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# Meteoric water alteration of soil and landscapes at Meridiani Planum, Mars

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ABSTRACT

The geomorphology and geochemistry data gathered by the MER Opportunity at Meridiani Planum is a rich data set relevant to soil research on Mars. Many of the data, particularly with respect to outcrops at Victoria Crater, have been only partially analyzed. Here, the previously published geochemical profile of Endurance Crater is compared to that of Victoria Crater, to understand aspects of the post-depositional aqueous and chemical alteration of the Meridiani land surface. The landsurface bears cracking patterns similar to those produced by multiple episodes of wetting and drying in expansive materials on Earth. The geochemical profiles at both craters are nearly identical, suggesting (using mass balance methods) that a very chemically homogenous sedimentary deposit has been engulfed by the apparent surficial addition of S, Cl, and Br (and associated cations) since exposure to the atmosphere. The chemistry and mineralogy at both locations is one where the most insoluble of the added components resides near the land surface (Ca sulfates), and the more soluble components are concentrated at greater depths in a vertical pattern consistent with their solubility in water. The profiles, when compared to those on Earth (and to physical constraints), are most similar those generated by the downward movement of meteoric water. When this aqueous alteration and soil formation occurred is not well constrained, but the processes occurred between late Noachian (?) to late Amazonian times. The exposure of the Victoria crater walls, which occurred likely less than $10^7$ y ago (late Amazonian), shows the accumulation of dust as well as evidence for aqueous concentration of NaBr and/or CaBr, possibly by deliquescence. By direct comparison to Earth, the regional soil at Meridiani Planum is a Typic Petrogypsid (a sulfate cemented arid soil), bearing similarities to very ancient soils formed in the Atacama Desert of Chile. The amount of water required to produce the soils ranges from a very low (and physically unlikely) quantity of 2–4 m, to possibly (and more likely) kilometers of water that were added in small individual increments over long spans of geological time.



## 1. Introduction

Our understanding of the surficial aqueous history of Mars is evolving, but has been marked by divergent views and interpretations of data. Recent revelations about Mars' aqueous history have been made by direct observations and physical analyses provided by rovers. There is clear evidence that Mars had streams (Williams et al., 2013), which formed alluvial fans (Palucis et al., 2014) and lacustrine deposits (Grotzinger et al., 2015) that contain phyllosilicate clay (Bristow et al., 2015). In the past decade, it has become clear that Mars has large exposures of secondary phyllosilicates (Bibring et al., 2006) that must have formed from significant aqueous weathering of rocks or sediments under near-neutral pH's. There is growing evidence of occasionally abundant surficial water, and of near neutral pH's, beyond Noachian times (Grotzinger et al., 2014). Alternatively, others emphasize a dry Mars since its early Noachian wet phase, with largely groundwater driven alteration of sediments by acids and/or redox chemistry in post-Noachian times (Hurowitz et al., 2010).

There is a rich geological and geochemical record at Meridiani Planum. Since January, 2004, the Mars Exploration Rover (MER) Opportunity has traversed >42 km, providing a wealth of observational data across diverse landforms. In the first 2000 sols, which is the focus on here, the rover geochemically examined two crater exposures and obtained nearly 200 APXS analyses of rocks, surface crusts, and dune sediment. This ground-based geology, combined with remotely sensed data, provides a geomorphic data set that rivals what is commonly obtained in many Earth-based geomorphic investigations.

This landing site is also a location where different interpretations of the history of aqueous alteration and sources of water

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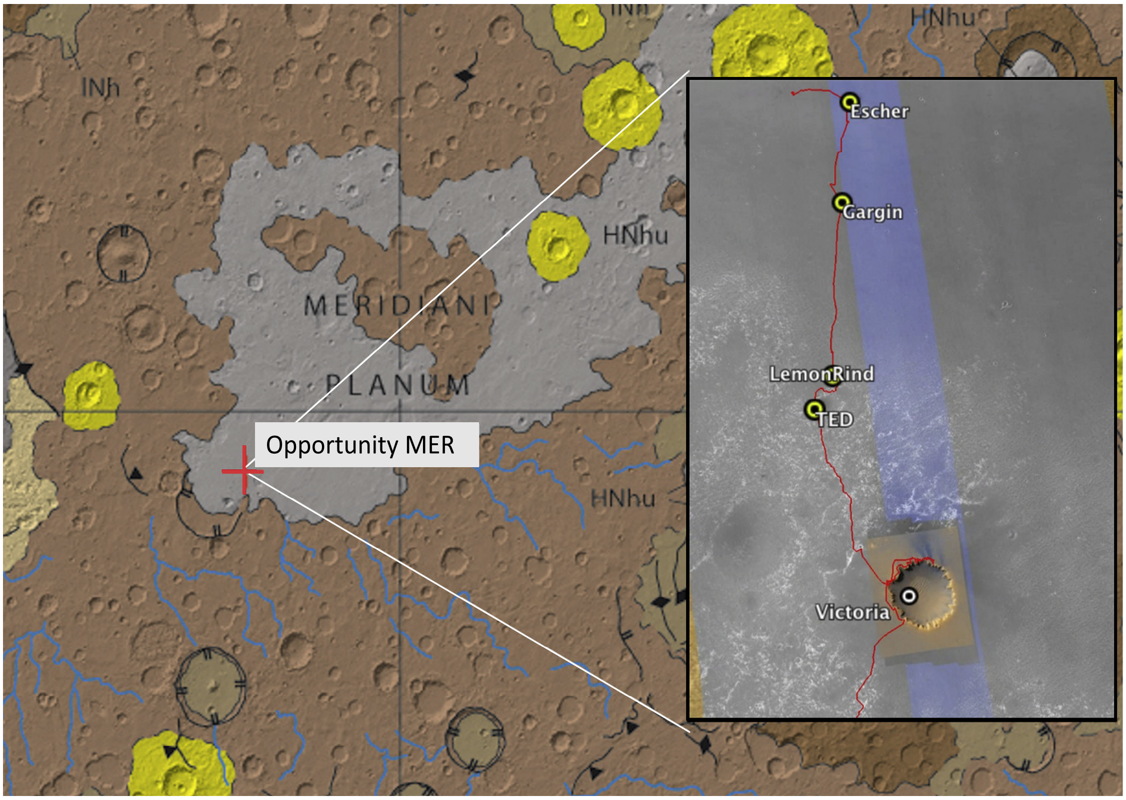


**Fig. 1.** Geological map of the region near the Opportunity landing site. Gray = HNhu (Hesperian and Noachian highlands), brown = mNh (middle Noachian highlands), and yellow = impact materials. Geological map and data from Tanaka et al. (2013). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

have emerged. Meridiani Planum is part of what are referred to as Equatorial Layered Deposits (ELD) (Pondrelli et al., 2015) that cover large areas at these latitudes. A growing set of observations (Pondrelli et al., 2015; Grotzinger et al., 2005) and modeling (Andrews-Hanna et al., 2010) suggest that the ELD are a combination of subaqueous playa and dune deposits mantled over heavily cratered Noachian landscapes. These deposits have likely been formed in, and subsequently been modified, by groundwater and surface water (Flahaut et al., 2015).

However, like any planetary surface, these deposits have been sculpted and modified by wind and (possibly) water in the billions of years since their initial deposition (Amundson et al., 2008). The effects of these collective processes leave their mark on the land surface. On Earth, the result of these processes is called *soil*, a regionally extensive in-situ diagenetic feature analogous to a geologic formation (USDA, 2014). The MER Opportunity has assembled a remarkable compilation of data that allows us to examine the features and arrive at a post-depositional alteration history at Meridiani Planum that provides new information about the post-Noachian climate of Mars.

This paper examines in detail the soil profiles revealed in the Endurance and Victoria craters, focusing on their geochemistry and morphology. The results suggests that there appears to be a regional soil weathered into the sedimentary rock in this portion of Meridiani Planum, one that parallels the surface of the gently undulating landscape, and that exhibits: (1) distinctive and replicated depth profiles caused by post-depositional redistribution of sulfate, chloride, and bromide salts, (2) visible diagenetic alteration of the upper $>1$ m of soil, (3) polygonal cracking patterns whose shapes are suggestive of multiple wetting and drying cycles at the surface, (4) late stage dust plus aqueous alteration of exposed soil at the landsurface, and (5) evidence of both dust and some minor aqueous alteration of exposed crater walls over the past $\sim 10^7$ y. The exact timing of when these features formed is uncertain, but they point toward a richer and more complex post-Noachian aqueous history than is sometimes assumed, but one that is in tune with observations and geochronological constraints now emerging at Gale Crater.

## 2. Geology of Meridiani Planum

Meridiani Planum is part of an ELD that covers a significant portion of the northern latitudes between the Equatorial highlands and the lower elevations to the north (Fig. 1). The layering is interpreted by some to show periodicity (Andrews-Hanna et al., 2010), and consists of units of spring deposits, dunes, and playa-like deposits that accumulated from Noachian into Amazonian times (Pondrelli et al., 2015). These landscapes have subsequently undergone modification by erosion, and are part of the so-called “etched terrains” of Mars (Hynek, 2004).

The landing region of the MER Opportunity is a unique exposure of sedimentary rock that dates from the Later Noachian to Early Hesperian era (Hayes et al., 2011) (Fig. 1). The sedimentary unit underlying the plain has been informally called the Burns formation (Grotzinger et al., 2005), which abuts and is suggested to unconformably overlaps stream incised landforms to the south. Due to the distance that the Opportunity Rover has traveled in the past 13 years, it has been able to obtain observations of strata at different elevations and portions of the stratigraphic section (Hayes et al., 2011).

The lowest segment, stratigraphically, of the Burns formation examined in great detail is that exposed at Endurance crater (Fig. 2). Here an $>8$ m impact crater exposure of the landscape reveals three stratigraphic intervals, with dune deposition consisting of a mix of basaltic and evaporitic sands in the lower units, and evidence of subaqueous deposition of mineralogically simi-