

NEOFORMATION, DIAGENESIS AND THE CLAY CYCLE ON EARLY MARS N. J. Tosca^{1,2} and J.A. Hurowitz³, ¹Dept. of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, United Kingdom; ²Planetary Science Institute, Tucson, AZ 85719, USA; ³JPL/Caltech, Pasadena, CA 91109, USA. (njt41@cam.ac.uk)

Introduction: Clay minerals are powerful recorders of atmosphere-hydrosphere-lithosphere interactions; on Earth, they participate in all aspects of the rock cycle [1]. From their occurrence in igneous and metamorphic rocks, soils and sediments, few minerals capture the range of physical and chemical conditions that clays do. But it is this ubiquity that obscures the identification of clay mineral source environments; and further complicating the picture is the susceptibility of clays to diagenetic change. Indeed, >90% of clay in ancient sedimentary rocks on Earth has been mixed and altered by complex post-depositional processes [2]. To circumvent this problem, isotopes, major/trace element geochemistry, crystallography and mineralogy are together used to infer provenance, in turn placing paleo-environmental constraints. MSL will follow a similar approach, and so broader geologic context for clay formation on Mars will provide a framework with which to pose and test hypotheses of formation.

First order comparisons to Earth: The lack of widespread tectonic recycling on early Mars would have led to fundamentally different basin-forming mechanisms than the Earth [3]. The lack of tectonically-driven basin formation would have narrowed the temperature/pressure window experienced by basin fill strata, in turn restricting the amount of clay formed by high temperature burial diagenesis and metamorphism.

In addition, a relative lack of igneous lithological diversity on Mars compared to the Earth will tend to be reflected in clay mineralogy. Clay minerals and their corresponding chemistry are controlled largely by the chemistry of the host rock [4] and so on a largely basaltic planet, clay minerals rich in K (and Na) such as glauconite and illites should be expected to be much less common than Mg and Fe-rich counterparts.

Also, climatic differences and the source of sediment with which to alter and form secondary clays are likely to account for remaining differences between ancient clay assemblages on Earth and Mars.

Clay formation at the early martian surface: The hallmarks of the Noachian and early Hesperian are impacts and volcanism. It is also clear that the Noachian surface possessed a hydrologic cycle at least until significant global-scale water and atmosphere loss [5]. The combination of these three factors, however, lead to a finite number of major clay-forming processes likely to be important at the martian surface.

Hydrothermalism. Impact-hosted (and to a lesser degree volcanically-hosted) hydrothermal systems were undoubtedly important in forming clays on early Mars

[6,7]. But distinguishing these systems from lower temperature systems may be difficult from orbital data without the identification of obvious high temperature phases. Furthermore, as hydrothermal systems develop and progressively cool, the effects of lower temperature overprinting on initially formed high temperature assemblages have the potential to obscure the effects of impact-hosted hydrothermalism on early martian surface mineralogy [8]. The hydrothermal component, then, may be much more substantial than is apparent from orbital data alone.

Subsurface/groundwater weathering. One of the consequences of an active groundwater system in the Noachian is the development of two separate and distinct aqueous geochemical systems [9]: (1) systems developed in isolation from the atmosphere at depth, buffered by water-rock interactions and, (2) systems developed at the martian surface when groundwater breaches the surface and is influenced by atmospheric processes. Indeed, Meridiani Planum chemical sediments appear to preserve direct evidence of the latter and imply the existence of the former [9]. SNC alteration assemblages may provide direct evidence of subsurface influenced systems. The clay mineralogy in isolated subsurface environments is likely to be controlled by the chemistry of the host rock and smectite-rich phases. However, this component, if present, may only form a minor contribution to the overall clay budget because weathering is likely to be transport-controlled and in near equilibrium with the substrate if geologically significant time-scales of aquifer regeneration are involved [5].

Surface alteration and sources of primary sediment. Chemical weathering of basaltic substrate at the surface of Mars is likely to provide a source of newly generated clay minerals to sedimentary systems at the surface of Mars. But a potentially underestimated source of primary material which is likely to provide a major portion, if not the bulk, of newly generated clay on the early martian surface is the alteration of volcaniclastic and impact-generated ash.

Particularly relevant on a volcanically active early Mars is that martian eruption conditions favor enhanced magma disruption and pyroclasts systematically finer grained than Earth deposits by a factor of 100 [10]. In addition, the authors state that almost every martian volcanic eruption would be accompanied by a vast amount of fine-grained pyroclastic material deposited up to several hundreds of kilometers.

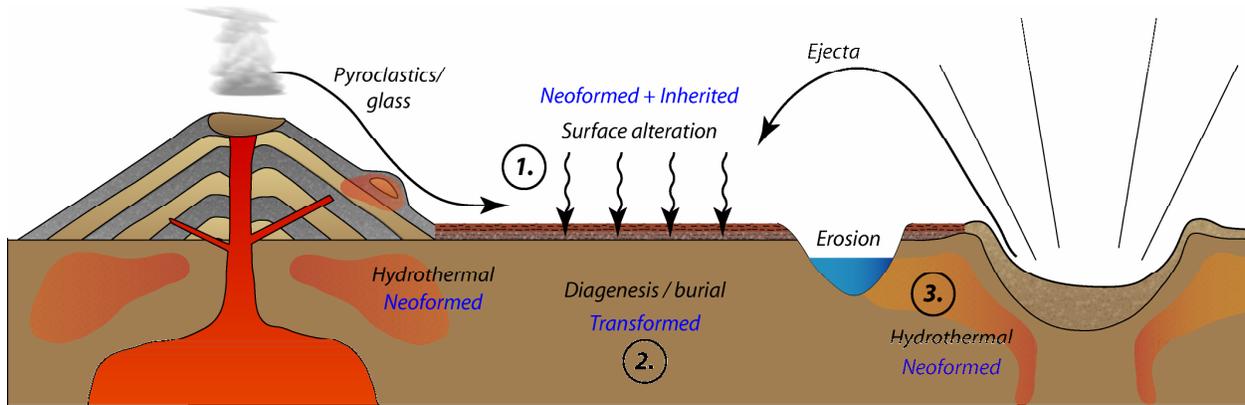


Figure 1. A simplified clay cycle on early Mars, indicating: (1) a surficial/sedimentary component, (2) diagenetic/burial component, and (3) a hydrothermal component.

On Earth, the alteration of a significant portion of volcanoclastic debris to clay is referred to as a bentonite deposit. During bentonite formation, pyroclastic material is rapidly altered almost entirely to smectite on geologically rapid timescales either by deposition in, or in the presence of, water [11]. A number of workers postulate that alteration of ash to smectite may even occur before the ash is even deposited [e.g., 12]. Wilson & Head [13] suggest that more water may be exsolved during martian eruptions than on Earth; this would act as the catalyst driving alteration. It is also well known that volcanic ash can be deposited at elevated temperatures and, in the presence of H₂O vapor, sustain a self-driven hydrothermal system capable of rapid and pervasive alteration to smectite [14].

Interestingly, examination of bentonites generated from basaltic pyroclastic precursors shows that the dominant material is Fe-bearing smectite (i.e., Fe-rich montmorillonite or Fe-rich beidellite) with lesser amounts of mica, kaolin phases, unaltered glass, and free silica liberated by the alteration stoichiometry [15]. Although less is known about the corresponding reactions with impact-generated ash, it is likely that fine-grained impact ejecta contributes to the newly formed clay budget in much the same fashion. Such a process, combined with sedimentary reworking may also contribute to layered clay bearing strata in a number of locations on Mars such as Mawrth Vallis [16].

Clay mineral diagenesis: Early diagenesis of clay minerals on Earth occurs when clays are out of equilibrium with new sedimentary environments, and the majority of these reactions are manifested as subtle mineralogical and geochemical changes induced while detrital clays are in diffusional contact with seawater before deep burial [2]. On Mars, early diagenesis is most likely to occur in response to fluctuating groundwater conditions in layered sediments at the subsurface or upon deposition into a standing water body. Given sufficient reaction time, major controls on clay mineral

diagenesis on Mars are likely to stem from redox control on Fe mobility, a_{SiO_2} levels and pH.

To first order, burial diagenesis and metamorphism are driven by water availability and the temperature experienced by basin fill strata. On Mars, deeply buried strata are likely to have reached the temperature conditions required to drive chloritization and perhaps illitization in the presence of locally high K levels [17]. However, over long time-scales the lack of sufficient liquid water for sustained geologic intervals may be the factor primarily responsible for inhibition of clay mineral burial diagenesis [17].

Conclusions: To summarize, the most important features of the clay cycle include: (1) lack of tectonic recycling and tectonically-driven basin development, (2) less lithologic diversity of igneous rocks, (3) a significant impact-hosted hydrothermal source for newly formed clays, (4) a significant volcanically (and impact) generated pyroclastic source for newly formed clays, (5) muted burial diagenesis due to limited long-term persistence of liquid water.

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