ROVING ACROSS MARS: SEARCHING FOR EVIDENCE OF FORMER HABITABLE ENVIRONMENTS

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My love affair with Mars started in the late 1960s when I was appointed a member of the Mariner 9 and Viking Orbiter imaging teams. The global surveys of these two missions revealed a geological wonderland in which many of the geological processes that operate here on Earth operate also on Mars, but on a grander scale. I was subsequently involved in almost every Mars mission, both US and non-US, through the early 2000s, and wrote several books on Mars, most recently *The Surface of Mars* (Carr 2006). I also participated extensively in NASA's long-range strategic planning for Mars exploration, including assessment of the merits of various techniques, such as penetrators, balloons, airplanes, and rovers. I am, therefore, following the results from Curiosity with considerable interest.

FIGURE 1 Mars rovers showing their evolution from 1996 to the present day. In the foreground is the tethered rover, Sojourner, launched in 1996. On the left is a model of the rovers Spirit and Opportunity, launched in 2004. On the right is Curiosity, launched in 2011. IMAGE CREDIT: NASA/JPL-CALTECH

The six papers in this issue outline some of the findings of the Mars rover Curiosity, which has spent the last two years on the Martian surface looking for evidence of past habitable conditions. It is not the first rover to explore Mars, but it is by far the most capable (FIG. 1). Included on the vehicle are a number of cameras, an alpha particle X-ray spectrometer (APXS) for contact elemental composition, a spectrometer (ChemCam/LIBS) for remote elemental composition, an X-ray diffractometer (CheMin) for mineralogy, and a mass spectrometer–gas chromatograph–laser spectrometer (SAM) for volatile and isotopic analysis. Although the rover has only recently reached its prime target (Mt. Sharp), it has already confirmed the former presence of habitable environments. Major questions remain, however, such as: How sustained were the habitable conditions? How widespread? When did they occur? Were they the result of just transient and local events or the result of global climate changes? And above all, did life ever exist on the planet?

Speculation that some form of life evolved on Mars has a long history dating back to the earliest telescopic observations. With the advent of the space age these speculations could be placed on a firmer footing. In the mid-1960s two Mars missions were approved. The Viking mission (1975 launch) placed two landers on the surface to analyze for organics and try to detect metabolism. Mariner 9 (1971 launch) prepared the way by searching for evidence of water or seasonal changes that might be life-related and by providing topographic and other data to support the Viking landings. While Mariner 9 found abundant evidence for past water activity, thereby raising hopes that there might be life, those hopes were dashed when the Viking landers found no organics in local soils and no evidence for metabolism (Klein 1979). Partly as a consequence of the negative Viking results, there followed an almost 20-year hiatus in Mars exploration.

A number of developments occurred that helped rekindle Mars exploration in the 1990s (NASA 1995). Life on Earth had been found surviving in much more extreme conditions than were thought possible in the 1970s. Evidence mounted that the search for life should focus less on detecting extant life and more on looking for evidence of life on early Mars where indications of water activity were most abundant. Miniaturization of instruments enabled more sophisticated payloads on modest-sized landed vehicles. Advances in guidance enabled landing at more interesting and promising places, and advances in robotics led to vehicles with more independent capabilities.

The geological exploration of Mars has proceeded in a very different way from that of the Earth. On Earth, numerous local ground observations were gradually integrated, sometimes over many years, into regional and global patterns. In contrast, on Mars, global patterns were identified first, and the details were subsequently filled in from higher-resolution remote sensing and then by ground observations. Since the year 2000, a number of missions have successfully landed on or orbited Mars, and, although large uncertainties remain, these missions have revealed the broad outlines of the geological history of Mars. The history can be divided into three eras (Scott and Carr 1978; Hartmann and Neukum 2001; Bibring et al. 2006): (1) the Noachian Era of heavy bombardment, which extended from the time of formation of the planet to roughly 3.7 billion years ago and was characterized, at least toward its end, by high impact rates, widespread fluvial erosion, and the presence of phyllosilicates; (2) the Hesperian Era, which extended from 3.7 to 3.0 billion years ago and was characterized by large floods and the formation of thick sulfate deposits; and (3) the Amazonian Era, which extended from 3.0 billion years ago to the present and is characterized by an oxidizing surface, with only rare indications of water activity.

The revitalized US Mars program of the late 1990s was initially guided by the invocation to "follow the water," water being universally agreed as necessary for life. The orbiter and lander instruments were selected to help better understand the history of water; the landers were sent to places where the orbital data indicated past or present water activity. These developments led to the landing of the first rover on Mars in 1997, a tethered shoebox-sized rover called Sojourner that carried cameras and an APXS for elemental analysis. This was followed in 2004 by the rovers Spirit and Opportunity: Spirit to a large Noachian crater, Gusev, in which water was thought to have pooled; and Opportunity to Meridiani Planum, where remote sensing had revealed mineralogical indications of water activity. Both rovers found abundant evidence of water. Although there was little evidence for pooling of water on the plains within Gusev, its central peak revealed compelling evidence of aqueous alteration and hydrothermal activity (Squyres et al. 2006). In addition, the sediments on which Opportunity landed in Meridiani Planum appear to have been deposited in an area of dunes with intermittent, acidic, interdune lakes (Grotzinger et al. 2005). The success

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of the various landers and orbiters in the early 2000s in finding abundant evidence for water led to a redirection of the exploration goal to not just follow the water but to determine where and when habitable conditions occurred.

These earlier rovers, while highly successful explorers, had limited analytical capabilities. In contrast, Curiosity has a broad complement of analytical instruments capable of measuring elemental composition, mineralogy, isotopes, volatiles, and organics. It was well equipped to search for evidence of former habitable conditions. The 155 km diameter Gale Crater was chosen as the landing site because remote sensing indicated that its central mound, Mt. Sharp, was comprised of a stratigraphic column that extends from late Noachian phyllosilicate- and hematite-bearing sediments upwards into sulfate-rich Hesperian deposits. Thus, a range of environments could be sampled, with the base of the column being of most interest because of the clear evidence of the presence of aqueous alteration products that dated back to the time for which we have the best evidence of conditions different from the present. The spacecraft landed on the level crater floor, as close to the central mound as the landing error ellipse (20 km × 7 km) allowed, and has since been making its way towards the central mound, pausing occasionally to make measurements on the materials of the crater floor. The results presented in this issue were acquired mainly during this traverse since, at the time of this writing, Curiosity had only recently arrived at the base of the central mound.

The plains on which Curiosity landed are comprised mostly of fine-grained sedimentary rocks with isolated outcrops of cemented pebbly conglomerates. To the north of the landing site is an alluvial fan fed by a channel that cuts through the northern rim of the crater. The conglomerates were probably deposited in channels cut into distal parts of this and other fans. The main rocks over which Curiosity travelled toward the central mound are, however, thinly bedded sandstones and mudstones. Drilling into the mudstones exposed materials in a reduced state, in contrast to the universally oxidized surface. This is an important finding in the search for life, for it may imply long-term preservation of organics within the rock materials. The mudstones are comprised of a nonequilibrium assemblage of primary basaltic phases, secondary phases such as clays, sulfates, and iron oxides, and an amorphous component. Chemical trends suggest that the secondary minerals are the result of isochemical alteration of the primary basaltic debris at their depositional site by groundwater or lake water rather than the result of weathering elsewhere and transport of chemically fractionated components to the landing site. The diagenesis appears to have taken place in a habitable environment with moderate pH and low salinity that persisted for thousands to millions of years. The finding of diagenetic minerals, particularly the phyllosilicates, in the floor sediments was a surprise. Their presence had been masked by dust at the surface. But it led to early confirmation of habitable conditions well before the main target, the clay-rich deposits at the base of Mt. Sharp, was reached. The neutral pH contrasts with the acid pH under which the sulfate-rich deposits at the Opportunity site in Meridiani accumulated and implies significantly more habitable conditions.

A major issue—hotly debated over the last few decades—is how warm and wet early Mars was at the end of the Noachian when most of the valley networks formed. One view is that the valleys were eroded by streams that resulted from rainfall fed by evaporation from transient oceans (e.g. Baker 2001; Craddock and Howard 2002). Warm, wet, Earth-like conditions are implied, enabling both evaporation and rainfall. An opposing view is that the valleys were formed by flowing water resulting from the melting of surface ice by impacts or volcanic events or under cold climatic conditions that enabled melting only a few days a year (Wordsworth et al. 2013). The Curiosity findings so far do not require the persistent, warm, wet surface conditions that are needed for surface weathering and the development of soils and so may favor the colder models, but it will be interesting to see what the Mt. Sharp deposits reveal.

Understanding the evolution of the atmosphere is crucial for assessing past habitable conditions and the conditions under which the valleys formed. The isotopic ratios of volatiles in the atmosphere evolve as lighter isotopes are preferentially lost to space and inventories are partly replenished by outgassing and the solar wind. SAM has the capability of measuring isotopic ratios both in the atmosphere and in rock samples. The deuterium/hydrogen ratio is of particular importance. The fact that the present atmosphere is highly enriched in deuterium (heavy hydrogen) has been used to constrain the total amount of water on the planet to very small values on the assumption that the enrichment is due to losses over the last few billion years. Early results from SAM showed, however, that the water fixed in the >3-billion-year-old sediments was already considerably enriched, so this loosens significantly the constraint on the exchangeable water reservoir. Analyses of isotopes of other gases will provide further insights. SAM also detected the components necessary for life (C, H, N, S, P, etc.) and chlorinated hydrocarbons in samples of the sediments. The implications of the hydrocarbons are still being debated.

In summary, Curiosity has travelled approximately 7 km from its landing site to its prime target at the base of Mt. Sharp. The rocks traversed were mostly fluvial and lacustrine mudstones and sandstones that subsequently underwent aqueous alteration under neutral pH conditions. Elemental and isotopic analyses of gases evolved from the sediments indicate the presence of components necessary for life and will provide new insights into how surface conditions have evolved over time. The seemingly reduced conditions preserved at shallow depths within the rocks sampled enhance the possibility that organics are preserved and accessible in near-surface rocks. All these results are encouraging in the search for life and will provide important guidance for the next step in the exploration of Mars, which we hope is sample return.

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