

**OUBLECK AND ORDER: THE AMORPHOUS HISTORY OF MARS.** K. M. Cannon<sup>1</sup> and J. F. Mustard<sup>1</sup>,  
<sup>1</sup>Brown University, Department of Geological Sciences, Providence, RI, USA, [kevin\\_cannon@brown.edu](mailto:kevin_cannon@brown.edu)

**Introduction:** X-ray diffraction measurements from MSL Curiosity revealed a significant amorphous component (20-40%) in both soils and rocks [1]. This amorphous material could be quenched impact glass, volcanic glass, poorly-crystalline alteration products or more likely a combination of the three. There are distinct processes that create and destroy these amorphous components, but the rates of these processes are not constant in time so neither should the average crystallinity of the martian surface remain constant. What processes have caused this evolution in crystallinity and how have the rates of these processes changed? In other words, what is the amorphous history of Mars?

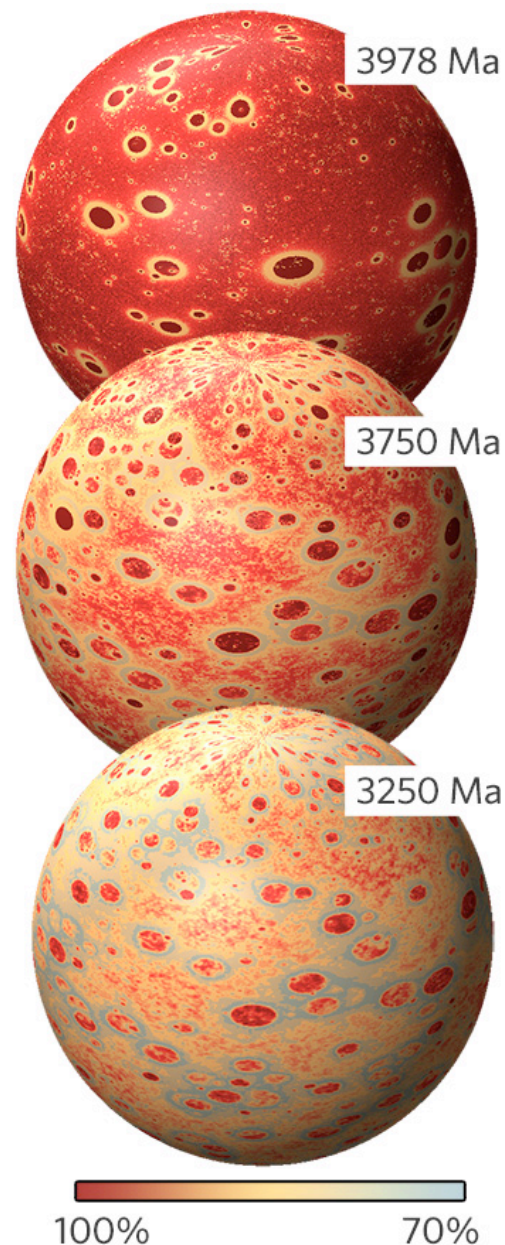
We hypothesize that four major processes are responsible for the largest changes in crystallinity: (1) impact melting, (2) volcanic resurfacing, (3) incipient chemical weathering, and (4) devitrification.

**Processes affecting crystallinity:** Impact melting produces distal quenched glassy products (e.g., spherules, bombs) [2,3] but also proximal melt ponds/seas that cool slowly to form crystalline igneous minerals. The effect of impacts on crystallinity is therefore complex and depends on the balance between these two types of products and the original crystallinity of the target surface. Impacts into more crystalline material will tend to lower average crystallinity, and vice versa. Amorphous materials may also be created by impacts further from the melted volume, for example diaplectic glass formed via shock metamorphism.

Explosive and effusive volcanic products cover underlying material with a mixture of glassy (e.g., ash) and crystalline (e.g., thick slowly cooled basalt) material [4,5]. As with impacts, volcanism has a complex control on crystallinity that depends on the crystallinity of the coating material and the underlying substrate.

In cold dry environments chemical weathering may not proceed past formation of poorly crystalline weathering products, leading to their accumulation [6,7]. This ‘amorphous weathering’ will act to always decrease the average crystallinity of the surface, with the extent controlled by rate/style of weathering and the amount of available crystalline source material.

Devitrification [8] acts to transform impact/volcanic glass into crystalline minerals. Its effect is always to increase crystallinity, the extent dependent on the rate of devitrification and the amount of glassy material present to be devitrified. The presence of liquid water significantly increases the rate of devitrification [8], and on Mars this means devitrification may have been more important in the Noachian and de-



**Figure 1.** Snapshots from the simplified model for the amorphous history of Mars. Crystallinity is shown as a percentage from 0 (amorphous) to 100 (crystalline).

clined with time. Glass may devitrify to common igneous minerals (e.g., pyroxene, plagioclase) or in the presence of water may transform directly into mature hydrated alteration minerals such as clays [9].

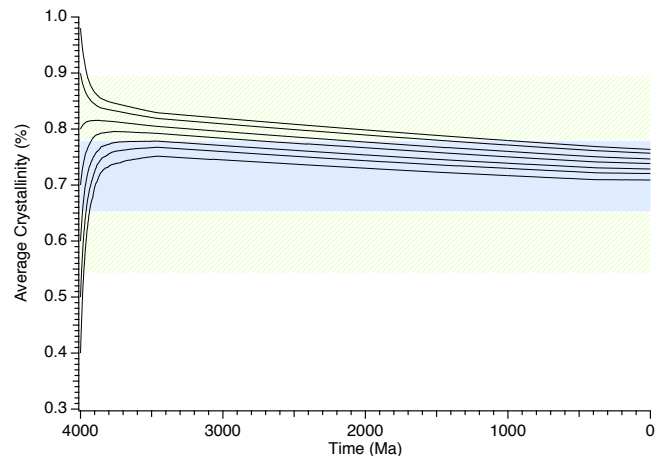
**Simulations:** We created a simplified and parameterized model to investigate the combined effects of

these four processes on crystallinity throughout martian history. The crystallinity of the upper 1 m of the surface is modeled on a 2000 x 2000 node square grid (6 km resolution). This upper meter is assumed to be well-churned by smaller impacts and each node's crystallinity is represented as a continuous value from 0 (completely amorphous) to 1 (completely crystalline). Impact craters are generated stochastically with a size-frequency distribution and impact rate from [10]. We assume that in large impacts (crater diameter >20 km), melting of the target rock will result in a melt pond with a scaled volume that cools slowly enough to completely crystallize. Outside this pond a layer of partially glassy ejecta covers the surface, falling off exponentially in thickness away from the crater. In reality this material may be distributed by winds over the entire martian surface [11], but we do not consider these effects here. Volcanic resurfacing rates from [12] were used with a parameterized crystallinity of the lavas and ashes that cover the surface over time. Amorphous weathering rates are highly unconstrained and we investigated many different possible values. Devitrification rates are calculated from [8] based on the time it takes to completely devitrify a volume of glass to 1  $\mu\text{m}$ -sized crystals.

**Results and implications for Mars:** Figure 1 shows snapshots from an animation of one of the simulation runs resulting in a final crystallinity matching Gale Crater materials (and possibly representative of the average martian surface today). An initially highly crystalline crust is subjected to intense bombardment during the early Noachian. This forms significant amounts of distal impact glass, some of which is remelted by subsequent impacts. A spike of volcanic resurfacing in the Hesperian further decreases the crystallinity to nearly present day values (in this example). Devitrification has a negligible effect with the rates we used [8], even if water is present.

From hundreds of initial simulation runs we find: (1) the final average crystallinity is highly independent of initial conditions due to heavy early bombardment and volcanic resurfacing (Fig. 2), (2) devitrification is never significant because of cold martian temperatures (although it may be locally important around fresh warm craters), (3) the most sensitive parameters are the glassiness of impact ejecta and volcanic products, and the rates of amorphous weathering. This weathering has been the only significant process affecting crystallinity since cessation of heavy volcanism at the end of the Hesperian, and in theory the MSL measurements of current crystallinity can set upper limits on its rate.

Future work will more fully address the issue of glass recrystallizing in the presence of water to form well-crystalline hydrated alteration phases (e.g., clays).



**Figure 2.** Simulation results showing average crystallinity of the surface from 4 Ga to present for a set of constant parameters while changing the initial crystallinity of the surface. Blue and green boxes show the measured crystallinity by CheMin at Gale crater (1 $\sigma$  and 2 $\sigma$  errors, respectively).

The effectiveness of this process can constrain past climate conditions and has strong implications for the stability of glassy materials on Mars over time.

**Conclusions:** The average crystallinity of the upper martian crust was likely set very early on by intense impact bombardment and volcanic resurfacing in the Noachian and Hesperian. Without sufficient heat and water for devitrification of impact/volcanic glass and ‘ripening’ of incipient poorly-crystalline weathering products, old amorphous materials have persisted at the surface and have accumulated somewhat during the Amazonian from additional weathering. These amorphous products are not stable in a warm and wet climate and their abundance through time places constraints on the possibly transitory nature of any clement conditions in the past. Investigations of orbital and landed observations to characterize glassy materials and their alteration products are ongoing [e.g., 13].

**References:** [1] Vaniman D. T. et al. (2013) *Science*, in press. [2] Schultz P. H. and Mustard J. F. (2004), *JGR*, 109, E01001. [3] Johnson B. C. and Melosh H. J. (2014), *Icarus*, 228, 347. [4] Wilson L. and Head J. W. (2007) *J. Volc. Geotherm. Res.*, 163, 83. [5] Kerber L. et al. (2012) *Icarus*, 219, 358. [6] Evans D. L. and Adams J. B. (1980) *LPSC XI*, p.757. [7] Salvatore M. R. et al. (2013) *GCA*, 115, 137. [8] Marshall R. R. (1960) *GSA Bull.*, 72(10), 1493. [9] Fiore S. et al. (2001) *Clay Minerals*, 36, 489. [10] Le Feuvre M. and Wieczorek M. A. (2011) *Icarus*, 214, 1. [11] Wrobel K. E. and Schultz P. H. (2007) *7<sup>th</sup> Int. Conf. Mars*, abs. #3093 [12] Tanaka K. L. et al. (2013) *PSS*, in press. [13] Cannon K. M. et al., *This volume*.