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Mineralogy and evolution of the surface of Mars: A review

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Abstract

We review the mineralogy of the surface of Mars, using data from various sources, including in situ characterisations performed by landers, remote observations from orbit, and studies of the SNC meteorites. We also discuss the possible alteration processes and the factor controlling them, and try to relate the mineralogical observations to the chemical evolution of the surface materials on Mars in order to identify the dominant process(es). Then we try to describe a possible chemical and mineralogical evolution of the surface materials, resulting from weathering driven by the abundance and activity of water. Even if weathering is the dominant process responsible for the surface evolution, all observations suggest that it is strongly affected locally in time and space by various other processes including hydrothermalism, volcanism, evaporites, meteoritic impacts and aeolian erosion. Nevertheless, the observed phases on the surface of Mars globally depend on the evolution of the weathering conditions. This hypothesis, if confirmed, could give a new view of the evolution of the martian surface, roughly in three steps. The first would correspond to clay-type weathering process in the Noachian, under a probable thick H_2O/CO_2-rich atmosphere. Then, during the Hesperian when water became scarcer and its activity sporadic, linked to volcanic activity, sulfate-type acidic weathering process would have been predominant. The third period would be like today, a very slow weathering by strongly oxidising agents (H_2O_2, O_2) in cold and dry conditions, through solid-gas or solid-films of water resulting frost-thaw and/or acid fog. This would favour poorly crystalline phases, mainly iron (oxy) hydroxides. But in this scenario many questions remain about the transition between these processes, and about the factors affecting the evolution of the weathering process.

Keywords: Mars; Surface; Mineralogy; Weathering; Alteration; Iron (oxy)hydroxides; Clays; Sulfates; Carbonates; Silicates

1. Introduction

Our objective is to provide an overview as complete as possible of our current knowledge of the martian regolith mineralogy, and its evolution with time. Classically, the regolith of a planet is defined as the uppermost surface layer, composed of unconsolidated erratic rocky blocks of various sizes and the associated dust particles, which result from meteoritic bombardment. This definition lacks in the explaination of the red colour of Mars, an obvious indicator of surface alteration. In the case of a complex planetary surface like that of Mars, the regolith is not only the uppermost dust layer covering the surface—including rock varnish—but also the underlying horizons, from partially altered but still coherent rocks, the so-called "saprolitic" horizons, down to the fresh parent rock. Therefore, the characterisation of the martian regolith involves not only the primary materials but also the minerals produced by the various processes occurring on the surface. Several approaches have been used, each giving complementary information. First there are direct measurements by spacecraft that have orbited (Mariner 9, the Viking Orbiters, Phobos 2, Mars Global Surveyor, Mars Odyssey, Mars Express) and landed on Mars (Viking Landers 1 and 2, Mars Pathfinder and Mars Exploration Rovers MER, Spirit and Opportunity, Fig. 1). Second, there are many petrologic, mineralogical, chemical and isotopic studies of the martian SNC meteorites. Third, there are laboratory measurements on analogue materials that have proven especially valuable in identifying models

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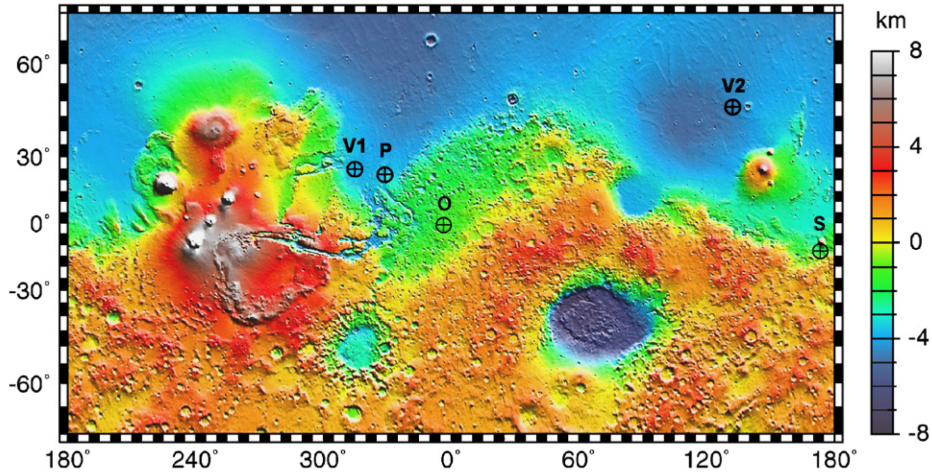

Fig. 1. Topographic image in false colours of the martian surface, generated with MOLA (Mars Orbiter Laser Altimeter) onboard Mars Global Surveyor. Symbols correspond to the various martian landers: V1: Viking 1, V2: Viking 2, P: Mars Pathfinder, O: MER Opportunity, S: MER Spirit. Credit: NASA/GSFC—http://ltpwww.gsfc.nasa.gov/tharsis/global_paper.html, Smith et al., 1999.

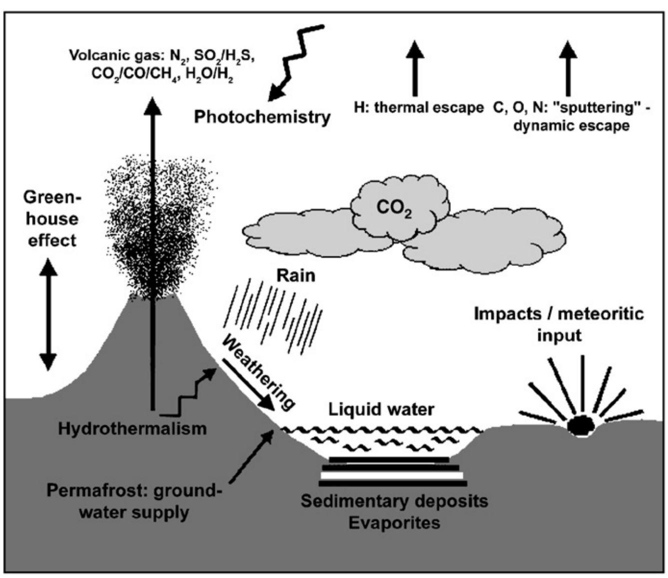

Fig. 2. Geodynamical environment on Early Mars (redrawn from Catling, 1999).

and interpreting direct observations from spacecraft. Somewhat related are studies of terrestrial analogues that can represent certain processes likely to occur on Mars. In parallel with laboratory measurements are theoretical studies of the thermodynamics of equilibrium assemblages on the martian surface. By the combination of these approaches it is possible to make reasonable assumptions on the complex mineralogy of the martian surface, and how the parageneses formed and evolved with time.

Therefore, in a second part of this paper we discuss the various processes susceptible to have altered the surface of Mars, depending on the prevailing geodynamical environment (Fig. 2). Generally, all hypotheses can be roughly classified in three main alteration processes: aqueous alteration and evaporitic process, hydrothermalism and weathering. Basically, the aqueous alteration is mainly linked to Opportunity discovery of sedimentary outcrops in Meridiani Planum, and sulfate deposits by Mars Express OMEGA. It supposes formation of salts by acidic alteration with subsequent deposition due to evaporation of a body of standing water. Hydrothermalism comes from SNC studies, chemistry of the regolith and its link to the volcanic activity which seems to be an important driving force for the evolution of the surface. Both of these processes remain generally localised in time and space. Finally we test the weathering hypothesis, which is defined by the interaction between primary bedrock, the surrounding atmosphere, the hydrosphere and the *biosphere*, leading to the formation of a regolith. In this case, weathering is able to act during the whole history of the planet as well as on its whole surface, depending on the evolution of the atmosphere/hydrosphere.

2. Mineralogy of the martian surface

2.1. Primary silicates

The silicates are the most abundant minerals on the surface of the telluric planets. On Mars, the primary silicate paragenesis is of basaltic to andesitic basaltic composition, as indicated by orbital observations by Mars Global Surveyor MGS and Mars Odyssey (Hamilton et al., 2003; Wyatt and McSween, 2002; Wyatt and McSween, 2003), in situ characterisations performed by the Viking Landers and Mars Pathfinder (Larsen et al., 2000; McSween et al., 1999) as well as studies on the SNC meteorites (McSween, 2002). The main silicates observed on the surface are olivine pyroxene and plagioclase, although recent evidence for silica-rich quartzo-feldspathic minerals (Bandfield et al., 2004) seems to indicate that magmatic differentiation may have proceed further than previously thought. Olivine, pyroxene and plagioclase have been identified and mapped