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Martian Igneous Processes based on Mars Pathfinder Lander and Sojourner Rover

* INTRODUCTION

Before Mars Pathfinder, the only information gathered on the surface of Mars was from the Viking 1 and 2 landers (Binder 1977, Mutch 1977, Clark 1977, Toulmin 1977). Pathfinder landed July 4, 1997 in the Vallis Ares region of Mars (Golombek 1997). After landing, the site was named the Sagan Memorial Station (Figure 1). The lander is located at 19.13N, 33.22W in the USGS reference frame and 19.28N, 33.52W in inertial space from spacecraft tracking (Golombek 1999) (Figure 2). Viking 1 landed relatively close by on July 20, 1976 in the Western Part of Chryse Planitia at 22.5N, 48.0W USGS. Viking 2 landed farther away on August 7, 1976 at 44N, 226W USGS (Carr 1981).

Mars Pathfinder was primarily to be a demonstration of entry, descent and landing systems. As such, engineering, not science, was the primary mission. The criteria for mission success were to return just one initial panorama from the landing site. The Pathfinder site was chosen to be a grab bag of samples in a safe landing area. To try to achieve a wide variety of rocks, the team chose a large outflow channel from a catastrophic flood (Britt 1998). The resulting landing site does indeed look like a flood plane and has 16% of the surface area covered in rocks.

The Pathfinder Mission lasted 3 months until NASA's Deep Space Network (DSN) lost contact with the lander. The lander returned 2.3 giga bits of data, which contained 16500 lander and 550 rover images. The rover, Sojourner, managed to traverse 100m clockwise around the lander collecting 5 rock and 6 soil samples with the Alpha Proton x-ray Spectrometer (APXS) (Figure 3). The rover transmitted all data to Pathfinder for a relay back to Earth. Once the lander failed, the rover was also effectively at the end of its mission.

* REGIONAL CHARACTERISTIC

Mars is a rocky inner solar system planet. It has a number of inactive volcanoes on it surface. The Martian crust has two general regions. The Southern hemisphere is generally is high, and the northern hemisphere is low. From Mars Global Surveyor orbital thermal emission spectra, there are also two different surface compositions that match the dichotomy (Bandfield 2000). The first type is a basaltic composition dominated by feldspar and clinopyroxene, which is found on the older surfaces. Type 2, the younger, is dominated by plagioclase feldspar and volcanic glass. The type 1 spectra are similar to the spectra seen of Earth of the Deccan Traps flood basalt in India. It matches ~60% by volume plagioclase and ~30% by volume clinopyroxene. Type 2 matches basaltic andesite with ~45 volume % plagioclase, ~40 volume % potassium rich glass, and ~10 volume % pyroxene. They believe that type 2 spectra may be due to silica enrichment, higher water contents, cumulate formation, and/or repeated partial melting. Sheet silicates, e.g. micas and clays, were seen in both but are probably surface weathering products.

From the Mars Global Surveyor thermal emission spectra (TEM), Bandfield and coworkers (2000) were not able to see large exposures of material that matches the Martian SNC meteorites. These rocks may be deep source cumulates that would have small or non-existent surface outcrops (McSween 1994). The TEM instrument is not able to see small exposures and may have missed SNC type materials.

In the Pathfinder region, there are two general types of geologic units (Britt 1998). There are Noachian-aged highlands. These are probably a mix of lava flows, pyroclastics, and impact breccias. There are also Hesperian-aged Ridged Plains that are extensive flows of what look like low viscosity lava.

* SOURCE OF MATERIAL FOR PATHFINDER SITE

In looking at the data returned from the Pathfinder site, it is important to consider where the site material originated. The Ares Vallis primary landform appears to be huge flood flow originating from the Tio and Ares catastrophic floods. According to McSween (1999), the rocks are Hesperian in age and are the lower most floors of an outflow channel. Ward (1999) calls the landing site relatively young at late Hesperian to early Amazonian (3.1-0.7 Ga). The Mouth of the flood channel is near both ridge plains and ancient heavily cratered terrain (Golombek 1999). The theory of the area being a flood channel is supported by super-resolution imaging from the Pathfinder of Twin Peaks (Stoker 1999) (Figure 4), which shows erosion (Britt 1998) and the imbrication of rocks in the rock garden (Golombek 1999).

Unfortunately, it would be hard for a flood to carry boulders 2 meters in size very far. It is approximately 800 km to the Southern Highlands, which is a long way to carry blocks and keep them angular (McSween 1999). Britt (1998) thinks that the transport is no more than 10's of km. The possible sources include rocks related to volcanic or sedimentary domes 100 km East of the site or rocks from local bedrock and streamlined islands which is thought to be older crust (Golombek 1999).

The second possible source material at the Pathfinder site is from impact ejecta (Figure 5). Carr (1981) describes the impact process with respect to Mars. The small size of the craters in the area implies that any ejecta at the site is from local impacts and will not contain deep material.

With the sort distance of flood transport and small diameter ejecta blankets in the region, it looks like all of the rock-sized material should be from a radius of 100 km.

* PATHFINDER CAMERAS

Mars Pathfinder had a total of 4 cameras. On the main lander had the Imager for Mars Pathfinder (IMP) camera (Smith 1997). The sojourner rover had three cameras (Newcott 1998).

The IMP camera is a bit unusual. It is a stereo camera with two eyes focused on one gray scale CCD imaging chip. In front of each eye is a filter wheel with six filters that run the range from 0.44 to 1.0 microns (Reid 1999) (Figure 6). To take a color image, the camera has to take 3 successive images, each with a different filter in front to get red, green, and blue. The camera is mounted on an expanding mast. After landing, a panorama was taken with the camera low down to the deck of the lander. Then an explosive bolt was fired and the mast unfurled to a higher vantage point.

The Sojourner rover has a stereo pair of two gray scale cameras mounted under the solar panels in the front. The extremely wide field of view of 120 degrees makes the images very spherically distorted and limits spatial resolution. At close range, the cameras give 0.7 to 1 mm per pixel resolution at close range. The back end of the rover has a color camera that was not especially useful do to different focal lengths for red green, and infrared bands (McSween 1999). It also has an extremely small dynamic range in the infrared. The rover has a huge advantage for detailed visual examination by being mobile and able to get close to the target.

* ROCK DESCRIPTIONS

The Pathfinder landing site has a variety of rocks. There are large tabular and subrounded rocks and subangular to subrounded pebbles, cobbles and boulders. Many of the larger rocks are perched (Golombek 1999). The large rocks are more weathered and are a meter and larger. The smaller rocks look like an impact ejecta blanket. They may be all from the same geologic unit (Britt 1998).

The rocks can be binned into 4 categories based on IMP spectra (Golombek 1999, McSween 1999). The four rock types are gray, red, pink and maroon. Grey and red are seen on different surface of the same rock. Pink rocks look to be soil crust and not actual rocks. Maroon rocks are large boulders and are mostly in the far field. The gray, red, and pink form a spectral trend. Britt (1998) interpreted this to be igneous rocks in two categories: dark unweathered, and bright weathered.

Parker (1998) describes the surface texture of the rocks. The general characteristics of the rocks fall into a number of categories: pits, linear features, knobs, and cracks.

The pits look more like Viking 1 surfaces than Viking 2. They typically have an abundance of 5-10% and range in size from a few mm to a few cm. Several look like volcanic vesicles, but it is far from conclusive. They could also be formed from chemical etching from occasional thin films of water. Another possibility is that they are ventifacts from saltating sand size particles (Golombek 1999). Bridges et al (1999) believe that half the rocks at the site are ventifacts and to into a detailed discussion. Figure 7 shows a view of pits up close from Sojourner.

Linear features may be layering. They are about 3-5 mm apart. If they are layering, there are a number of possibilities for their origin, for example orientation of stresses in the rocks, alignment of bubbles or minerals, zones of weakness, or sedimentary layering. Other suggestions (Golombek 1999) include volcanic flow banding and metamorphic foliation.

There are two rocks that have features not seen on other rocks. Squash appears to have a knobby shape with lobes and protrusions ~10cm in size. This could be autobrecciated lava, pillow basalt, impact breccia, or volcanic rocks with lithic fragments. Another suggestion is sediments with large clasts (Golombek 1999). Chimp is the only rock showing a fracture. Parker (1998) suggests that this is exfoliation and could be do to freeze-thaw cycles.

* APXS INSTRUMENT

On the back of the Sojourner rover is a deployable arm that has an Alpha Proton x-ray Spectrometer (APXS). This device is able to measure a subset of elemental composition. The alpha backscatter is detects C, N, and O. The proton mode detects Na, Mg, Al, Si, S, and N. The x-ray mode can detect the major elements above Na (Foley 2000). The APXS needs 3 hours of integration time for the x-ray mode and 10 hours for the alpha and proton modes. Shorter times did work, but had more noise (Golombek 1999). The daytime x-ray data was noisy, so most of the measurements were done during the afternoon and night.

Each of the instrument modes has some interference from the Martian atmosphere (Foley 2000). The proton spectra see the atmospheric nitrogen, but the signal is small since only 2.7% of the atmosphere is nitrogen. The x-ray mode intensities are lower from having the atmosphere in the way. Alpha scattering has interference from atmospheric carbon dioxide scattering. This interference varied with diurnal pressure and temperature in addition to the APXS distance from the sample. The APXS is mounted on a passive deployment arm that has only one degree of freedom. As a result, the instrument is not always flush with the surface of the target. Samples A-2 and A-9 are known to have poor surface contract. Sol (Martian day) number 22 had an air shot that completely missed any sample. Initial rock compositions were complicated by the high errors in alpha and proton modes and most analysis relied just on the x-ray mode to determine element abundances (e.g. Rieder, 1997).

* DISCUSSION OF MPF SITE ROCKS

There is an additional complication with the rock abundance; the rock surfaces are definitely not fresh. All of the rocks have some level of dust coating. Dust coatings are inferred to be high in magnesium and sulfur with significant amounts of chlorine. Britt (1998) saw that the weathering trend depletes silica and aluminum while enriching titanium, magnesium, and sulfur with respect to the rocks. In addition the red/blue ration when compared to sulfur APXS correlates to show that there is a linear APXS mixing line between dust and rock (McSween 1999).

Based on the APXS readings and using an analysis to remove the dust component, a soil free rock composition has been determined by a number of authors. These numbers have been refined of the last few years and the most recent results are by Foley et al (2000) in Figure 8. Based on these results, the rocks are all uniform and plot in the andesite field. The general conclusion is that rocks are similar to anorogenic tholeiitic andesite like icelandites (Golombek 1999, Britt 1998, Foley 2000). This is shown in Figure 9, with a plot of weight % Na_2O + K_2O versus weight % NiO_2. Britt 1998 points out that it is not associated with subduction and is probably fractionated basaltic volcanism that is laterally extensive but volumetrically minor. This would match with the MGS-TES results that see part of the planet covered a basaltic andesite.

Finding a good definition of an icelandite seems a bit difficult. A simple description of icelandites is in Guomundsson and Kjartansson (1996):

> The magma contain less water and the dark primary mineral pyroxene occurs instead of the water-rich hornblende or biotite found in the continental rocks. The Icelandic variants are richer in iron than the foreign andesites. The terms icelandite and basaltic icelandite ... are not uncommon for the Icelandic rocks.

Andesite is not the only possibility for the rock composition. It could be clastic sediments, impact melt, or breccias (McSween 1999). However, such other alternatives should cause spectral mottling in the APXS data that is not scene. McSween et al assert that the data does not allow unique identification of mineralogy or petrology. Golombek et al (1999) believe that the Pathfinder site may be dominated by distinctive, perhaps unusual lithology.

Based on the APXS results of something like an icelandite, there should be a signature of the 0.9-1.0 micron pyroxene absorption band seen in the IMP spectral images. There is no evidence for seeing this absorption in any of the Pathfinder images (Britt 1998). If the rocks contain pyroxene, it may be masked by impact glass or magnetite. Another alternative is that the pyroxenes are Ca and Fe rich which moves the absorption band outside of the IMP filter range (McSween 1999).

* CONCLUSIONS FOR WHOLE PLANET

Based on the visual and APXS results from the Mars Pathfinder mission, many scientists have tried to understand the igneous processes that have occurred on Mars. Unfortunately, give the current data set, the situation is much more unconstrained than the Earth's processes. Comparing the soil free rock values with the SNC meteorites has yielded a number of results. Dreibus et al (1998) found that Mg/Si and Al/Si shows a relationship (Figure 10). A variety of igneous material from Earth plot along one line, while Martian samples plot along two other lines. The new results from Foley et al (2000) put the soil free rock right on the main Martian line. Shergotty and Zagami form a second fractionation line that could be derived from younger intrusions into older Martian Crust. It is assumed that Shergotty and Zagami were both ejected from Mars in one event at 2.8 Mya.

However, McSween et al (1998) thinks that the relationship with SNC is weak. They compared liquid lines of descent, which suggested that the parental basaltic magma would have higher aluminum content than SNC melts, more like MORB. This difference may indicate a more primitive mantle source that had not yet been depleted in aluminum by partial melting. Based on the belief that Mars differentiated very early, they think the Pathfinder rocks may be much older.

Lowman (1998) compared these results to Armstrong's theory of continental crust formation. He predicts a two stage crustal evolution for early Mars. First, there is a felsic differentiation under hydrous conditions, which produces an andesitic continental crust. Finding andesite with Pathfinder supports this. The second stage is a basaltic differentiation, which is supported by SNC meteorites. The current data on Mars is too sparse to hard to prove or disprove this theory. According to this theory, most of the Martian crust formed by andesitic volcanism accompanying out gassing of the primordial mantle. To contrast with Lowman, Golombek et al (1999) say that if the soil free rock is actually from the ancient heavily cratered terrain, this suggest that Mars was a widespread differentiated crust, similar to continental crust on Earth.

Driebus et al (1998) used numerical modeling of partial melting primitive Martian mantle to produce SNC melts and Pathfinder material. They concluded that the most probably Martian asthenosphere is harzburgitic and that the crustal thickness is close to 200 to 250 km. Moment of inertia studies have constrained the metal core to 1300-2000 km. Given the Martian radius of 3397 km, this results in a mantle that is 1147 to 1897 km thick.

None of the papers review had relative abundance diagrams similar to spider diagrams. Figure 11 compares the Foley 2000 values with compositions of C1 Carbonaceous chondrites and bulk silicate earth from McDonough and Sun (1995). Primitive mantle and MORB values are available from Hofmann (1988). Additionally, There is one rock from the GEOROC database (Busch 2000) that is classified as an icelandite.

The SNC meteorites have been in analyzed in detail, which resulted in their being classified as basalts, lherzolite, clinopyroxenite, and dunite (Dardana). The SNC and Pathfinder soil free rock may not compare well. Many of the SNC meteorites are described as cumulates, so they may run down a different line of fractionation. The number of data points for these plots is extremely low for the Earth, so the statistical significance is much lower. It is unknown how these Martian rocks relate to each other. Without more samples that are known to be related to each other, it is difficult to be certain of any conclusion.

* FUTURE WORK

In going through the current literature, several questions came to mind that have not been answered. One question is from how far down can an impact draw material for each size crater? If some of the Pathfinder rocks are perched, were they perhaps deposited with a sandy matrix, which has since been removed by eolean processes? How much water is required to transport boulders the size seen with Pathfinder? And for that size flow, what kind of fluvial structures would be expected? Would that kind of flow produce the dunes that are seen in 3D models that have wavelengths of 5-10 meters?

One question I think I can answer is related to hydrothermal fluid flow. What does it mean that no hydrothermal rocks were seen at the site? Several scientists were hoping that they would see material from hydrothermal systems. Not seeing any such material should have little bearing on the possibility of extinct or extant hydrothermal systems on Mars. In Yellowstone National Park, the siliceous material that forms sinter is seen to break down to sand sized particles after transport of one to two hundred meters. Such material should disintegrate if transported in any sort of flood that is transporting boulders.

* REFERENCES

J. L. Bandfield, V. E. Hamilton, P. R. Christensen, "A Global View of Martian Surface Compositions from MGS-TES," Science, Vol. 287, p. 1626-1630, 3 March 2000.

A. B. Binder, R. E. Arvidson, E. A. Guinness, K. L. Jones, E. C. Morris, T. A. Mutch, D. C. Pieri, C. Sagan," The Geology of the Viking Lander 1 Site," Journal of Geophysical Review, Vol. 82, No. 28, pages 4439-4451, September 30, 1977.

N. T. Bridges, R. Greeley, A. F. C. Haldemann, K. E. Herkenhoff, M. Kraft, T. J. Parker, A. W. Ward, "Ventifacts at the Pathfinder landing site," Journal of Geophysical Research, Vol. 104, No. E4, Pages 8595-8615, April 25, 1999.

D. T. Britt, R. Anderson, J. F. Bell III, J. Crisp, T. Economou, K. E. Herkenhoff, M. B. Madsen, H. Y. McSween, S. Murchie, R. Reid, R. Rieder, R. B. Singer, L. Soderblom, "The Mineralogy of the Mars Pathfinder landing site", 29th Lunar and Planetary Science Conference, United States, Houston, TX, 1998.

U Busch, B. Sarbas, C. Metz, U. Nohl, H. Schafer, http://georoc.mpch-main.gwdg.de/

M. H. Carr, The surface of Mars, pp. 232, Yale University Press, 1981.

B. C. Clark III, A. K. Baird, H. J. Rose, Jr., P. Toulmin III, R. P. Christian, W. C. Kelliher, A. J. Castro, C. D. Rowe, K. Keil, G. R. Huss, "The Viking X Ray Flourescence Experiment: Analytical Methods and Early Results," Journal of Geophysical Review, Vol. 82, No. 28, pages 4577-4594, September 30, 1977.

C. Dardana, C. Agee, "Meteorites from Mars," http://www-curator.jsc.nasa.gov/curator/antmet/marsmets/contents.htm.

G. Dreibus, I. Ryabchikov, R. Rieder, T. Economou, J. Brucknet, M. Y. McSween Jr., H. Wanke, "Relationship Between Rocks and Soil at the Pathfinder Landing Site and the Martian Meteorites," 29th Lunar and Planetary Science Conference, United States, Houston, TX, 1998.

C. N. Foley, T. E. Economou, W. Dietrich, R. N. Clayton, "Chemical Composition of Martian Soil and Rocks: Comparison of the Results from the Alpha, Proton, and X-Ray Modes of the Pathfinder APXS," 63rd Annual Meteoritical Society Meeting, abstract #5311, 2000.

M. P. Golombek, R. A. Cook, T. Economou, W. M. Folkner, A. F. C. Haldemann, Ph. H. Kallemeyn, J. M. Knudsen, R. M. Manning, H. J. Moore, T. J. Parker, R. Rieder, J. T. Schofield, P. H. Smith, R. M. Vaughan, "Overview of the Mars Pathfinder Mission and Assessment of Landing Site Predictions, Science, Vol. 278, pages 1743-1748, 5 December 1997.

M. P. Golombek, R. C. Anderson, J. R. Barnes, J. F. Bell III, N. T. Bridges, D. T. Britt, J. Bruckner, R. A. Cook, D. Crisp, J. A. Crisp, T. Economou, W. M. Folkner, R. Greeley, R.M. Haberle, R.B. Hargraves, J. A. Harris, A. F. C. Haldemann, K. E. Herkenhoff, S. F. Hviid, R. Jaumann, J. R. Johnson, P. H. Kalleyn, H. U. Keller, R.L. Kirk, J.M. Knudsen, S. Larsen, M. T. Lemmon, M. B. Madsen, J.A. Magalhaes, J. N. Maki, M. C. Malin, R.M. Manning, J. Matijevic, H. Y. McSween Jr., H. J. Moore, S. L. Murchie, J. R. Murphy, T. J. Parker, R. Rieder, T.P. Rivellini, J. T. Schofield, A. Seiff, R. B. Singer, P. H. Smith, L. A. Soderblom, D. A. Spencer, C. R. Stoker, R. Sulliva, N. Thomas, S. W. Thurman, M. G. Tomasko, R. M. Vaughan, H. Wanke, A. W. Ward, and G. R. Wilson, "Overview of the Mars Pathfinder Mission: Launch through landing, surface operations, data sets, and science results", Journal of Geophysical Research, Vol. 104 No E4, Pages 8523-8553, April 25, 1999.

A. T. Guomundsson, H. Kjartansson, "Earth in Action, The Essential Guide to the Geology of Iceland," Published by Vaka-Helgafell, pages 142-144, 1996.

A. W. Hofmann, "Chemical differentiation of the Earth: the relationship between mantle, continental crust, and oceanic crust," Earth and Planetary Science Letters, Vol. 90, pages 297-314, 1998.

P. D. Lowman, "Andesites on Mars: Implications for the origin of Terrestrial Continental Crust," 29th Lunar and Planetary Science Conference, United States, Houston, TX, 1998.

W. F. McDonough, S.-s. Sun, "The composition of the Earth," Chemical Geology, Vol. 120, pages 223-253, 1995.

H.Y. McSween, Jr., J. P. Greenword, A. Ghosh, "Rocks of Andesitic Composition at the Mars Pathfinder Site: What Do They Mean?," 29th Lunar and Planetary Science Conference, United States, Houston, TX, 1998.

H. Y. McSween Jr., S. L. Murchie, J. A. Crisp, N. T. Bridges, R. C. Anderson, J. F. Bell III, D. T. Britt, J. Bruckner, G. Dreibus, T. Economou, A. Ghosh, M. P. Golombek, J. P. Greenwood, J, R. Johnson, H. J. Moore, R. V. Morris, T. J. Parker, R. Rieder, R. Singer, and H. Wanke, "Chemical, multispectral, and textural constraints on the composition and origin of rocks at the Mars Pathfinder landing site," Journal of Geophysical Research, Vol. 104, No E4, Pages 8679-8715, April 25, 1999.

H. Y. McSween, "Invited Review: What we have learned about Mars from SNC meteorites," Meteoritics, Vol. 29, No. 6, pages 757-779, November 1994. Also in Scientific American, http://www.sciam.com/1297issue/1297mars.html.

M. E. Minitti, M. J. Rutherford, "Genesis of the Mars Pathfinder "sulfur-free" rock from SNC parental liquids," Geochimica Et Cosmochimica Acta, 64: (14), pages 2535-2547.

T. A. Mutch, R. E. Arvidson, A. B. Binder, E. A. Guinness, and E. C. Morris, "The Geology of the Viking Lander 2 Site," Journal of Geophysical Review, Vol. 82, No. 28, pages 4452-4467, September 30, 1977.

W. R. Newcott, "Return to Mars", National Geographic, Val 194, No. 2, pages 2-29, August 1998.

T. J. Parker, H. J. Moore, J. A. Crisp, M. P. Golombek, "Petrogenetic interpretations of rock textures at the pathfinder landing site," 29th Lunar and Planetary Science Conference, United States, Houston, TX, 1998.

R. J. Reid, P. H. Smith, M. Lemmon, R. Tanner, M. Burkland, E. Wegryn, J. Weinberg, R. Marcialis, D. T. Britt, N. Thomas, R. Kramm, A. Dummel, D. Crowe, D. J. Bos, J. F. Bell III, P. Rueffer, F. Gliem, J. R. Johnson, J. N. Maki, K. E. Herkenhoff, R. B. Singer, "Imager for Mars Pathfinder (IMP) image calibration," Journal of Geophysical Research, Vol. 104, No. E4, Pages 8907-8925, April 25, 1999.

R. Rieder, T. Economou, H. Wanke, A. Turkevich, J. Crisp, J. Bruckner, G. Dreibus, H. Y. McSween Jr., "The Chemical Composition of Martian Soil and Rocks Returned by the Mobile Alpha Proton X-ray Spectrometer: Preliminary Results from the X-ray Mode," Science, Vol. 278, pages 1771-1774, 5 December 1997.

P. H. Smith, J. F. Bell III, N. T. Bridges, D. T. Britt, L. Gaddis, R. Greeley, H. U. Keller, K. E. Herkenhoff, R. Jaumann, J. R. Johnson, R. L. Kirk, M. Lemmon, J. N. Maki, M. C. Malin, S. L. Murchie, J. Oberst, T. J. Parker, R. J. Reid, R. Sablotny, L. A. Soderblom, C. Stoker, R. Sullican, N. Thomas, M. H. Tomasko, W. Ward, E. Wegryn, "Results from the Mars Pathfinder Camera," Science, Vol. 278, pages 1758-1765, 5 December 1997.

P. Toulmin III, A. K. Baird, B. C. Clark, K. Ceil, H. J. Rose, Jr., R. P. Christian, P. H. Evans, W. C. Kelliher, "Geochemical and Mineralogical Interpretations of the Viking Inorganic Chemical Results, Journal of Geophysical Review, Vol. 82, No. 28, pages 4625-4633, September 30, 1977.

A. W. Ward, L.R. Gaddis, R. L. Kirk, L. A. Soderblom, K. L. Tanaka, M. P. Golombek, T. J. Parker, Ronald Greeley, and R. O. Kuzmin, "General geology and geomorphology of the Mars Pathfinder Landing Site," Journal of Geophysical Research, Vol. 104, No. E4, Pages 8555-8571, April 25, 1999.

FIGURES

Figure 1 – Sojourner image of the Sagan Memorial Station (a.k.a. Mars Pathfinder.) Rover image 05525.

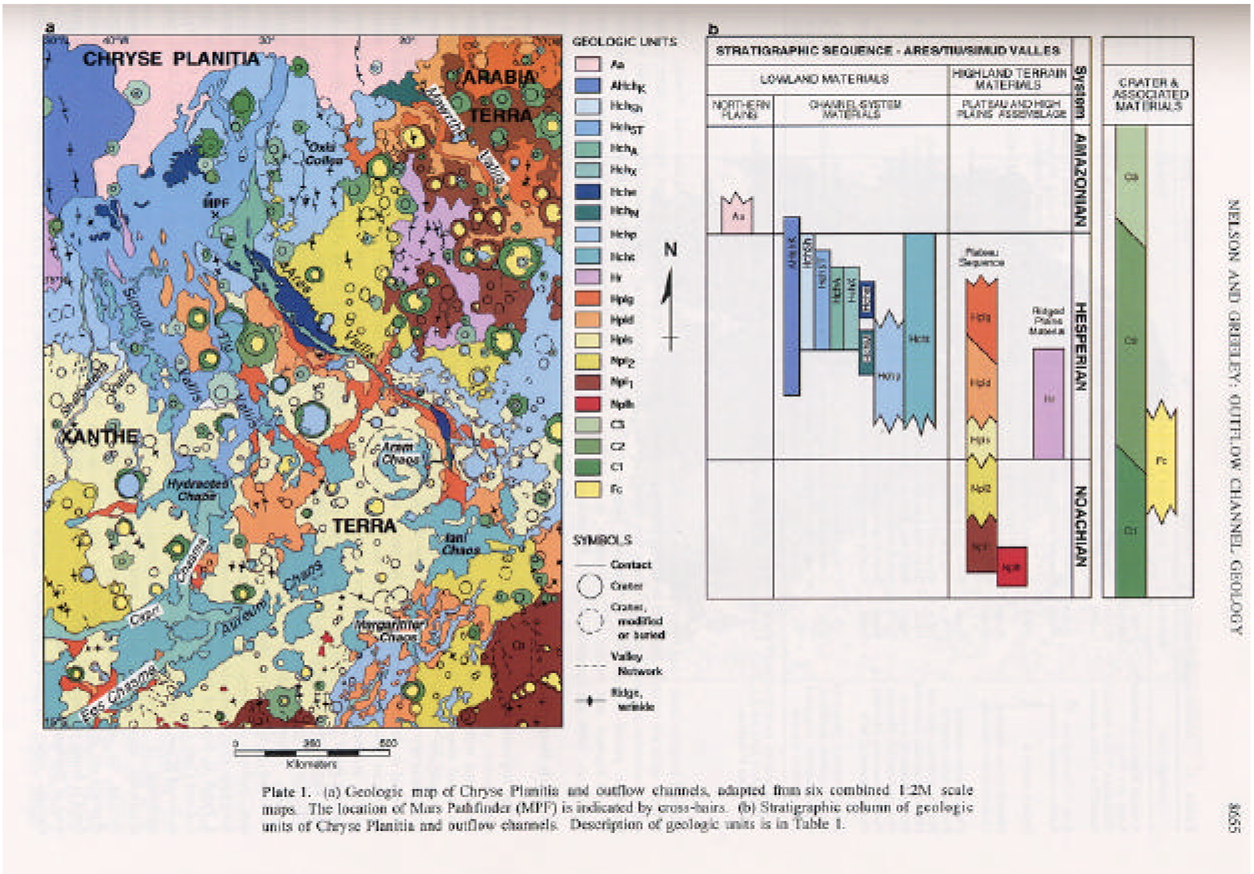

Figure 2 – Geologic map of the region around the Pathfinder landing site. From McSween 1999, page 8655.

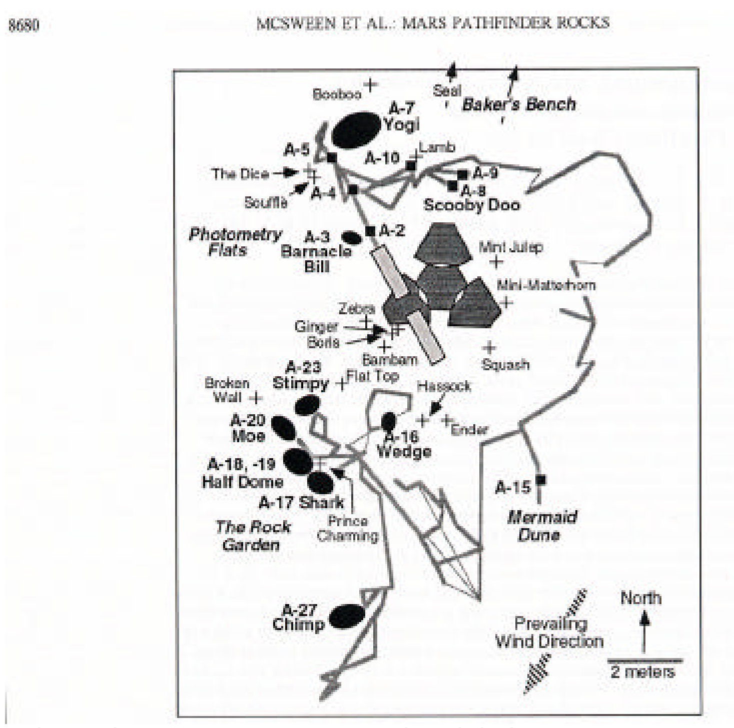

Figure 3 – Map showing Sojourner's traverse around Pathfinder. From McSween 1999, page 8680.

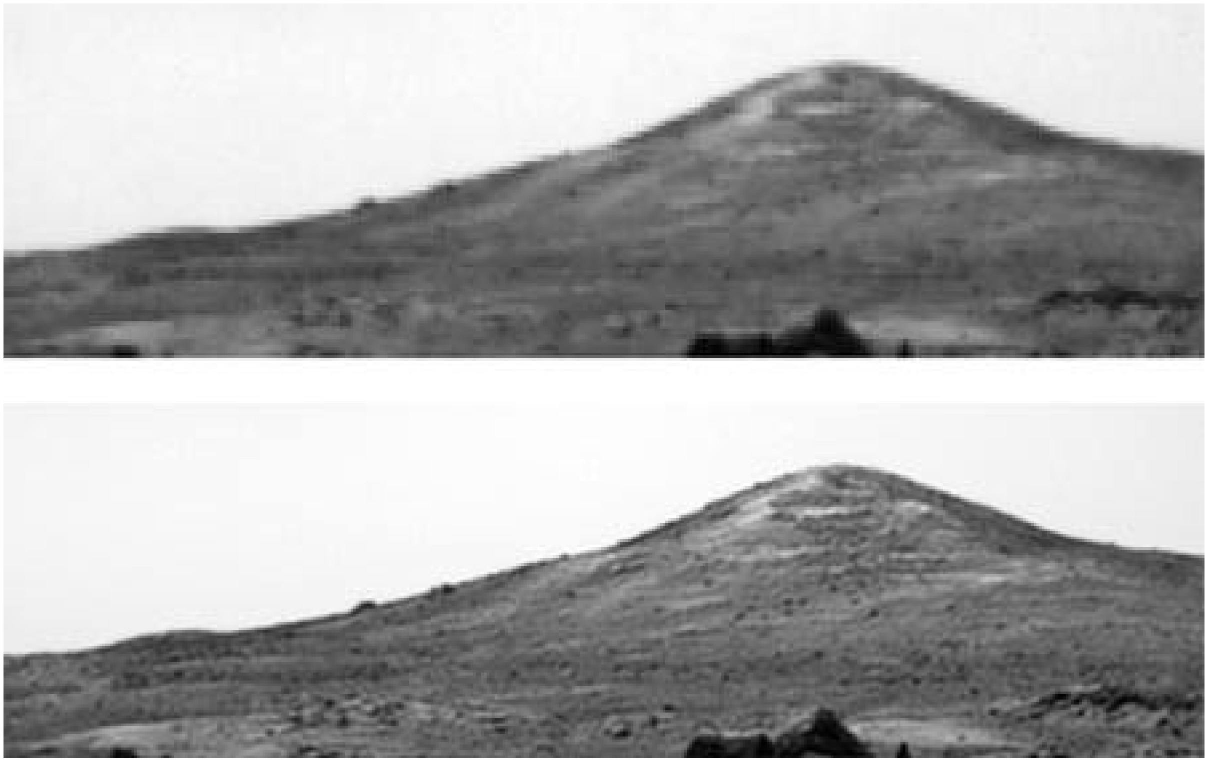

Figure 4 – Twin Peaks view in super-resolution image.

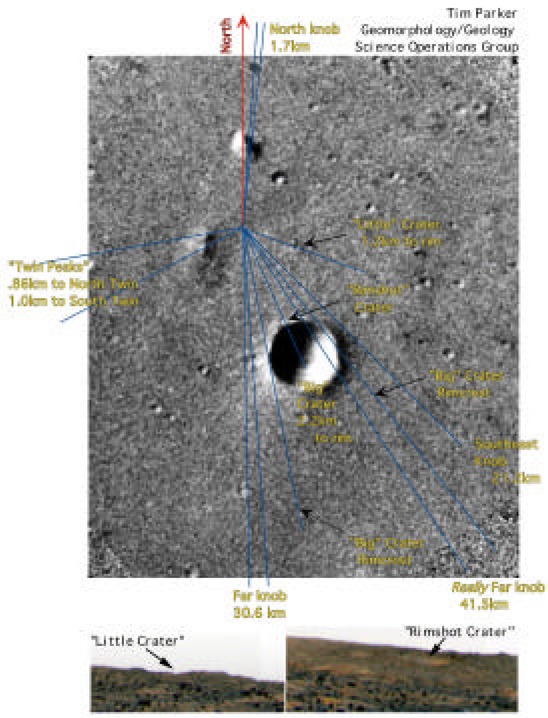

Figure 5 – Landing site localization figure by Parker from the MPF web pages. Shows Big Crater being 2.2 km from the lander.

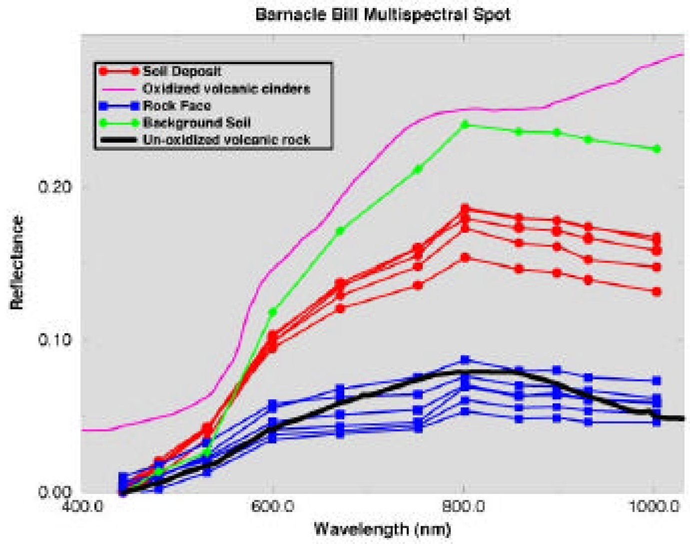

Figure 6 – Shows the location of the spectral bands for the IMP camera filters. From the MPF web site.

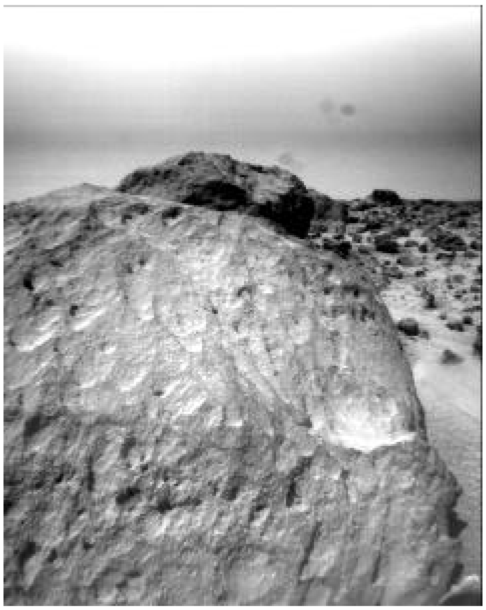

Figure 7 – Close-up view of the pits scene on many rocks. Rover image 70078.

X-ray Soil-Free Rock Composition

Oxide	Wt % ± error %	Mineral	Weight%*
Na_2O^{τ}	2.5 ± 0.4	Apatite	1.3
MgO	1.8 ± 0.5	Chromite	0.1
Al_2O_3	11.5 ± 0.1	Ilmenite	1.1
SiO_2	57.7 ± 2.9	Orthoclase	8.8
P_2O_5	0.5 ± 0.2	Albite	21.2
Cl	0.3 ± 0.1	Anorthite	15.8
K_2O	1.2 ± 0.04	Magnetite	1.4
CaO	6.9 ± 0.3	Wallostonite	6.2
TiO_2	0.6 ± 0.1	Enstatite	0.9
Cr_2O_3	0.1 ± 0.02	Ferrosilite	5.9
MnO	0.3 ± 0.1	Hyp.En	3.6
FeO_T	16.6 ± 0.5	Hyp.Ferr	22.7
Sum	100	Quartz	11.7

Key: $^{\tau}Na_2O$ value from alpha/proton mode, *calculated wt% norm assumes $Fe_2O_3/FeO = 0.026$, average basaltic shergottite value [4].

Figure 8 – Latest soil free rock composition estimate from Foley 2000.

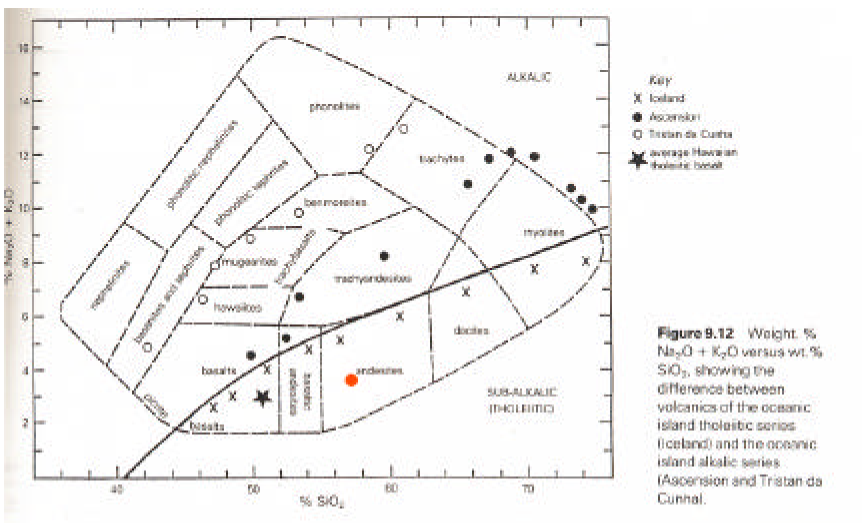

Figure 9 – Foley 2000 soil free rock composition plots in the andesites field. Figure from Wilson 1989.

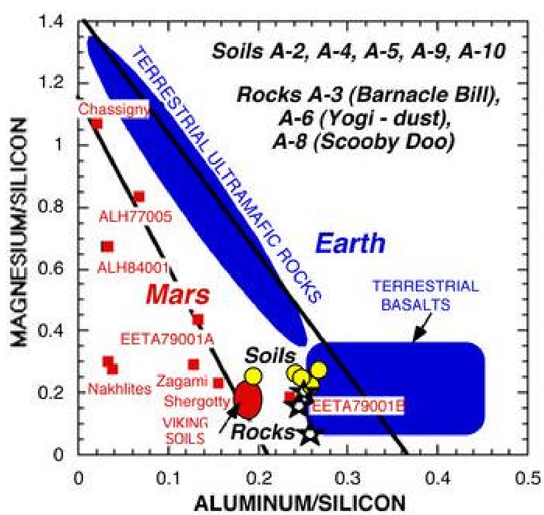

Figure 10 – Mg/Si versus Al/Si plot from the MPF website. With the Foley 2000 soil free rock composition plot right on the main Martian line (not plotted here).

	Foley 2000	C1 Model	NMORB 4	Icelandite		Foley/C1	Foley/NMO	Foley/Icela
Si02	57.7	49.9	50.55	57.85	Si02	96.16667	1.141444	0.997407
TiO2	0.6	0.16	1.31	0.99	TiO2	0.052174	0.458015	0.606061
Al2O3	11.5	3.65	16.28	13.36	Al2O3	0.692771	0.706388	0.860778
FeO*	16.6	8	9.03	10.64	FeO*	55.33333	1.838317	1.56015
MnO	0.3	0.13	0.16	0.14	MnO	0.166667	1.875	2.142857
MgO	1.8	35.15	7.8	4.7	MgO	0.26087	0.230769	0.382979
CaO	6.9	2.9	11.62	6.21	CaO	2.76	0.593804	1.111111
Na2O	2.5	0.34	2.79	2.77	Na2O	2.083333	0.896057	0.902527
K2O	1.2	0.022	0.09	0.3	K2O	2.4	13.33333	4
P2O5	0.5	0.021	0.13	0.07	P2O5	0.03012	3.846154	7.142857
FeO	16.6	8	7.76	3.81				
Fe2O3			1.27	6.83				

Mg/Si	0.031196	0.704409	0.154303	0.081245
Al/Si	0.199307	0.073146	0.322057	0.230942
Ca/Si	0.119584	0.058116	0.229871	0.107347
Fe/Si	0.287695	0.160321	0.178635	0.183924
Fe/MnO	55.33333	61.53846	56.4375	76

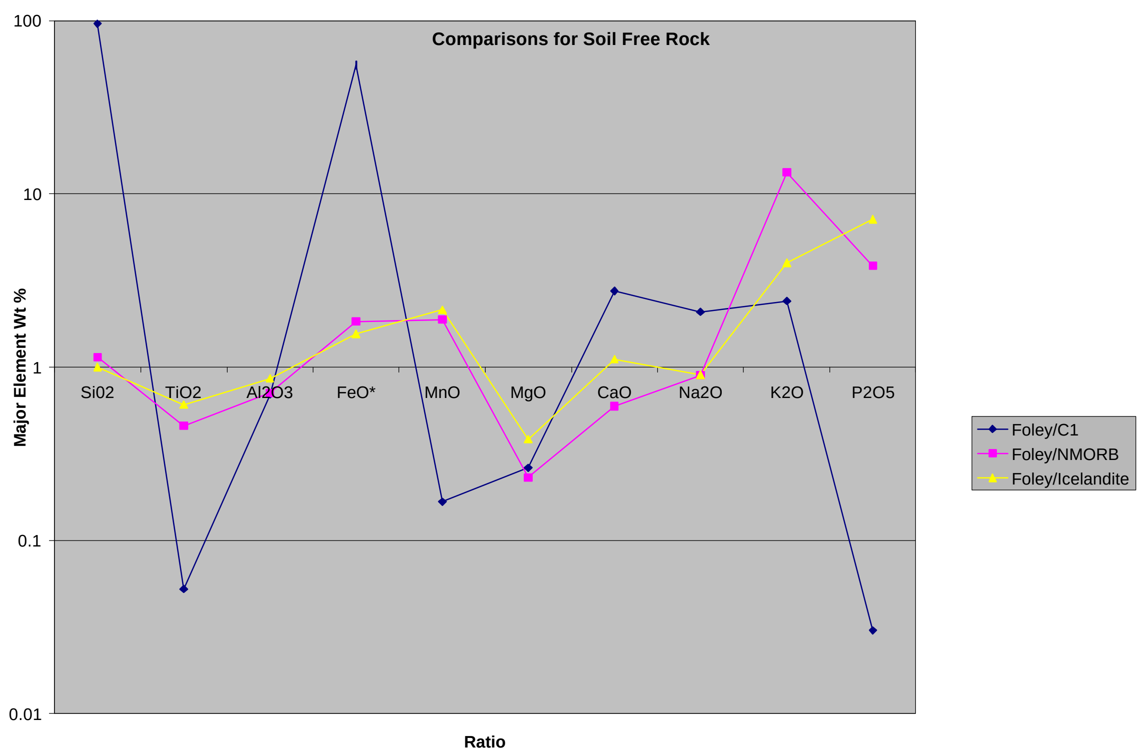

Figure 11 – Comparison of Foley 2000 with C1 Chondrite, NMORB, and an Icelandite.