact as a strong possibility. So the Columbia Hills might be an impact-related uplift, either formed during the Gusev impact itself or, more likely, formed later by one or more smaller impacts into materials that were deposited on the floor of Gusev crater.

How are the rocks of the Columbia Hills related, if at all, to the aqueous episode that created Ma'adim Vallis, a large water-carved channel that debouches into Gusev crater [*e.g., Cabrol et al.*, 2003]? Most of the rocks that we have found in the Columbia Hills clearly are not water-lain sediments. Peace Class rocks, however, could be an exception. Nothing about the stratification in the Peace and Alligator outcrops clearly implicates water as the agent that transported the rock's basaltic sand grains, nor as the fluid in which they were deposited. However, the sulfate cement that weakly binds the sand grains clearly points to evaporation of water that saturated the sands after their deposition. So Peace Class rocks could conceivably be sediments formed by Ma'adim Vallis flooding – ultramafic sand transported into Gusev crater by water and then cemented by sulfate salts as the water evaporated. It is also quite plausible, though, that Peace Class rocks were formed during an earlier and much more limited aqueous episode, and that the Columbia Hills were uplifted to their present configuration before the Ma'adim flooding occurred. If this latter idea is correct, then Spirit still has not

encountered the Ma'adim-related sediments that originally drew us to Gusev crater as a landing site [*Golombek et al.*, 2003].

Most rocks in the Columbia Hills underwent substantial alteration after their formation. The action of liquid water is most clearly implicated in the massive non-isochemical alteration that was suffered by Clovis Class rocks. Some Watchtower Class rocks have also undergone substantial alteration, although the nearly isochemical nature of that alteration points to a low water/rock ratio. It is intriguing that alteration is so variable within Watchtower Class rocks, with materials of widely different Fe^{3+}/Fe_{Total} in close proximity to one another. As noted above, this might have resulted from short-lived local flows of hydrothermal fluids or vapors set up within a hot ejecta deposit immediately after its deposition.

After the materials in the Columbia Hills were uplifted to their current configuration, geologic activity within the hills has been limited. Small impacts have fragmented and mixed surface materials, and mass wasting processes have further obscured the underlying geology. Eolian transport has left some outcrops exposed, and has probably buried many others. Blocks of Backstay Class basalt have been emplaced high on Husband Hill, either by local igneous activity within the hills or by ballistic transport from impacts elsewhere.

So the Columbia Hills have been geologically quiescent, under dominantly cold, dry environmental conditions, for most of their history. However, the earliest record preserved in the ancient rocks of the Columbia Hills points to substantial geologic activity in which impact was a dominant process and water was commonly present.

References

Arvidson, R.E., S.W. Squyres, R.C. Anderson, J.F. Bell III, J. Brückner, N.A. Cabrol, W.M. Calvin, M.H. Carr, P.R. Christensen, B.C. Clark, L. Crumpler, D.J. Des Marais, C. d'Uston, T. Economou, J. Farmer, W.H. Farrand, W. Folkner, M. Golombek, S. Gorevan, J.A. Grant, R. Greeley, J. Grotzinger, E. Guinness, B.C. Hahn, L. Haskin, K.E. Herkenhoff, J.A. Hurowitz, S. Hviid, J.R. Johnson, G. Klingelhöfer, A.H. Knoll, G. Landis, C. Leff, M. Lemmon, R. Li, M.B. Madsen, M.C. Malin, S.M. McLennan, H.Y. McSween, D.W. Ming, J. Moersch, R.V. Morris, T. Parker, J.W. Rice Jr., L. Richter, R. Rieder, D.S. Rodionov, C. Schröder, M. Sims, M. Smith, P. Smith, L.A. Soderblom, R. Sullivan, S.D. Thompson, N.J. Tosca, A. Wang, H. Wänke, J. Ward, T. Wdowiak, M. Wolff, and A. Yen, Overview of the Spirit Mars Exploration Rover mission to Gusev crater: Landing site to the Backstay rock in the Columbia Hills, *J. Geophys. Res.*, in press, 2005.

Banin, A., F. X. Han, I. Kan, and A. Cicelsky, Acidic volatiles and the Mars soil. *J. Geophys. Res., 102*, 13,341-13,156, 1997.

Bell, J.F. III, S.W. Squyres, K.E. Herkenhoff, J.N. Maki, H.M. Arneson, D. Brown, S.A. Collins, A. Dingizian, S.T. Elliot, E.C. Hagerott, A.G. Hayes, M.J. Johnson, J.R. Johnson, J. Joseph, K. Kinch, M.T. Lemmon, R.V. Morris, L. Scherr, M. Schwochert, M.K. Shepard, G.H. Smith, J.N. Sohl-Dickstein, R.J. Sullivan, W.T. Sullivan, and M. Wadsworth, Mars Exploration Rover Athena Panoramic Camera (Pancam) investigation, *J. Geophys. Res.*, *108*(E12), 8063, doi:10.1029/2003JE002070, 2003.

Cabrol, N.A., E.A. Grin, M.H. Carr, B. Sutter, J.M. Moore, J.D. Farmer, R. Greeley, R.O. Kuzmin, D.J. Des Marais, M.G. Kramer, H. Newsom, C. Barber, I. Thorsos, K.L. Tanaka, N.G. Barlow, D.A. Fike, M.L. Urquhart, B. Grigsby, F.D. Grant, and O. de Goursac, Exploring Gusev Crater with Spirit: Review of science objectives and testable hypotheses, *J. Geophys. Res.*, *108*(E12), 8076, doi:10.1029/2002JE002026, 2003.

Christensen, P.R., G.L. Mehall, S.H. Silverman, S. Anwar, G. Cannon, N. Gorelick, R. Kheen, T. Tourville, D. Bates, S. Ferry, T. Fortuna, J. Jeffryes, W. O'Donnell, R. Peralta, T. Wolverton, D. Blaney, R. Denise, J. Rademacher, R.V. Morris, and S. Squyres, Miniature Thermal Emission Spectrometer for the Mars Exploration Rovers, *J. Geophys. Res.*, *108*(E12), 8064, doi:10.1029/2003JE002117, 2003.

Farrand, W. H., J. F. Bell III, J. R. Johnson, S. W. Squyres, J. Soderblom, and D. W. Ming, Spectral variability among rocks in visible and near infrared multispectral Pancam data collected at Gusev Crater: Examinations using spectral mixture analysis and related techniques, submitted to *J. Geophys. Res.*, 2005.

Gellert, R., R. Rieder, J. Brückner, B. Clark, G. Dreibus, G. Klingelhöfer, G. Lugmair, D. Ming, H. Wänke, A. Yen, J. Zipfel, and S. Squyres, The Alpha Particle X-Ray Spectrometer (APXS): Results from Gusev crater and calibration report, submitted to *J. Geophys. Res.*, 2005.

Golombek, M.P., J.A. Grant, T.J. Parker, D.M. Kass, J.A. Crisp, S.W. Squyres, A.F.C. Haldemann, M. Adler, W.J. Lee, N.T. Bridges, R.E. Arvidson, M.H. Carr, R.L. Kirk, P.C. Knocke, R.B. Roncoli, C.M. Weitz, J.T. Schofield, R.W. Zurek, P.R. Christensen, R.L. Fergason, F.S. Anderson, and J.W. Rice, Jr., Selection of the Mars Exploration Rover landing sites, *J. Geophys. Res.*, *108*(E12), 8072, doi:10.1029/2003JE002074, 2003.

Golombek, M.P, L. S. Crumpler, J. A. Grant, R. Greeley, N. A. Cabrol, T. J. Parker, J. W. Rice Jr., J. G. Ward, R. E. Arvidson, J. E. Moersch, R. L. Fergason, P. R. Christensen, A. Castaño, R. Castaño, A. F. C. Haldemann, R. Li, J. F. Bell III, and S. W. Squyres, Geology of the Gusev cratered plains from the Spirit rover traverse, submitted to *J. Geophys. Res*., 2005.

Gorevan, S.P., T. Myrick, K. Davis, J.J. Chau, P. Bartlett, S. Mukherjee, R. Anderson, S.W. Squyres, R.E. Arvidson, M.B. Madsen, P. Bertelsen, W. Goetz, C.S. Binau, and L. Richter, Rock Abrasion Tool: Mars Exploration Rover Mission, *J. Geophys. Res*., *108*(E12), 8068, doi:10.1029/2003JE002061, 2003.

Gorevan, S., *et al.*, to be submitted to *J. Geophys. Res*., 2005.

Grant, J. A., R.E. Arvidson, J. F. Bell, III, N.A. Cabrol, M.H. Carr, P.R. Christensen, L. Crumpler, D.J. Des Marais, B.L. Ehlmann, J. Farmer, M. Golombek, F.D. Grant, R. Greeley, K. Herkenhoff, R. Li, H.Y. McSween, D.W. Ming, J. Moersch, J.W. Rice, Jr., S. Ruff, L. Richter, S.W. Squyres, R. Sullivan, and C. Weitz, Surficial deposits at Gusev crater along Spirit rover traverses, *Science, 305*, 807-810, 2004.

Hamilton, V.E., P.R. Christensen and H.Y. McSween, Determination of martian meteorite lithologies and mineralogies using vibrational spectroscopy, *J. Geophys. Res., 102*, 25,593-25,603, 1997.

Haskin, L. A., A. Wang, B.L. Jolliff, H.Y. McSween, B.C. Clark, D.J. Des Marais, S.M. McLennan, N.J. Tosca, J.A. Hurowitz, J.D. Farmer, A. Yen, S.W. Squyres, R.E. Arvidson, G. Klingelhöfer, C. Schröder, P.A. de Souza, Jr., R.V. Morris, D.W. Ming, R. Gellert, J. Zipfel, J. Brückner, J.F. Bell, III, K. Herkenhoff, P.R. Christensen, S. Ruff, D. Blaney, S. Gorevan, N.A. Cabrol, L. Crumpler, J. Grant, and L. Soderblom, Water alteration of rocks and soils on Mars from the Spirit rover site in Gusev crater, *Nature, 437*, 66-69, 2005.

Herkenhoff, K.E., S.W. Squyres, J.F. Bell III, J.N. Maki, H.M. Arneson, P. Bertelsen, D.I. Brown, S.A. Collins, A. Dingizian, S.T. Elliott, W. Goetz, E.C. Hagerott, A.G. Hayes, M.J. Johnson, R.L. Kirk, S. McLennan, R.V. Morris, L.M. Scherr, M.A.

Schwochert, L.R. Shiraishi, G.H. Smith, L.A. Soderblom, J.N. Sohl-Dickstein, and M.V. Wadsworth, Athena Microscopic Imager investigation, *J. Geophys. Res.*, 108(E12), 8065, doi:10.1029/2003JE002076, 2003.

Herkenhoff, K.E., S.W. Squyres, R. Anderson, B.A. Archinal, R.E. Arvidson, J.M. Barrett, K.J. Becker, J.F. Bell III, P. Bertelsen, C. Budney, N.A. Cabrol, M.G. Chapman, D. Cook, B. Ehlmann, J. Farmer, B. Franklin, L.R. Gaddis, D.M. Galuszka, P.A. Garcia, T.M. Hare, E. Howington-Kraus[1], J.R. Johnson, S. Johnson, K. Kinch, R.L. Kirk, E.M. Lee, C. Leff, M. Lemmon, M.B. Madsen, J.N. Maki, K.F. Mullins, B.L. Redding, L. Richter, M.R. Rosiek, M.H. Sims, L.A. Soderblom, N. Spanovich, R. Springer, R.M. Sucharski, T. Sucharski, R. Sullivan, and J.M. Torson, Overview of the Microscopic Imager investigation during Spirit's first 360 sols in Gusev crater, to be submitted to *J. Geophys. Res.*, 2005.

Hurowitz, J. A., S. M. McLennan, N. J. Tosca, R.E. Arvidson, J.R. Michalski, D. W. Ming, C. Schröder, and S.W. Squyres, In-situ and experimental evidence for acidic weathering of rocks and soils on Mars, submitted to *J. Geophys. Res.*, 2005.

Hurowitz, J.A., *et al.*, in preparation, 2006.

Klingelhöfer, G., R.V. Morris, B. Bernhardt, D. Rodionov, P.A. de Souza Jr., S.W. Squyres, J. Foh, E. Kankeleit, U. Bonnes, R. Gellert, C. Schröder, S. Linkin, E. Evlanov, B. Zubkhov, and O. Prilutski, Athena MIMOS II Mössbauer spectrometer investigation, J. Geophys. Res. 108(E12), 8067, doi:10.1029/2003JE002138, 2003.

Le Bas, M. J., R. W. Le Maitre, A. Streckeisen, and B. Zanettin, A chemical classification of volcanic rocks based on the total alkali-silica diagram, *J. Petrol.*, *27*, 745-750, 1986.

McSween, H.Y., R.E. Arvidson, J.F. Bell, III, D. Blaney, N.A. Cabrol, P.R. Christensen, B.C. Clark, J.A. Crisp, L.S. Crumpler, D.J. Des Marais, J.D. Farmer, R. Gellert, A. Ghosh, S. Gorevan, T. Graff, J. Grant, L.A. Haskin, K.E. Herkenhoff, J.R. Johnson, B.L. Jolliff , G. Klingelhöfer, A.T. Knudson, S. McLennan, K.A. Milam, J.E. Moersch, R.V. Morris, R. Rieder, S.W. Ruff, P.A. de Souza, Jr., S.W. Squyres, H. Wänke, A. Wang, M.B. Wyatt, A. Yen, and J. Zipfel (2004), Basaltic rocks analyzed by the Spirit rover in Gusev crater, *Science, 305*, 842-845, 2004.

McSween, H.Y., M.B. Wyatt, R. Gellert, J.F. Bell III, R.V. Morris, K.E. Herkenhoff, L.S. Crumpler, K.A. Milam, K.R. Stockstill, L. Tornabene, R.E. Arvidson, P. Bartlett, D. Blaney, N.A. Cabrol, P.R. Christensen, B.C. Clark, J.A. Crisp, D.J. Des Marais, T. Economou, J.D. Farmer, W. Farrand, A. Ghosh, M. Golombek, S. Gorevan, R. Greeley, V.E. Hamilton, J.R. Johnson, B.L. Jolliff, G. Klingelhöfer, A.T. Knudson, S. McLennan, D. Ming, J.E. Moersch, R. Rieder, S.W. Ruff, C. Schroeder, P.A. de Souza Jr., S.W. Squyres, H. Wänke, A. Wang, A. Yen, and J. Zipfel, Characterization and petrologic interpretation of olivine-rich basalts at Gusev Crater, Mars, *J. Geophys. Res.*, in press, 2005.

Ming, D.W., D.W. Mittlefehldt, R.V. Morris, D.C. Golden, R. Gellert, A. Yen, B.C. Clark, S.W. Squyres, W.H. Farrand, S.W. Ruff, R.A. Arvidson, G. Klingelhöfer, H.Y. McSween, D.S. Rodionov, C. Schröder, P.A. de Souza, Jr., and A. Wang, Geochemical and mineralogical indicators for aqueous processes in the Columbia Hills of Gusev crater, Mars, to be submitted to *J. Geophys. Res.*, 2005.

Morris, R.V., *et al.*, Mössbauer mineralogy of rock and soil at Gusev Crater: Spirit's journey through weakly altered olivine basalt on the Gusev plains and pervasively altered basalt in the Columbia Hills, to be submitted to *J. Geophys. Res.*, 2005.

Newsom, H.E., Hydrothermal alteration of impact melt sheets with implications for Mars, *Icarus*, 44, 207-216, 1980.

Rieder, R., R. Gellert, J. Brückner, G. Klingelhöfer, G. Dreibus, A. Yen, and S.W. Squyres, The new Athena alpha particle X-ray spectrometer for the Mars Exploration Rovers, J. Geophys. Res. 108(E12), 8066, doi:10.1029/2003JE002150, 2003.

Ruff, S.W., P.R. Christensen, D.L. Blaney, W.H. Farrand, J.R. Johnson, J. Michalski, J.E. Moersch, and S. Wright, The rocks of Gusev crater as viewed by the Mini-TES instrument, to be submitted to *J. Geophys. Res.*, 2005.

Squyres, S.W., R.E. Arvidson, J.F. Bell, III, J. Brückner, N.A. Cabrol, W. Calvin, M.H. Carr, P.R. Christensen, B.C. Clark, L. Crumpler, D.J. Des Marais, C. d'Uston, T. Economou, J. Farmer, W. Farrand, W. Folkner, M. Golombek, S. Gorevan, J.A. Grant, R. Greeley, J. Grotzinger, L. Haskin, K.E. Herkenhoff, S. Hviid, J. Johnson, G. Klingelhöfer, A. Knoll, G. Landis, M. Lemmon, R. Li, M.B. Madsen, M.C. Malin, S.M. McLennan, H.Y. McSween, D.W. Ming, J. Moersch, R.V. Morris, T. Parker, J.W. Rice, Jr., L. Richter, R. Rieder, M. Sims, M. Smith, P. Smith, L.A. Soderblom, R. Sullivan, H. Wänke, T. Wdowiak, M. Wolff, and A. Yen (2004a), The Spirit Rover's Athena Science Investigation at Gusev Crater, Mars, *Science, 305*, 794-799, 2004*a*.

Squyres, S.W., J.P. Grotzinger, R.E. Arvidson, J.F. Bell III, P.R. Christensen, B.C. Clark, J.A. Crisp, W.H. Farrand, K.E. Herkenhoff, J.R. Johnson, G. Klingelhöfer, A.H. Knoll, S.M. McLennan, H.Y. McSween Jr., R.V. Morris, J.W. Rice Jr., R. Rieder, and L.A. Soderblom, In situ evidence for an ancient aqueous environment on Mars, *Science, 306,* 1709-1714, 2004*b*.

Wang, A., R.L. Korotev, B.L. Jolliff, L.A. Haskin, L. Crumpler, W.H. Farrand, K.E. Herkenhoff, P. de Souza Jr., A.G. Kusack, J.A. Hurowitz, N.J. Tosca, Evidence of phyllosilicate in Wooly Patch, an altered rock encountered at West Spur, Columbia Hills by the Spirit Rover, submitted to *J. Geophys. Res.*, 2005.

Yen, A.S., R. Gellert, C. Schröder, J.F. Bell III, A.T. Knudson, R.V. Morris, B.C. Clark, D.W. Ming, R.E. Arvidson, D. Blaney, J. Brückner, P.R. Christensen, J.A. Crisp, D.J. Des Marais, P.A. de Souza Jr., T.E. Economou1, A. Ghosh, B.C. Hahn, K.E. Herkenhoff, L.A. Haskin, J.A. Hurowitz, B.L. Jolliff, J.R. Johnson, G. Klingelhöfer,

M.B. Madsen, S.M. McLennan, H.Y. McSween, L. Richter, R. Rieder, D. Rodionov, L. Soderblom, S.W. Squyres, N.J. Tosca, A. Wang, M. Wyatt, and J. Zipfel, An integrated view of the chemistry and mineralogy of martian soils, *Nature*, 436, 49-53, 2005.

Tables

Class	Major Element Geochemistry (compared to Adirondack)	Fe Mineralogy	Fe^{3+}/Fe_{Total}	Other Mineralogy	Morphology and Texture	Specific Grind Energy ($J\ mm^{-3}$)	Primary Location	Description and Possible Origin
Adirondack	---	52±6% Ol, 34±2%Px, 6±2% npOx, 8±6% Mt, 1±2% Hm	0.12±0.05	Plagioclase	Fine-grained, massive	50-60	Plains	Olivine-rich basalt, emplaced after uplift of Columbia Hills.
Clovis	Enriched in S, Cl, Br. Enriched in Ni.	2±2% Ol, 23±8%Px, 29±7% npOx, 15±7% Mt, 13±4% Hm, 19±11% Gt	0.72±0.09	Glassy component, minor sulfates	Massive to layered; clastic and poorly sorted (Figs. 2-4)	4-9	West Spur	Impact ejecta (or perhaps tephra) of basaltic bulk composition; aqueously altered.
Wishstone	Depleted in Fe. Enriched in Al. Strongly enriched in Ti, P. Strongly depleted in Cr.	23±6% Ol, 27±3% Px, 6±2% Ilm, 16±2% npOx, 11±2% Mt, 13±3% Hm, 5±9% Gt	0.43±0.04	Plagioclase, minor phosphates	Knobby, pitted surface; irregular 1-2 mm clasts in fine matrix (Figs. 5-6)	15-24	Northwest Flank	Pyroclastic deposits (or perhaps impact ejecta); relatively unaltered.
Peace	Strongly depleted in Al, Na, K. Strongly enriched in S.	27±7% Ol, 30±2% Px, 15±2% npOx, 28±8% Mt	0.35±0.06	16-17% Mg and Ca sulfates, bound water	Finely layered, cemented (Figs. 7-9)	2	Northwest Flank	Ultramafic, magnetite-rich sandstone cemented by Mg- and Ca-sulfates. Subaerial or subaqueous sand deposition, wetting and evaporation.
Watchtower	Depleted in Fe. Enriched in Al. Strongly enriched in Ti, P. Strongly depleted in Cr. More Mg, S, Cl than Wishstone	6±5% Ol, 15±17% Px, 4±3% Ilm, 39±19% npOx, 5±5% Mt, 25±10% Hm, 6±6% Gt	0.74±0.18	---	Diverse, including massive, finely layered, and globular (Figs. 10-13)	13	Cumberland Ridge	Possible ejecta from impacts into mixed Wishstone and more ferromagnesian-rich material. Aqueously altered at low H_2O/rock ratios.
Backstay	Enriched in Ti, Al, K, and Na. Depleted in Fe	35±2% Ol, 37±2% Px, 3±2% Ilm, 13±2% npOx, 11±2% Mt, 2±2 Hm	0.23±0.03	Plagioclase	Fine-grained, massive (Fig. 15)	unknown	Cumberland Ridge	Basalt/trachybasalt. Emplacement age unknown, but may postdate uplift of Columbia Hills

Table 1: Major properties of the rock types discovered to date by Spirit at Gusev crater.
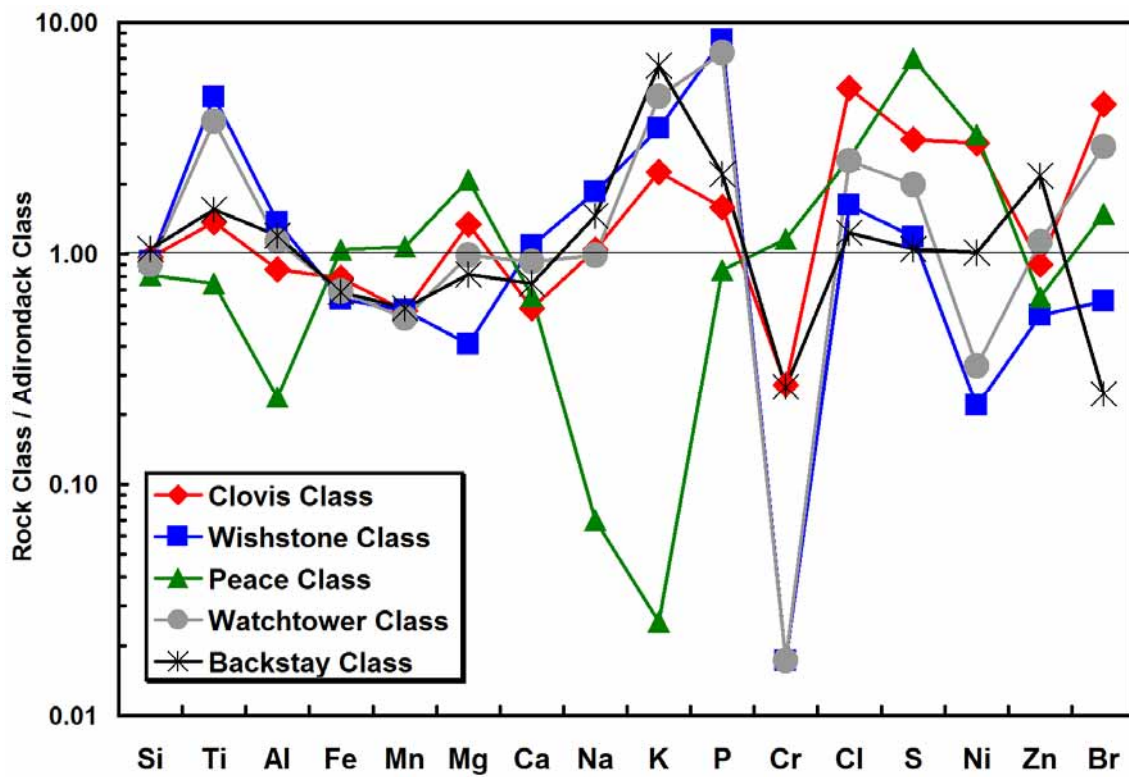
Figures

Figure 1: Average major-element chemistry of each of the rock types of the Columbia Hills. Each class of rock is ratioed to Adirondack Class, the olivine-rich basalts found on the plains of Gusev crater.
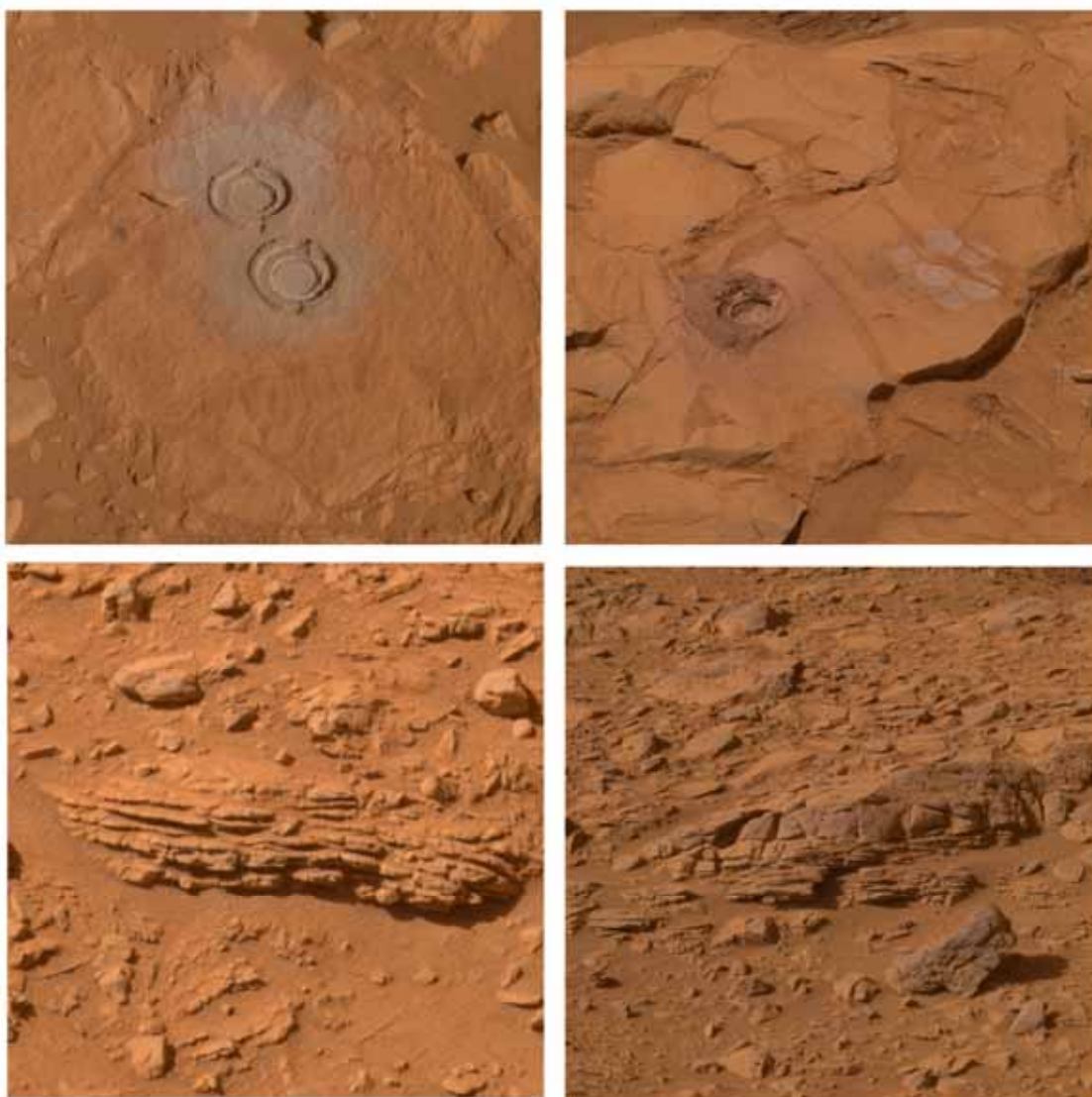
Figure 2: Approximate true color Pancam images of Clovis Class rocks. (a) upper left: Wooly Patch (Sol 200, Sequence p2556). (b) upper right: Clovis (Sol 226, Sequence p2569). (c) lower left: Tetl (Sol 264, Sequence p2598). (d) lower right: Palenque (Sol 269, Sequence p2534).
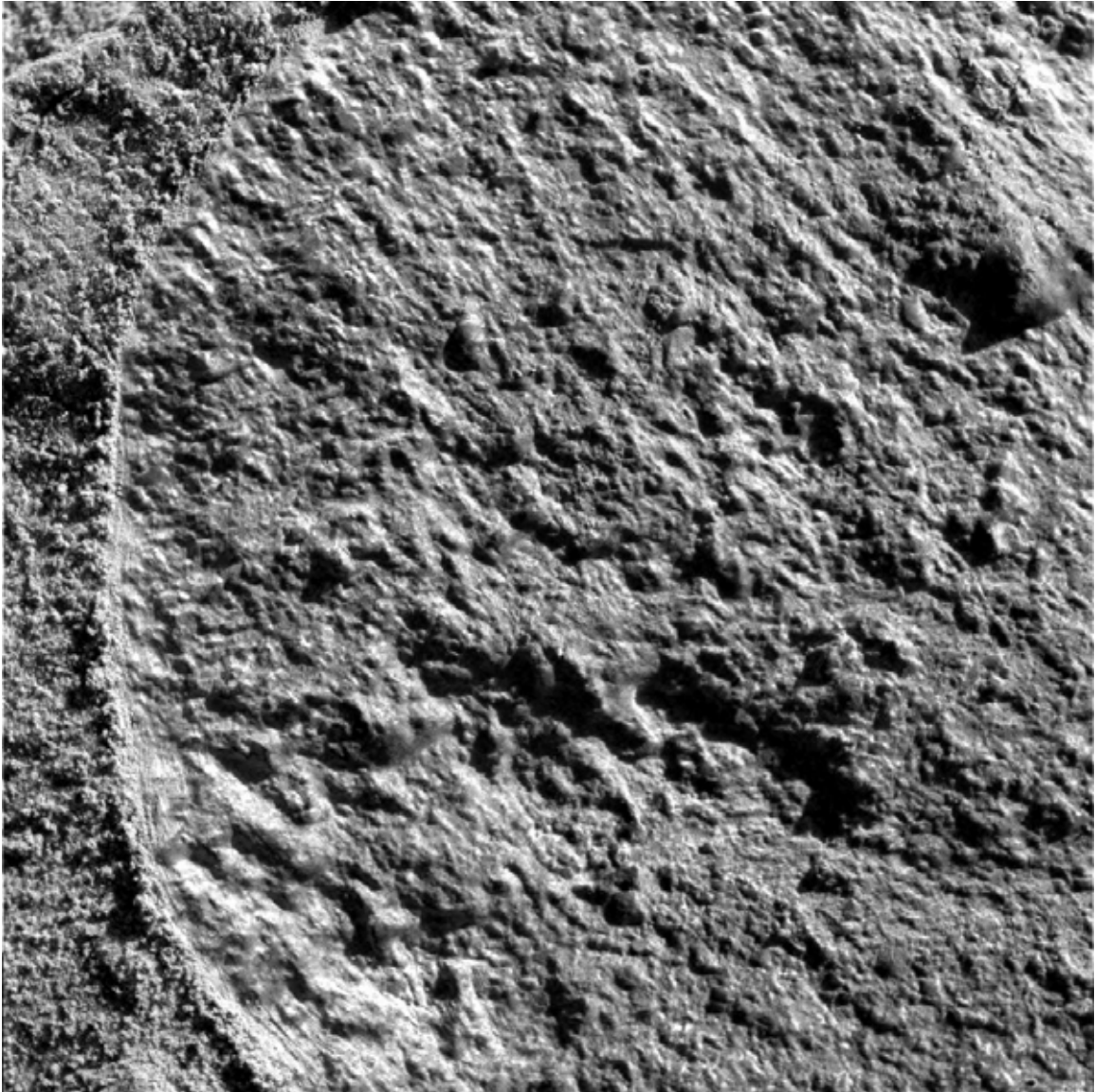
Figure 3: Microscopic Imager image of the Clovis Class rock Lutefisk after brushing by the Rock Abrasion Tool (Image ID 2M152916149). The rock is clastic in nature and poorly sorted, with angular clasts ranging from the resolution limit of the image up to several mm in size. Scale across the image is 3 cm.
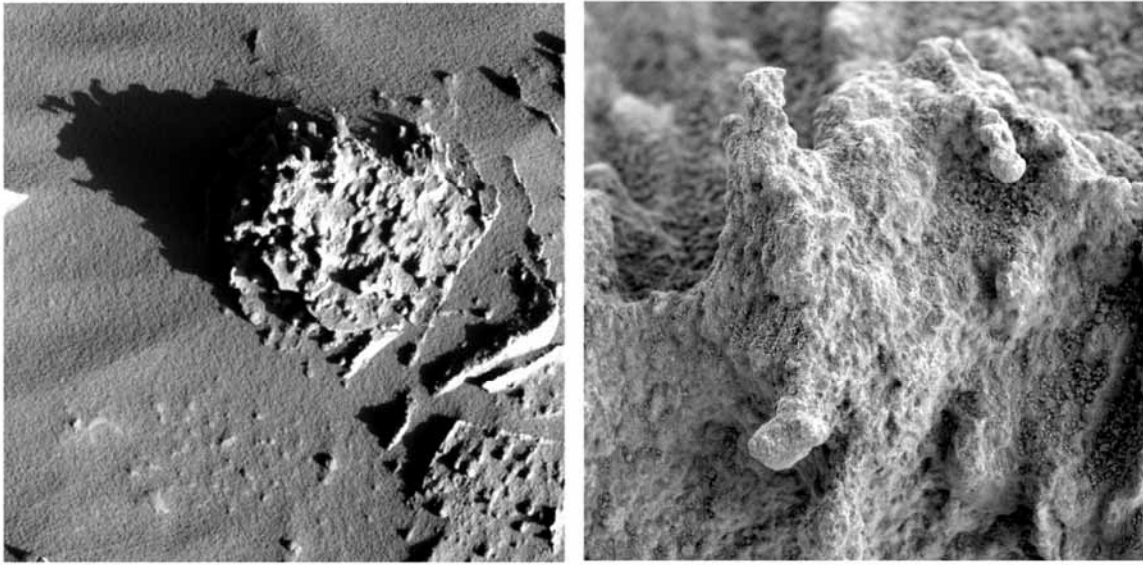
Figure 4: The probable Clovis Class rock Pot of Gold. (a) left: Pancam image (Image ID 2P140936727). (b) right: Microscopic Imager image (Image ID 2M140752297). The rock is ~10 cm in size, and has a shape characterized by clasts several mm in size that are suspended at the ends of thin stalks of rock. Note the outline of the rock's shadow in the Pancam image. Scale across the MI image is 3 cm.
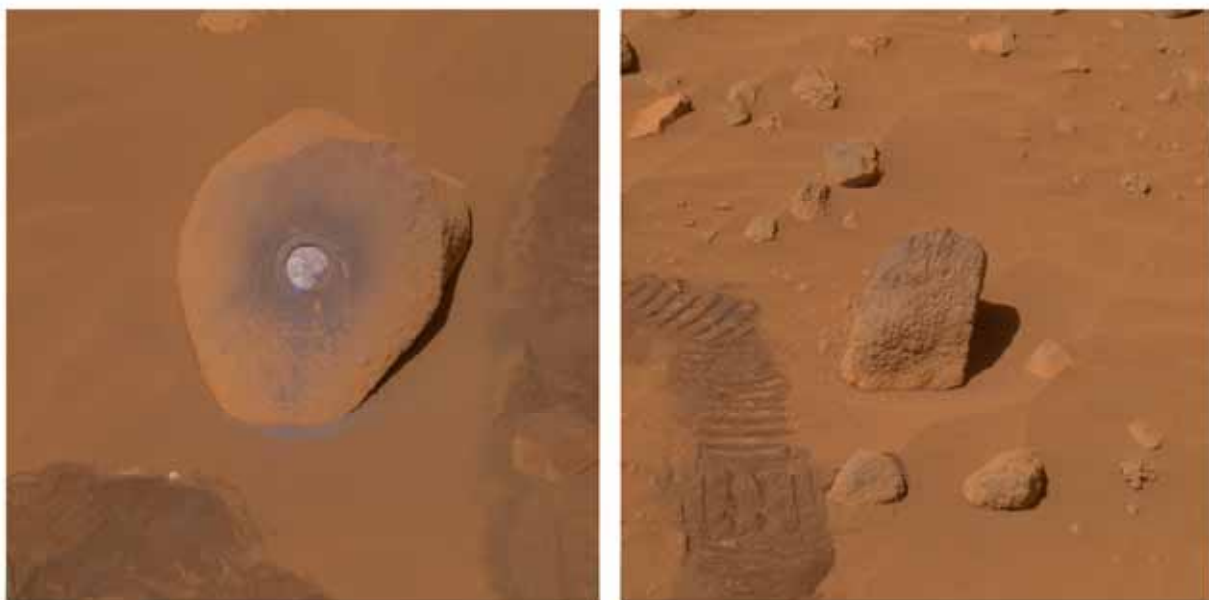
Figure 5: Approximate true color Pancam images of Wishstone Class rocks. (a) left: Wishstone, after grinding by the Rock Abrasion Tool (Sol 337, Sequence p2569). (b) right: La Brea (Sol 343, Sequence p2574). La Brea is inferred to be of Wishstone Class based on surface texture and Mini-TES spectra, but it was not investigated with the in-situ instruments.
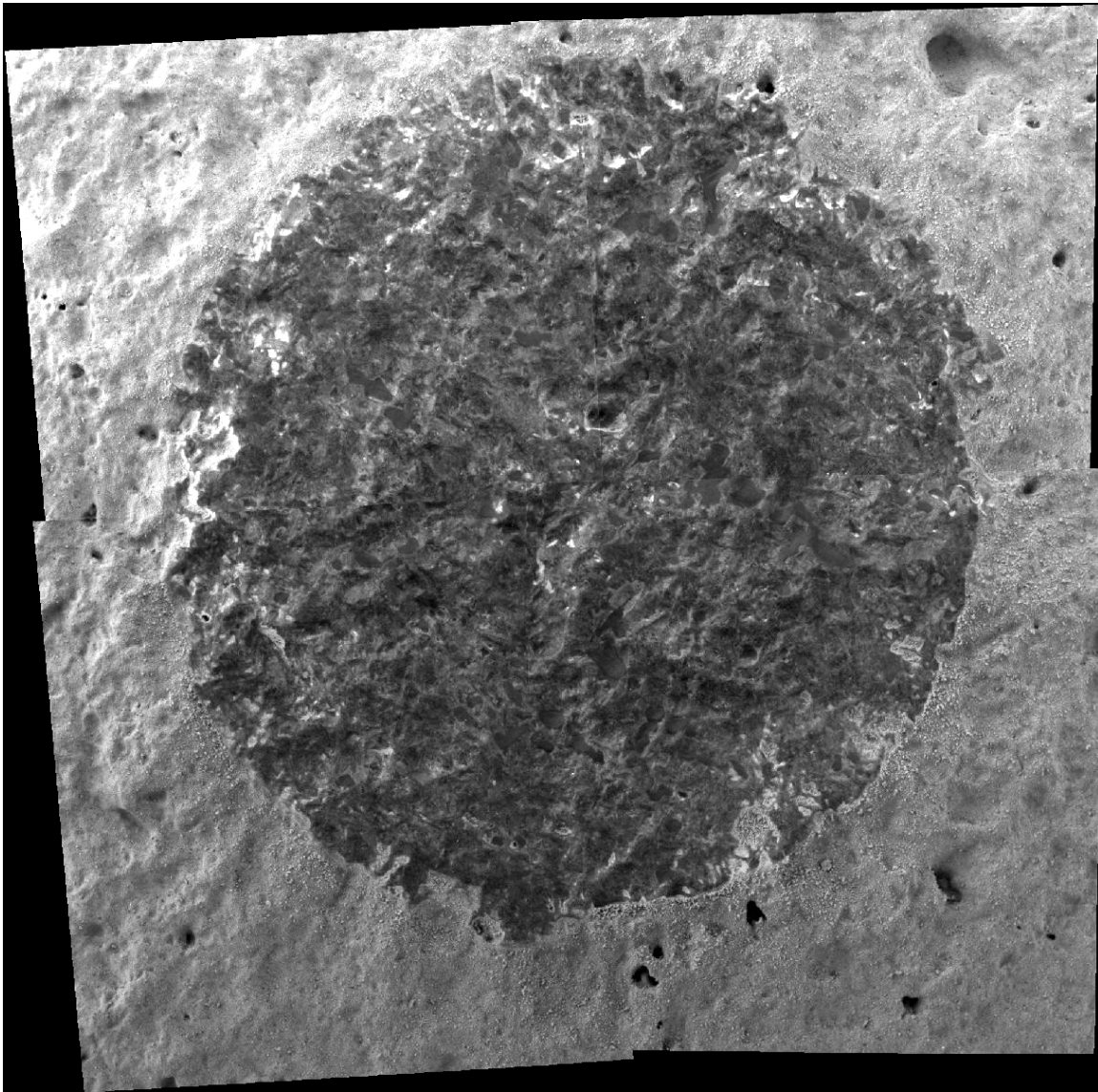
Figure 6: 2×2 Microscopic Imager mosaic of the surface of the rock Wishstone after brushing by the Rock Abrasion Tool (Sol 333, Sequence p2936). The rock contains irregular clasts up to ~2 mm in size, some of them highly angular, embedded in a fine-grained matrix. Scale across the image is ~5.5 cm.
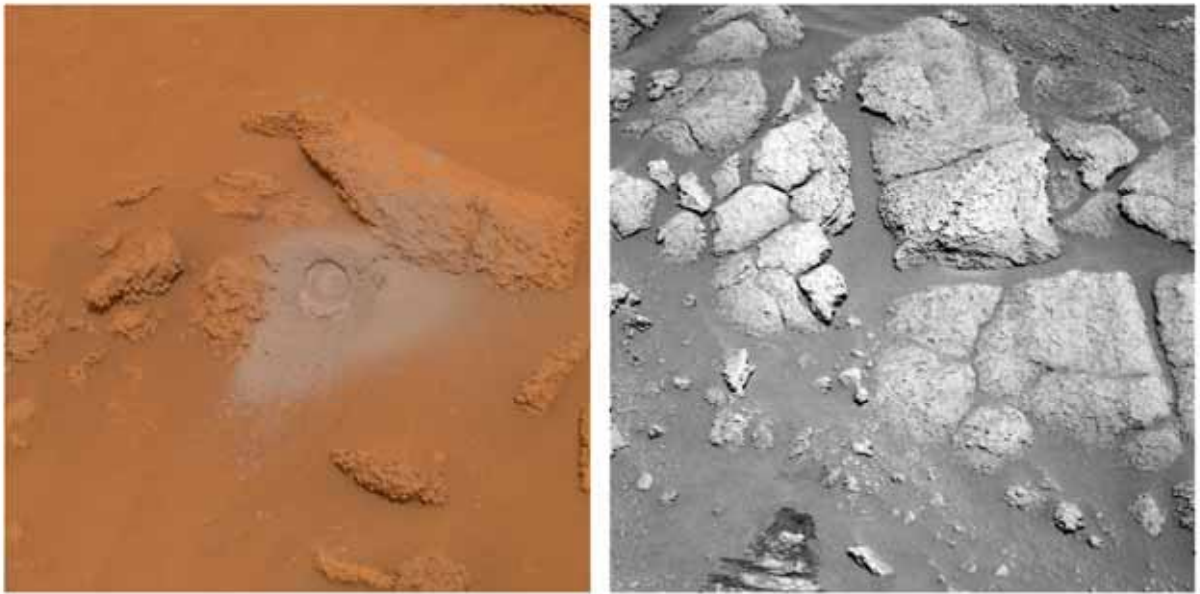
Figure 7: Pancam images of Peace Class rocks. (a) left: Peace (approximate true color, Sol 381, Sequence p2543), after grinding by the Rock Abrasion Tool. (b) right: Alligator (Image ID 2P160810226).
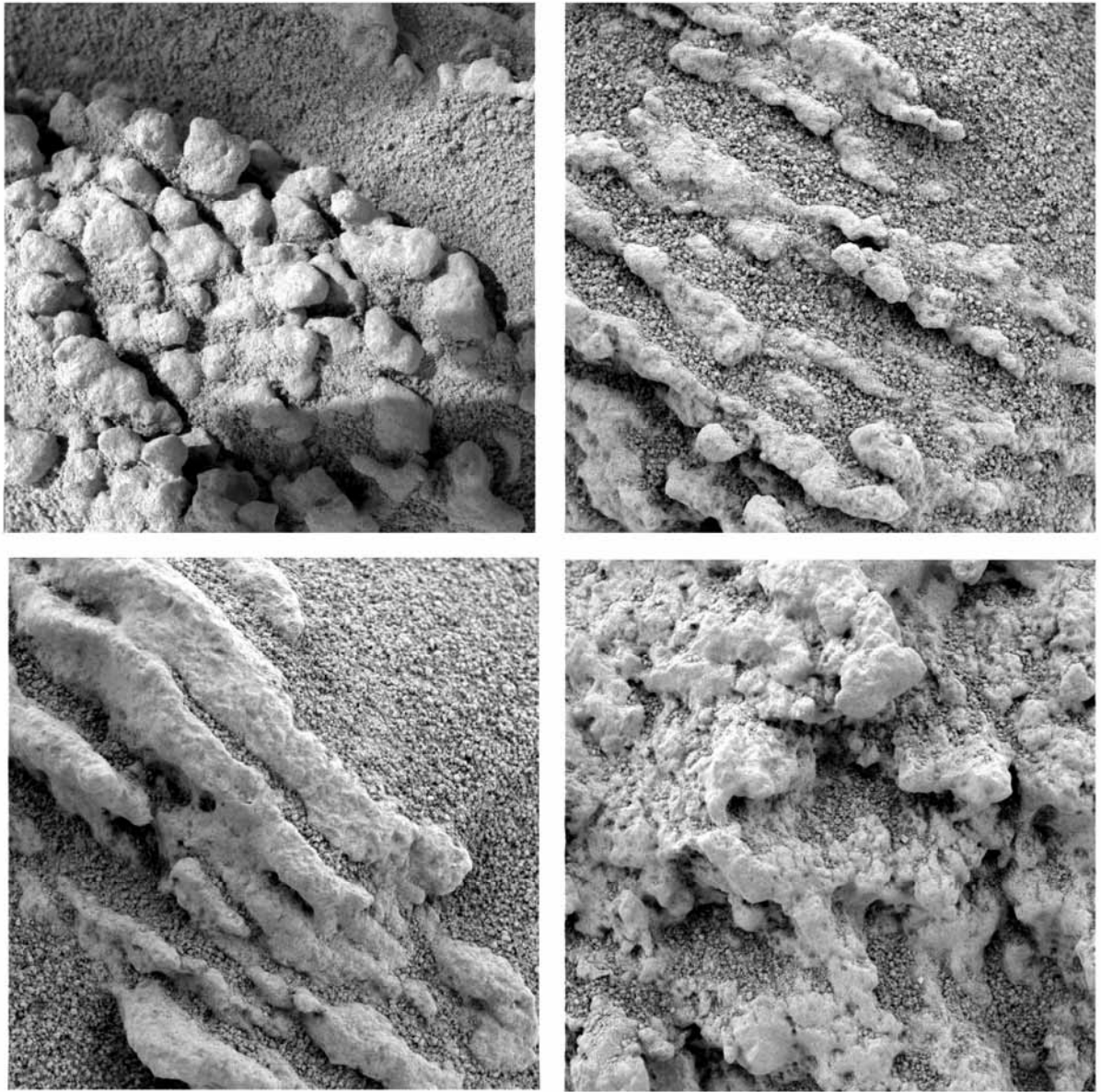
Figure 8: Microscopic Imager images of the rock Peace. (a) upper left: Coarse clasts up to a few mm in size (Image ID 2M159392855). (b) upper right: Fine layers a few mm thick (Image ID 2M159478927). (c) lower left: Layers several mm thick (Image ID 2M159478497). (d) lower right: Spongy texture with poorly sorted, cemented clasts (Image ID 2M159479393). All images were acquired without brushing or grinding by Rock Abrasion Tool, so loose soil is present in low areas. Scale across each image is ~3 cm.
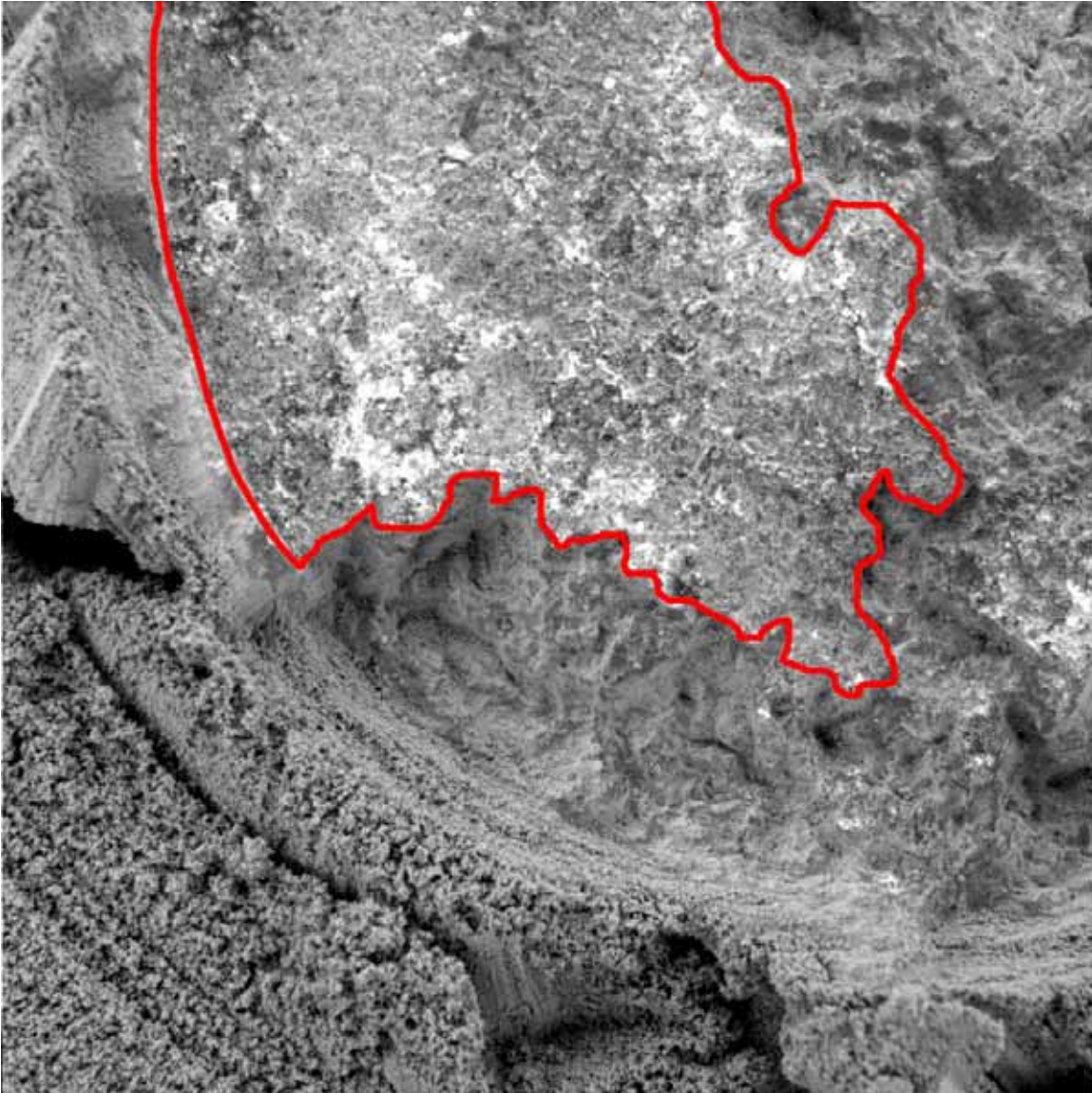
Figure 9: Microscopic Imager image of the rock Peace after partial abrasion with the Rock Abrasion Tool (Image ID 2M159744892). The portion of the rock outlined in red has been abraded and then brushed clean by the RAT, and shows a granular texture with typical grain sizes of 0.1-0.2 mm. Scale across the image is ~3 cm.
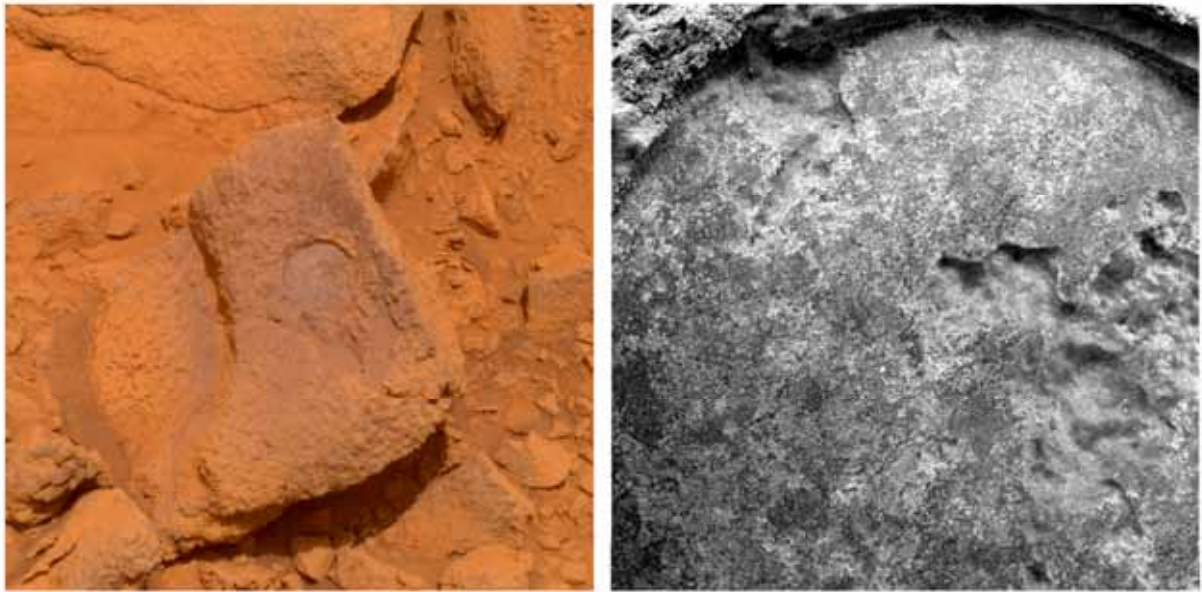
Figure 10: The rock Watchtower. (a) left: Pancam image, after grinding by the Rock Abrasion Tool (approximate true color, Sol 419, Sequence p2574). (b) right: Microscopic Imager image, after grinding by the Rock Abrasion Tool (Image ID 2M163385223). Scale across the MI image is ~3 cm.

Figure 11: Approximate true color Pancam image of the Watchtower Class rock
Keystone (Sol 473, Sequence p2567). This rock is part of the outcrop called Methuselah.
Note the spot on the lower left portion of the rock that was brushed by the Rock Abrasion
Tool.
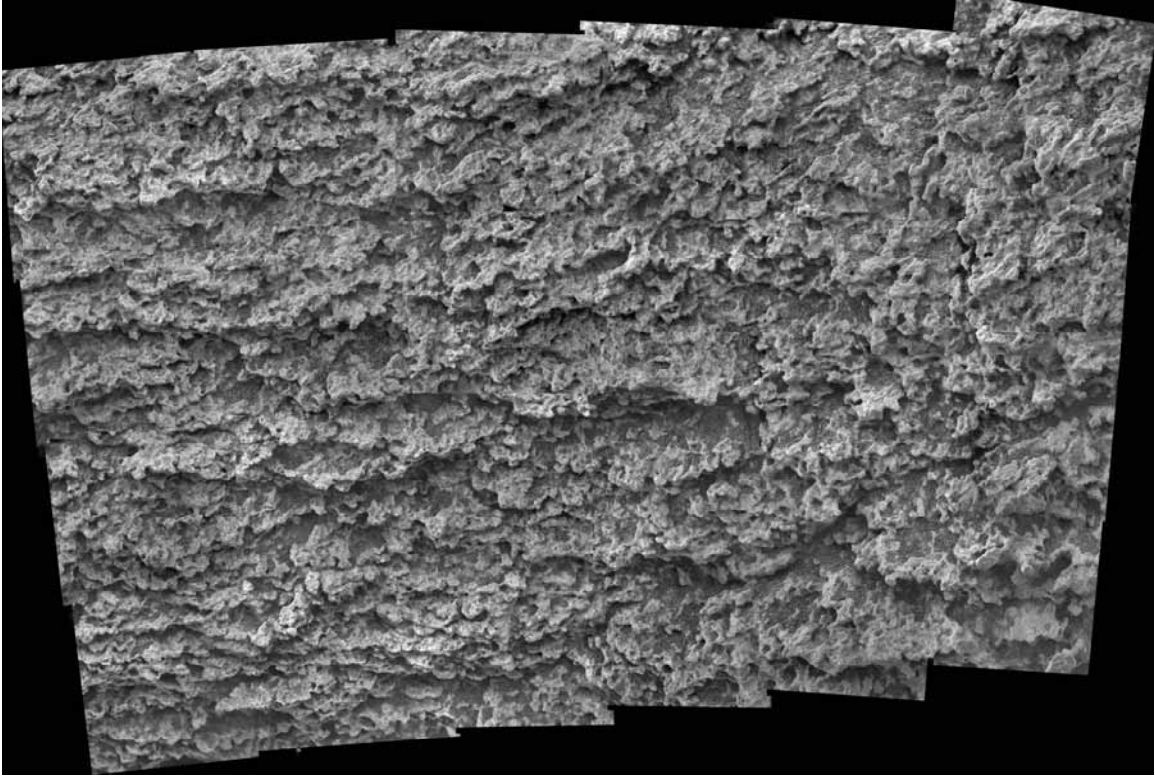
Figure 12: 4×6 Microscopic Imager mosaic of the Watchtower Class rock Keystone (Sols 469-470, Sequence p2957). The rock exhibits fine-scale laminations with characteristic thicknesses of 1-2 mm. Scale across the mosaic is ~15 cm.
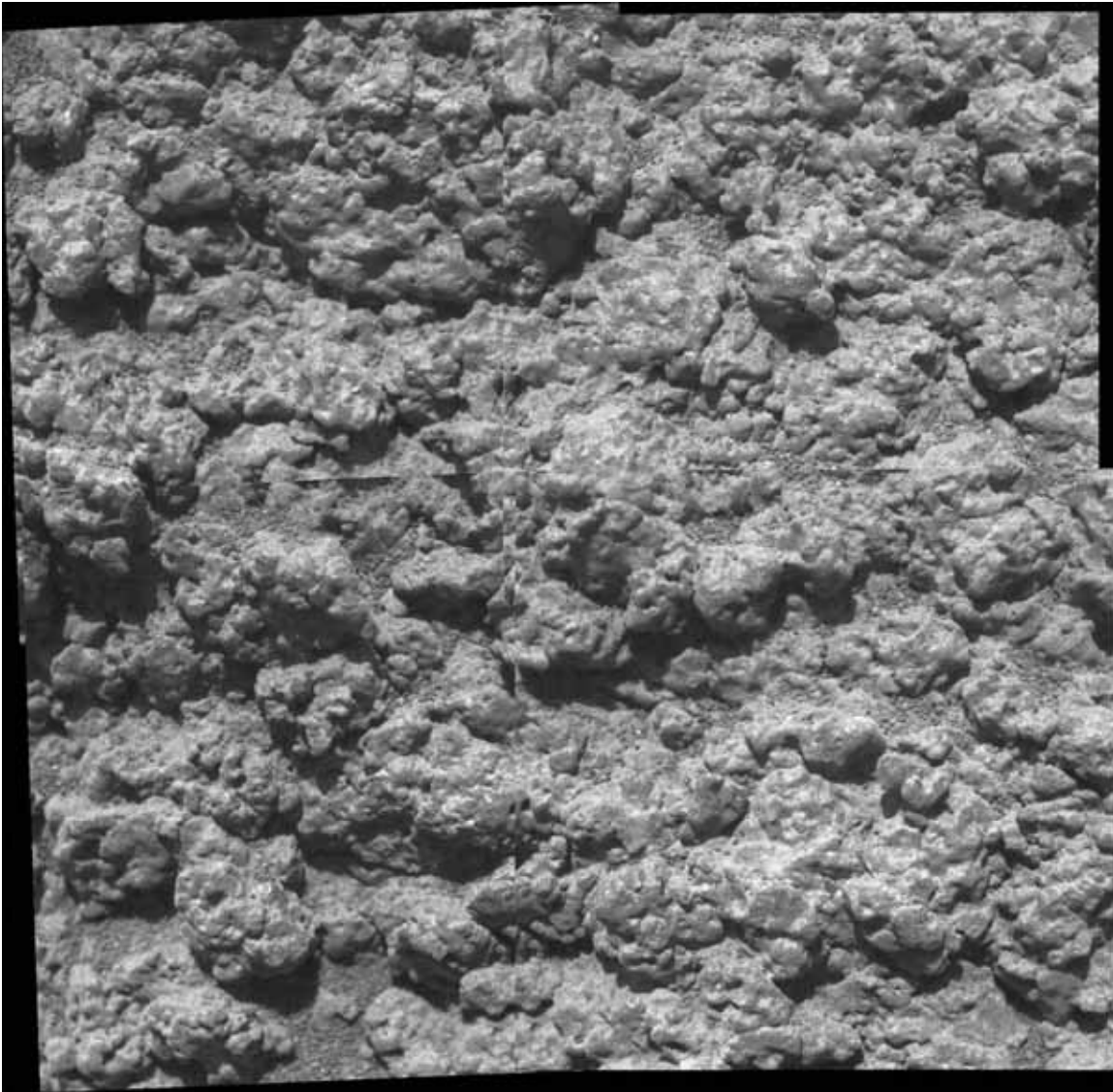
Figure 13: 2×2 Microscopic Imager mosaic of the Watchtower Class rock Pequod (Sol 496, Sequence p2956). Scale across the image is ~5.5 cm.
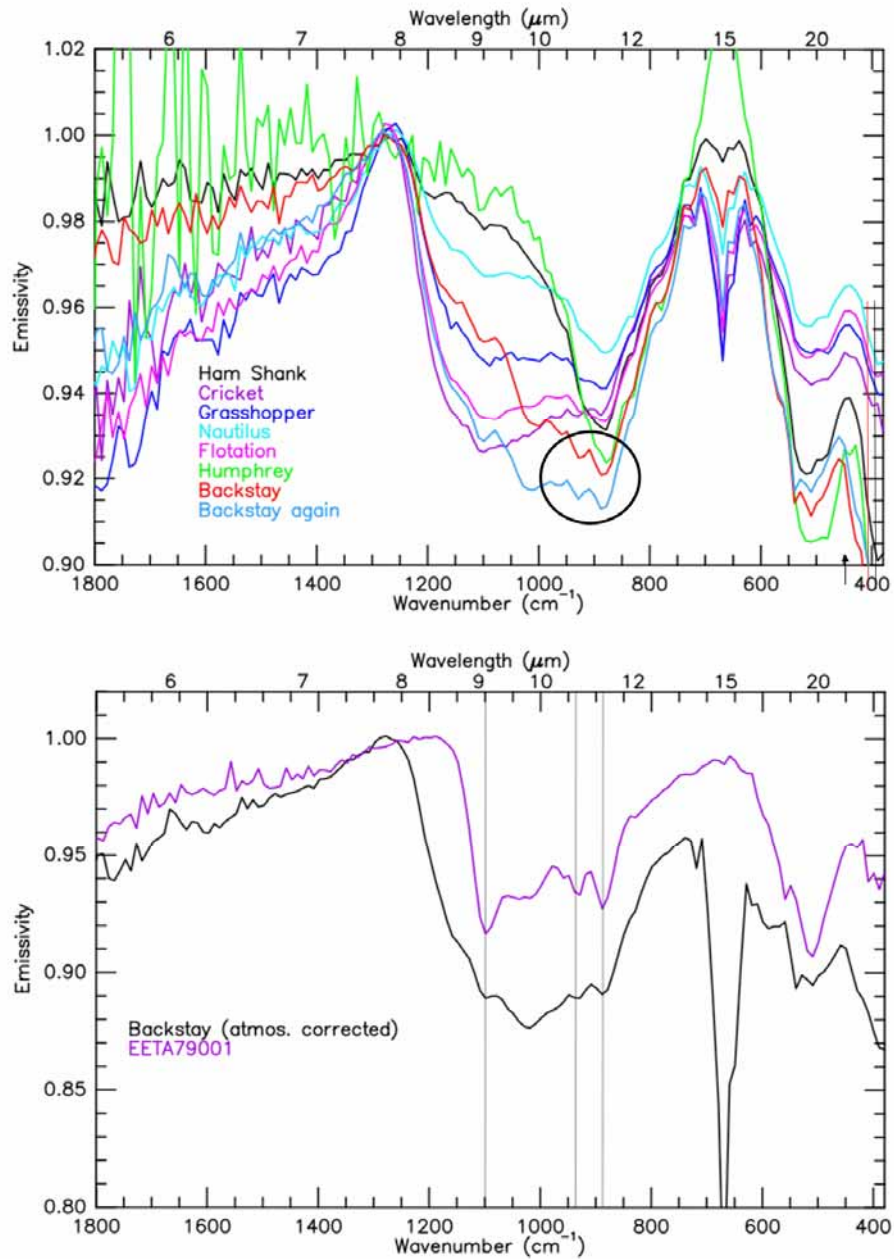
Figure 14: Mini-TES spectra of the rock Backstay, the only rock of its class investigated to date by Spirit. (a) top: Two spectra of Backstay, along with spectra of several other basaltic rocks investigated by Spirit; the circled region shows spectral features unique to Backstay. (b) bottom: A spectrum of Backstay, corrected for atmospheric effects, compared to a laboratory spectrum of the SNC meteorite EET79001.
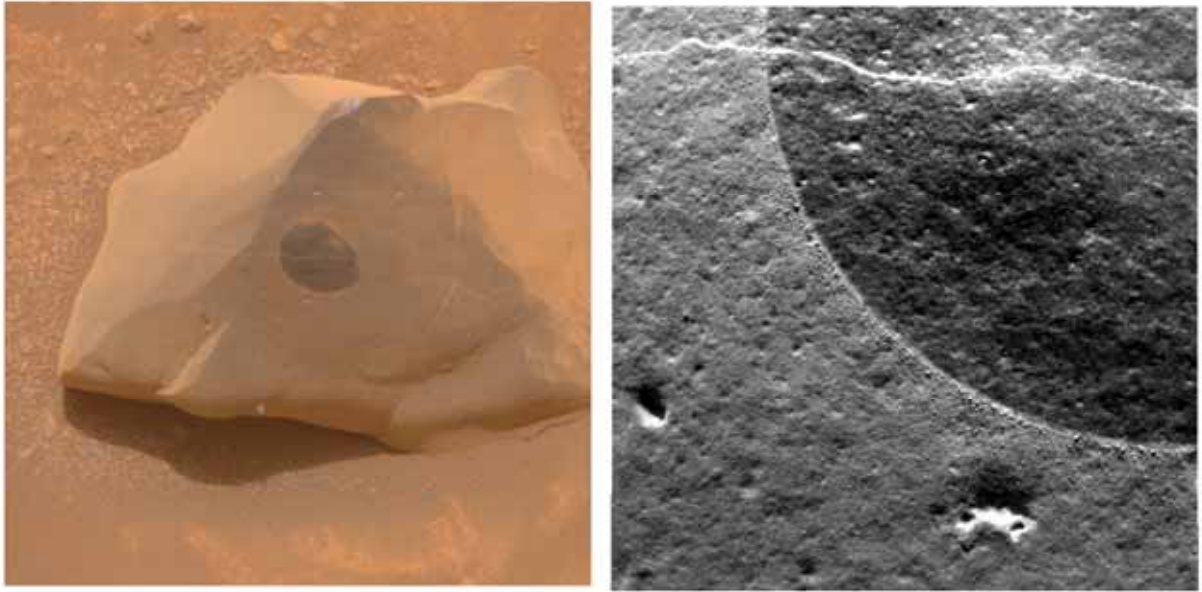
Figure 15: The rock Backstay. (a) left: Approximate true color Pancam image, acquired after brushing of Backstay with the Rock Abrasion Tool (Sol 511, Sequence p2563). (b) Microscopic Imager image, showing both brushed and unbrushed regions of the rock (Image ID 2M171727481). Scale across the MI image is 3 cm.