PRIMORDIAL CLAYS ON MARS FORMED BENEATH A STEAM OR SUPERCRITICAL ATMOSPHERE. K. M. Cannon[1], S. W. Parman[1], and J. F. Mustard[1], [1]Brown University, Department of Earth, Environmental and Planetary Sciences, Providence RI, 02912. Email: kevin_cannon@brown.edu

Introduction: Mars' basaltic crust has reacted with water in the past to form hydrated clay minerals (phyllosilicates) that occur in hundreds of exposures, often excavated from many kilometers beneath the surface [1-4]. The majority of these minerals are located in Noachian terrains and are classified as 'crustal clays' [5] having no clear genetic link to surface weathering, or impact-driven hydrothermal systems. Previous studies have focused on clay-forming processes between ~4.1-3.7 Ga [5-6], because the geologic units that contain these minerals are dated to this time. Here, we explore an alternative scenario in which a significant proportion of these clays are primordial and were inherited from much earlier, when Mars' primary crust reacted with a dense H_2O-CO_2 steam or supercritical atmosphere (SSA) outgassed during the later stages of magma ocean cooling [7-9].

Alteration Experiments: We conducted aqueous alteration experiments by reacting synthetic crystalline basalts of bulk martian crustal composition in H_2O and H_2O-CO_2 mixtures at conditions near the H_2O critical point. These conditions are predicted to have been present near the surface and deeper in the crust beneath an SSA during magma ocean cooling (Fig. 1) [7]. Experiments were conducted in the liquid, vapor and supercritical fields of the H_2O phase diagram to explore the effects of the physical state of the fluids in the experiments. Our previously reported results [10] show that Fe/Mg-clays form in just two weeks in the supercritical, liquid and vapor fields near the critical point; no clays formed in a reference experiment at 5 km depth-equivalent on a 20 K/km geotherm over the same time period, demonstrating that alteration is highly efficient under the unique PT conditions beneath an SSA (Fig. 1).

Crustal Evolution Model: The primary martian crust should have quickly developed porosity from both thermally contracting during cooling, and from early impact bombardment [11]. This would allow alteration to penetrate to depth beneath the SSA, perhaps to a maximum of 10 km that is the estimated pore closure depth for the Noachian megaregolith [12]. At the PT conditions in question, the $O(10^7)$ year survival time of the SSA [13] is likely more than enough to completely alter material in the upper porous crust, forming a thick layer of clay-rich material. However, the fate of this layer is uncertain in the face of secondary crust emplacement and intense early impact bombardment.

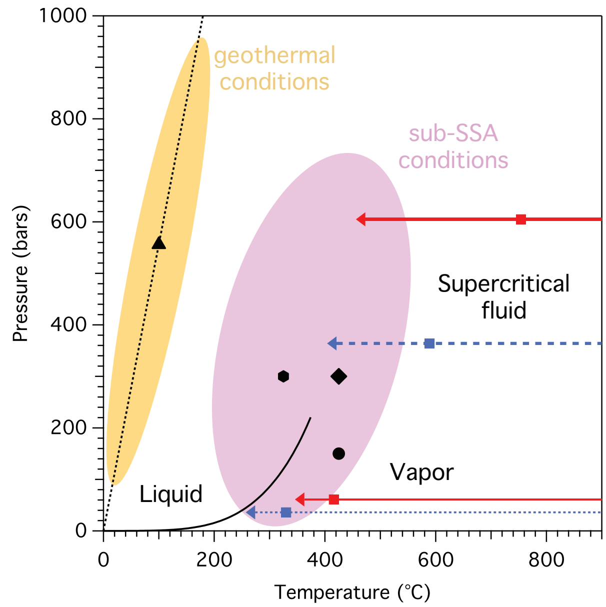

Figure 1. PT phase diagram for H_2O. Solid line is vapor-liquid phase curve, dotted line is 20 K/km geotherm. Red and blue lines are surface cooling pathways reproduced from [7] for different magma ocean parameters. Black symbols are experimental conditions.

We constructed a parameterized 3D crustal evolution model to track an altered layer subjected to these processes. The model runs from 4.538 to 3.538 Ga with a timestep of 10^5 years on a section of crust representing 10% of Mars' surface area, with a cell resolution of ~7 km (xy) by 0.5 km (z). Each cell has a continuous value from 0 (completely consisting of unaltered material) to 1 (altered material). We apply a Monte Carlo impactor population with a size-frequency distribution derived from [14] and rates from [15], and an exponentially decaying secondary crustal production rate derived from [16]. We vary the initial clay layer thickness, the survival time of the SSA, and the total volume of locally erupted secondary crustal material to evaluate different scenarios.

Model Results: Figure 2 shows three stages of a model run for an initial clay layer 10 km thick, 10 km of extruded secondary crustal material, and an SSA lasting for 30 Ma (full model animation at http://planetary.brown.edu/grad_pages/Cannon/LPSC). While the SSA is present, the clay-rich layer thickens due to unaltered material being excavated from depth and subsequently altered at the surface.

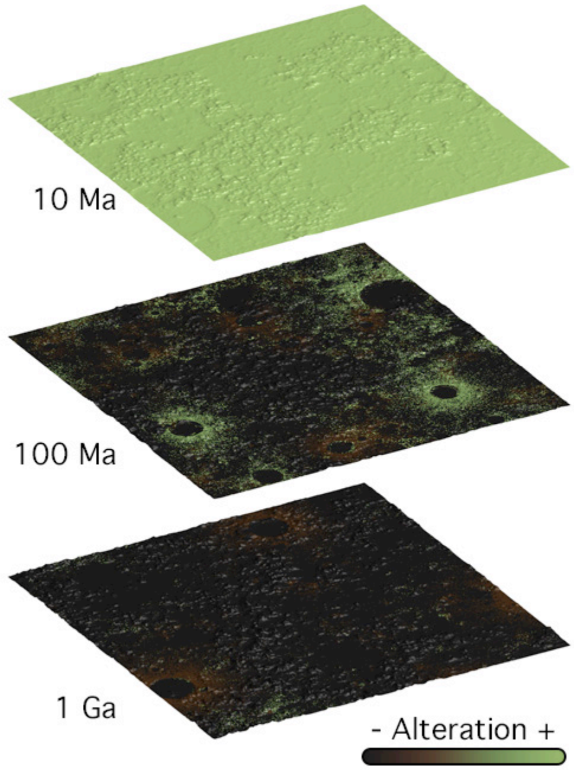

Figure 2. Perspective view of martian surface during a model run with an initial 10 km thick clay layer, an SSA lasting 30 Ma and 10 km of secondary crust added locally. See full animation at: http://planetary.brown.edu/grad_pages/Cannon/LPSC

When the atmosphere is lost, unaltered material builds up via impact melt and volcanism, and is mechanically mixed with the clay-rich layer, diluting and burying it. At the end of the model run, the clay layer is mostly intact at depth but is buried beneath unaltered material.

Figure 3 shows a plan view of the alteration extent at the surface for the same model parameters but three different SSA survival times. White pixels indicate 20% alteration or greater, a proxy for being detectable via orbital remote sensing. Altered material occurs in splotchy patterns, mostly associated with the walls and ejecta of impact craters, but also in diffuse exposures in intracrater plains. These results are highly consistent with actual surface clay exposures, for example from CRISM multispectral map tiles of the BD2300 spectral parameter.

Implications: The primordial clay scenario has a number of important implications for Mars: (1) Most clay formation may not be coupled to surface climate, and clays would therefore not be a climate constraint. (2) A buried clay-rich layer explains the anomalously low density of the southern highlands crust. This was entertained by [17] but dismissed because clays were not expected to be found >1 km deep, but they have since been found up to 10 km deep or greater [4]. (3) A low(ish) density, mechanically weak clay layer may have impeded the eruption of magma through it, but also could have formed clay diapirs if buried by thick layers of denser basaltic overburden.

The primordial clay scenario is difficult to test directly, but returned samples of deep crustal clays from Mawrth Vallis, Valles Marineris or Nili Fossae would help constrain the timing and PT conditions of deep crustal clay formation on Mars.

References: [1] Bibring J.-P. et al. (2005) *Science*, *307*, 1576. [2] Mustard J. F. et al. (2008) *Nature*, *454*, 305. [3] Carter J. et al. (2013) *JGR*, *118*, 831. [4] Sun V. Z. and Milliken R. E. (2015) *JGR*, *120*, 2293. [5] Ehlmann B. L. et al. (2011) *Nature*, *479*, 53. [6] Carter J. et al. (2015) *Icarus*, *248*, 373. [7] Elkins-Tanton L. (2008) *EPSL*, *271*, 181. [8] Abe Y. (1993) *Lithos*, *30*, 223. [9] Zahnle K. J. et al. (1988) *Icarus*, *74*, 62. [10] Cannon K. M. et al. (2016), *AGU*, Paper #P21C-2121. [11] Soderblom J. M. et al. (2015) *GRL*, *42*, 6939. [12] Clifford S. M. (1993), *JGR*, *98*, 10,973. [13] Lammer H. et al. (2013) *Space Sci. Rev.*, *174*, 113. [14] Robbins S. J. and Hynek B. M. (2012) *JGR*, *117*, E05004. [15] Le Feuvre M. and Wieczorek M. A. (2011) *Icarus*, *214*, 1. [16] Morschhauser A. et al. (2011) *Icarus*, *212*, 541. [17] Baratoux D. et al. (2014) *JGR*, *119*, 1707.

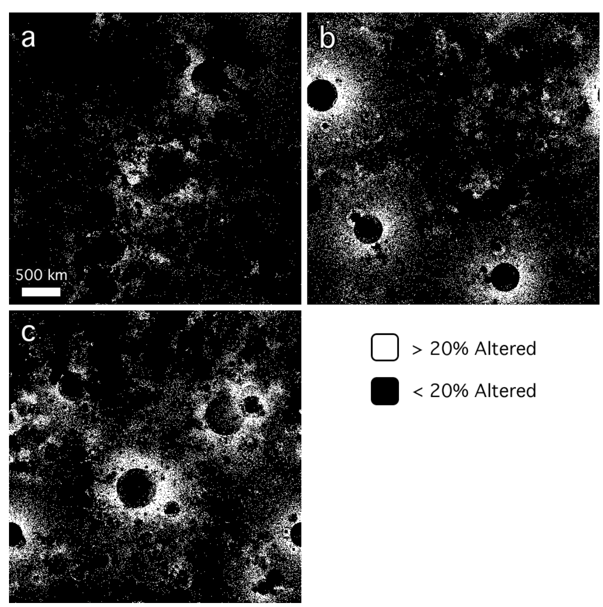

Figure 3. Plan view of the upper surface of crustal evolution models after 1 Ga with a 10 km thick initial clay layer and 10 km of added secondary crust. (a) SSA lasts for 20 Ma. (b) 30 Ma. (c) 40 Ma.