2003 MARS EXPLORATION ROVER MISSION: ROBOTIC FIELD GEOLOGISTS FOR A MARS SAMPLE RETURN MISSION. D. W. Ming, NASA Johnson Space Center, Mail Code KX, Houston, TX 77058 (douglas.w.ming@nasa.gov).

Introduction: The Mars Exploration Rover (MER) Spirit landed in Gusev crater on Jan. 4, 2004 and the rover Opportunity arrived on the plains of Meridiani Planum on Jan. 25, 2004. The rovers continue to return new discoveries after 4 continuous Earth years of operations on the surface of the red planet. Spirit has successfully traversed 7.5 km over the Gusev crater plains, ascended to the top of Husband Hill, and entered into the Inner Basin of the Columbia Hills. Opportunity has traveled nearly 12 km over flat plains of Meridiani and descended into several impact craters.

Spirit and Opportunity carry an integrated suite of scientific instruments and tools called the Athena science payload. The Athena science payload consists of the 1) Panoramic Camera (Pancam) that provides high-resolution, color stereo imaging, 2) Miniature Thermal Emission Spectrometer (Mini-TES) that provides spectral cubes at mid-infrared wavelengths, 3) Microscopic Imager (MI) for close-up imaging, 4) Alpha Particle X-Ray Spectrometer (APXS) for elemental chemistry, 5) Mössbauer Spectrometer (MB) for the mineralogy of Fe-bearing materials, 5) Rock Abrasion Tool (RAT) for removing dusty and weathered surfaces and exposing fresh rock underneath, and 6) Magnetic Properties Experiment that allow the instruments to study the composition of magnetic martian materials [1].

The primary objective of the Athena science investigation is to explore two sites on the martian surface where water may once have been present, and to assess past environmental conditions at those sites and their suitability for life. The Athena science instruments have made numerous scientific discoveries over the 4 plus years of operations. The objectives of this paper are to 1) describe the major scientific discoveries of the MER robotic field geologists and 2) briefly summarize what major outstanding questions were not answered by MER that might be addressed by returning samples to our laboratories on Earth.

Spirit in Gusev crater: Aqueous alteration in Gusev crater ranges from minor alteration on the surfaces and interiors of rocks and within the regolith on the basaltic plains, to highly altered outcrops and rocks in the Columbia Hills including the Inner Basin [2-5]. Some outcrops and rocks in the Colombia Hills appear to be extensively altered as suggested by their relative "softness" as compared to crater floor basalts, high Fe^{3+}/Fe_T ratios, iron mineralogy dominated by nanophase Fe^{3+} oxides, hematite, and goethite, and high Br, S, and Cl concentrations in rock interiors exposed by grinding with the RAT [2,3]. The discovery of goethite in Columbia Hills rocks is very important to understanding the history of water in Gusev crater, because this mineral can only form in the presence of water, in contrast to hematite that can form by either aqueous or non-aqueous processes [2]. MB measurements also detected the presence of a ferric-sulfate in the Paso Robles class surface soils [2,6]. Observations by Mini-TES suggest that the sulfate is hydrated [7]. The extreme mineralogical and chemical compositions of Paso Robles class soils very strongly implicate aqueous processes that involved the movement of liquid water (highly acidic) through the host material [3,6].

Nanophase Fe-oxides (npOx) are also detected by the MB in soils and rocks at Gusev crater [2]. The mineralogy of npOx phases is not known but these phases may contain H_2O/OH; however, the concentration of Fe associated with npOx increases as the concentration of S+Cl increases, showing that npOx is an alteration product [8,2].

Recently, deposits of amorphous silica (>90% SiO_2) have been discovered around Home Plate located in the Inner Basin of the Columbia Hills [9]. These deposits appear to have formed under hydrothermal conditions associated with volcanic deposits in the Columbia Hills [9,10].

Water has played a significant role in the alteration of rocks and soils in the Columbia Hills. The occurrence of goethite, ferric sulfate, and amorphous silica alone suggests that liquid water was involved in their formation. The pervasively altered materials in the Columbia Hills outcrops and rocks may have formed by low-temperature and/or hydrothermal aqueous alteration of basaltic rocks, volcaniclastic materials, and/or impact ejecta by solutions that were rich in acid-volatile elements; although high pH solutions cannot be ruled out in the formation of amorphous silica deposits.

Opportunity on Meridiani Planum: The occurrence of jarosite, other sulfates (e.g., Mg-and Ca-sulfates), and hematite along with siliciclastic materials in outcrops of sedimentary materials at Meridiani Planum are strong indicators of aqueous processes [11-14]. Jarosite can only form by aqueous processes under very acidic conditions; *i.e.*, acid-sulfate weathering conditions. Hematite occurs as small particles (below MI resolution of ~30 µm/pixel) embedded within the outcrop, as spherules (average size around 4 mm) embedded in the Meridiani outcrop, and a lag deposit where the hematite has physically weathered out of the outcrop and concentrated at the surface. The hematite-rich spherules have been interpreted to be concretions that have formed in the outcrop during a complex diagenetic history, as suggested by episodes of cementation and recrystallization, formation of the hematite-rich spherules, and dissolution and formation of crystal mold vugs in outcrops [13].

Squyres *et al.* [11] suggested that the outcrops formed when ancient Meridiani once had abundant acidic groundwater, arid and oxidizing surface conditions, and occasional liquid flow on the surface. Another hypothesis is that regional heating caused a release of sulfide-rich hydrothermal waters that formed pyrite-rich deposits, and the subsequent aqueous oxidation of these deposits formed the sulfates and hematite in Meridiani outcrops [15]. McCollum and Hynek [16] and Knauth *et al.* [17] have suggested that the aqueous alteration occurred during flows induced by volcanic and impact base surges, respectively.

Mars Sample Return (MSR): The robotic field geologists of MER have been highly successfully in advancing our knowledge about aqueous processes on the surface of Mars; however, questions remain unanswered about the mineralogy, chemistry, and formation conditions of many materials encountered by the rovers. Mars samples returned to our laboratories may be the only way to answer some of these unresolved questions, although future robotic missions (2007 Mars Phoenix Scout, 2009 Mars Science Laboratory) may address some of these unanswered questions.

Several unresolved questions are briefly presented here (Table 1), but detailed accounts of these unresolved MER questions and the merits of MSR are presented elsewhere in this volume [18,19]. Several unresolved questions focus on the mineralogy of phases encountered by MER. No doubt, detailed mineralogy could be thoroughly described by the plethora of analytical instruments available in our terrestrial laboratories. Mineralogical identification of these phases would significantly enhance our understanding of their formation processes. Additional constraints on their formation conditions and ages could be obtained by detailed isotopic analyses that can only be preformed with high precision in our terrestrial laboratories (e.g., light isotopes, noble gases, stable isotopes, etc.).

MER landing sites for a MSR Mission? No doubt, a debate will rage through the planetary science community on where to land the first and subsequent MSR missions. The MER landing sites have several key advantages over other landing sites. First and foremost, the MER landing sites have been characterized by robotic field geologists for over 4 Earth years. These sites provide a substantial advantage over other sites in understanding the geology of a MSR mission to Gusev or Meridiani. Another advantage is that MER provided convincing evidence for phases that have formed under the influence of liquid water, which directly addresses NASA's Mars Exploration goal of "follow the water." There is always the possibility that a new site may not readily provide materials that have formed in the presence of liquid water.

There are however several disadvantages of returning to a MER site with a MSR mission. Orbiters (e.g., Mars Express, MRO) have identified many interesting sites on Mars that may have experienced previous episodes of liquid water. Could more be learned about aqueous processes on Mars by going to one of these sites and returning samples? Another confounding problem about returning to an MER site such as Gusev crater is that it might be difficult to acquire representative samples that were identified by Spirit. Will MSR have a rover and the instrumental capability to find important samples? These are questions that the Mars scientific community will have to evaluate over the coming years.

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Table 1. Unresolved questions at the MER landing sites that could be addressed by a MSR mission.

Gusev crater
What is the mineralogy of npOx in soils and dust?
Did npOx form by aqueous processes?
What is the ferric sulfate mineralogy in some soils?
Are phyllosilicates present in some altered rocks?
What is the mineralogy S, Cl, & Br in soils & rocks?
How did amorphous silica form?
What is/was the habitability potential at Gusev?
Meridiani Planum
What is the mineralogy of Ca and Mg sulfates?
What is the mineralogy of siliciclastic sediments?
How were the sediments emplaced?
Do sediments harbor signs of ancient life?
What is/was the habitability potential at Meridiani?