AQUEOUS CHEMISTRY, PHYSICAL CHEMISTRY, AND SEDIMENTOLOGY OF ROCKS AT THE MARS ROVER LANDING SITES. J.S. Kargel, [1]U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ86001, USA, Email: jkargel@usgs.gov.

Introduction and Summary: The Mars Exploration Rovers, *Opportunity* and *Spirit*, have provided critical ground truth observations pertinent to global data sets and observations that have been interpreted in terms of an aqueous past [1-3]. Most crucial from these new rover missions has been their ability to travel to rock outcroppings and probe the weathered exteriors and fresher interiors of rocks with chemical and mineralogical and a variety of optical imaging systems. Both rovers have returned data indicating layer-by-layer aqueous deposition or aqueous alteration under conditions that were almost certainly highly acidic and hypersaline but not as cold as current conditions [4-9]. The two landing sites are very different, but the rover observations dovetail nicely with synoptic observations made from orbiters. The accumulated sets of observations for both sites indicate periods of hydrogeologic processes involving huge amounts of liquid water. Both rovers have produced data consistent with possible continued aqueous processes, most likely involving minute traces of acidic, saline brines that are liquid and chemically active in the upper centimeters on warm days, but frozen much of the time [5-6]. Terrestrial analog sites provide a rich variety of insights into the cause of the observed chemistry, mineralogy, and physical sedimentology at each rover site. A sea or big lake is implicated for Meridiani Planum [2-3], and a huge debris flow is likely at Gusev Crater. Room remains for alternate or modified interpretations, but water is unavoidable.

Meridiani Planum., *Opportunity's* site at Merdiani Planum indeed appears to have been a hypersaline, acid sea or large lake, as the MER team has well substantiated. Chemical analogs from acid-mine drainage sites, such as Rio Tinto (Spain)[9], and acid-brine evaporative lakes, such as Lake Tyrell (Australia), explain much about the chemistry and mineralogy of these rocks. Physical sedimentologic and evaporite analogs such as the Permian Basin and active saline playas of the southwestern U.S. explain many other features [5]. Banded iron-formations of Western Australia and elsewhere, and the eroded sedimentary rock bluffs, butte, and mesas of Monument Valley (Arizona) offer additional partial analogs to parts of Merdiani Planum.

Multielement covariation diagrams (Fig. 1), using rover data published by [10], basic aqueous chemical phase equilibria and physical chemistry of relevant salts [9] suggest the following sequence of events at Meridiani Planum. (1) An acid sulfate brine permeated a laminated volcanic tuff or, more likely, digested Bounce-like volcanic rocks and then re-precipitated a laminated sequence of impure magnesium-iron-calcium sulfates. (2) A chloride brine (possibly a modified remnant of the first brine) oxidized iron, selectively re-dissolved and removed some sulfates (especially magnesium sulfate), and generated porosity. (3) The brine's dregs precipitated sodium and potassium chlorides in the pores as the sediment dried and cracked. (4) The aqueous epoch was followed by a long, cold, dry period of small impacts and continuing wind activity, probably with continued slow digestion of silicate rocks by super-brine films that are liquid during the warm days.

The total period elapsed in the tightly sequenced events represented by stages 1 to 3, and presumably similar events for the preceding deposition of the underlying rock sequence at Merdiani Planum, may encompass a quarter million Mars years if the lamina seen by *Opportunity* are annual. By contrast, stage 4 probably represents billions of years.

Gusev Crater. The most compelling evidence for major aqueous activity at Gusev Crater comes from the orbiter observations: Imaging shows intense erosional downcutting of Ma'adim Vallis, which sliced across Gusev Crater and deposited material inside it. The source terrain for the debris is the cratered highlands and probably lava flows from Apollinaris shield volcano. *Spirit* has explored a rubble-strewn field not terribly unlike that seen by *Mars Pathfinder* and *Viking Lander 1*—both of which landed on outflow channel deposits most plausibly linked to giant debris flows issued through those catastrophic fluid flow systems. A similar deposit, though morphologically older, probably describes the plains in Gusev Crater and much of the material in the Columbia Hills.

Spirit's observations add critical details. Indeed, most of the rocks are volcanic rock rubble. But more critically, the rover's instruments have identified (1) local layered rocks which may represent local extrusion of muddy debris and cementation by precipitates of saline solutions, and (2) chemical indications of aqueous alteration.

Most intriguing, according to recent press released data, has been the recent analysis of Wishstone, which is a hugely phosphrous-enriched rock. Martian rocks in general tend to be P-rich, but this one has several times the average amount of what must be phosphate minerals. Discounting bird or bat guano-derived and other biochemically precipitated phosphates and phosphorites, terrestrial rocks that contain inordinate amounts of P include carbonatites and kindred super-alkaline igneous rocks, certain types of evaporites, and hydrothermally altered crustal and mantle rocks. Lunar KREEP and lunar granite are alternative possible analogs. Some type of hydrothermally altered rock seems the most probable explanation, especially with Apollinaris Patera not too far away. Since phosphates are not highly soluble except in extremely hot waters, or in extremely acidic water, one or the other of those conditions is implied if we are to discount biogeochemical precipitation; an alternative is that extreme igneous fractionation under CO_2-H_2O-fluid-rich mantle conditions, remains as a possibility. These alternatives will be difficult to sort though without chemical analysis that can measure other large ion lithophile elements, such as rare earths.

The rock debris in Gusev is principally volcanic, so it is not difficult to imagine alteration by immiscible late-stage fluids, such as a phosphoric acid-rich metasomatic fluid of a type commonly responsible for formation of vein-cemented and nodular igneous breccias.

Spirit rover and orbiter observations suggest a sequence of (1) volcanism, including the antecedant to or root of Apollinaris Patera; (2) development of cratered highlands by large and small impacts into volcanic rocks, including formation of Gusev Crater, with continued volcanism, including later stages of Apollinaris Patera's construction and distal flow emplacement; (3) fluid alteration by either hot volcanic brines or hot brines produced by impact activity; (4) destabilization of highlands material by excess pore-water pressure and gravitational collapse, thus producing Ma'adim Vallis and depositing a debris flow made of volcanic derbis and some impact brecciated highlands debris; (5) a long, continuing period of small impacts, slow aqueous alteration by "super-brine" films acting along grain boundaries, eolian abrasion, and eolian redistribution of debris. The first four stages are dominantly Noachian events, though some volcanic activity at Apollinaris may have continued into more recent eons, which are dominated by the events listed in stage 5.

Conclusions: Mars is without doubt not just an ice world, but a water world. Its rocks retain a rich record of hydrogeologic events and evolution of environmental conditions. We are just beginning to read that record. It remains to be seen whether these rocks also contain a record of past life, or even if present day life survives in special niches. The Mars exploration program and planetary protection plans must make the assumption that such life exists.

References:

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Figure 1. Selected element covariation diagrams make part of the case for the sequence of aqueous processes indicated in the text. Data from [10].