UNDERSTANDING ANCIENT AND RECENT CLAY FORMATION ON MARS FROM A GLOBAL SURVEY OF CRATER CENTRAL PEAKS.

V. Z. Sun[1] and R. E. Milliken[1], [1]Dept. of Earth, Environmental, and Planetary Sciences, Brown University, RI 02912, Vivian_Sun@brown.edu.

Introduction: Impact craters are crucial to our understanding of Mars' geologic and aqueous history. These landforms expose subsurface materials in their walls and central peaks, allowing us to probe the composition of the martian crust using orbital spectroscopy. Impact craters also host the majority of all hydrated mineral occurrences on Mars [1], highlighting the need to examine the geologic context of these deposits in more detail.

Hydrated minerals in crater central peak regions are particularly important as they may represent deep-seated materials and possibly ancient aqueous processes. Observations of clays in central peaks have previously been interpreted to indicate a warm and wet clay-forming Noachian climate that later transitioned to colder and drier conditions during the Hesperian and Amazonian [e.g., 2,3,4,5]. However, central peak clays can also represent minerals formed authigenically after the impact event, either in a hydrothermal system (Toro crater [6]) or from alteration of impact melt (e.g., Holden [7], Ritchey [8] craters). Such cases may represent more recent Hesperian or Amazonian clay formation rather than simple excavation of Noachian-aged clays. Distinguishing between pre-impact (excavated) and post-impact (likely authigenic) origins provides important information about water availability at very different times in martian history.

Here we present results from a global survey of hydrated minerals at crater central peaks. We focus on clay minerals as they are pervasive and may indicate formation under clement, possibly habitable conditions. We assess the pre- or post-impact origin of these clays and constrain their formation ages through crater counts. By determining the vertical distribution and possible origins of clays in the martian crust we can better resolve the periods of clay-forming conditions on Mars.

Methods: 550 craters with both CRISM and HiRISE coverage over their central peak regions were selected for study. CRISM data from 1-2.6 μm are used to characterize hydrated mineralogy at each crater. Mineral detections are then placed into geologic context using HiRISE observations of stratigraphic and morphologic units to assess pre- or post-impact origin. Pre-impact minerals occur in units that are clearly excavated and represent ancient uplifted materials. Those determined to be in post-impact units were emplaced after the impact event and may be detrital (e.g., in a sedimentary deposit [9]) or authigenic in origin (e.g., in impact melt [6,8]). Formation ages of the hydrated minerals are estimated from crater counts on the ejecta of the host crater, allowing us to constrain the oldest age of post-impact minerals and the youngest age of excavated minerals.

Results: Results are presented from the 300 craters examined thus far, 141 of which have evidence of hydrated minerals at their central peaks. Fe/Mg smectite or mixed-layer chlorite/smectite is the most prevalent hydrated phase (in 83% of craters with hydrated mineralogy), followed by hydrated silica (21%), chlorite (17%), zeolite (8%), and sulfate (3%). Pre-impact clays comprise ~55% of central peak clays, indicating the excavation of possibly deep-seated Noachian clays. This is apparent by the high density of excavated clays in the ancient Noachian region of Terra Tyrrhena (Figure 1). However, post-impact clays represent a significant portion of the clay detections and constitute ~23% of central peak clays, split between possible detrital (10%) and authigenic (13%) origins. The remaining ~22% of central peak clay detections have an indeterminate origin and are not associated with well-defined geologic units.

Excavated Clays: Pre-impact clays are observed in either massive or layered uplifted bedrock at the central peak. The layered units are observed only in craters that impacted into Hesperian ridged plains, consistent with their interpretation as containing stacked lava flows. Uplifted massive clay-bearing units are found in the majority of craters and may represent ancient, altered Noachian crust that has been brecciated by impacts [10].

Depth and Age of Noachian Alteration: All craters hosting excavated clays are ≤66 km in diameter (Figure 2), corresponding to a maximum excavation depth of ~6 km [11]. This 15-66 km diameter range is similar to that of northern plains craters with excavated clays at their central peaks (20-60 km [4]), indicating that the global crust may be altered to similar depths. Craters larger than 66 km either bear authigenic clays at their central peaks (80 km Ritchey [8]) or excavated clays from shallower strata in the inner and outer rims (230 km Lyot [4]). This implies that the presence of clays in the Noachian crust may only extend to ~6 km depth, and underlying material was either formed during a period of non-clay-forming conditions or clay minerals have not been preserved. The exceptions to this global trend are in the Tharsis region, where the range of craters excavating clays is only 15-36 km (Figure 1), indicating a shallower depth of clay-bearing strata.

Host crater ages provide a lower limit on the formation ages of excavated clays. The oldest crater with excavated clays is ~3.93 Ga, suggesting these clays may have formed even earlier in the Noachian. Alternatively, these clays could have formed more recently via subsurface alteration [12] rather than ancient surface weathering.

Detrital Clays: Detrital clays are associated with sedimentary depositional environments and in some cases exhibit clays in the sediment source regions; these cases may represent pre-impact clays that have been redistributed by post-impact processes. The craters hosting these likely detrital clays are all dated to 3.6-4.1 Ga, which constrains the maximum age of the fluvial activity and is consistent with the timing of valley network formation near the Noachian/Hesperian boundary [13].

Authigenic Clays: An authigenic designation is given when unaltered, uplifted bedrock is superposed by a clay-bearing unit that is commonly observed to have characteristics of impact melt, including brecciation and a draping morphology [8]. Authigenic clays appear to have a random spatial distribution (Figure 1), which is appropriate given their formation in localized crater environments. The frequency of authigenic clays appears random from 2.5-3.8 Ga, suggesting that the ability of impacts to generate clays may have been constant throughout martian history. This also indicates that clay-forming conditions were not restricted to the Noachian and that near-surface water availability, and possibly habitable conditions, may have existed locally during the Hesperian and Amazonian.

Conclusions: We find that clays in the Noachian crust may extend to a maximum depth of ~6 km, possibly corresponding to a minimum formation age of 3.93 Ga. The crust beneath this zone lacks clear evidence of hydrous phases and records or has been affected by very different conditions. Our results place tighter age constraints on the possible depth and timing of aqueous alteration on Mars. We find that impact-related clay formation may have occurred locally within individual crater systems as recently as 2.5 Ga. Collectively, these results indicate that widespread habitable conditions may have existed very early in martian history, followed by habitable environments present only in localized areas that may be linked to impact processes.

References: [1] Carter, J. et al. (2013), *JGR 118*, E004145; [2] Bibring, J.-P. et al. (2006), *Science 312*, 400-404; [3] Mustard, J. et al. (2008), *Nature 454*, 305-309; [4] Carter, J. et al. (2010), *Science 328*, 1682-1686; [5] Quantin, C. et al. (2012), *Icarus 221*, 436-452; [6] Marzo, G.A. et al. (2010), *Icarus 208*, 667-683; [7] Tornabene, L.L. et al. (2009), *LPSC 40*, #1766; [8] Sun, V.Z. and Milliken, R.E. (2014), *JGR 119*, E004602; [9] Ehlmann, B.L., et al. (2008), *Nature Geoscience* 1, 355-358; [10] Caudill, C.M. et all. (2012), *Icarus* 221, 710; [11] Grieve, R.A.F. and Pilkington, M. (1996), *J. Aus. Geol. Geophys.* 16, 399-420; [12] Ehlmann, B.L., et al. (2011), *Nature* 479, 53-60; [13] Fassett, C.I. and Head, J.W. (2008), *Icarus 195*, 61-89.

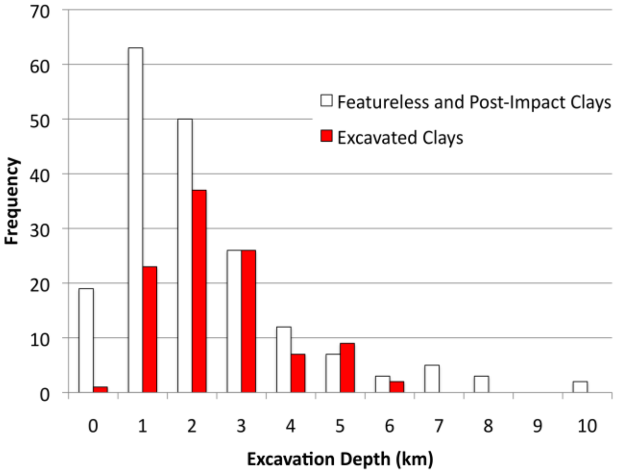

Figure 2. Histogram of the clay excavation depth. All excavated clays are uplifted from a depth of ≤~6 km.

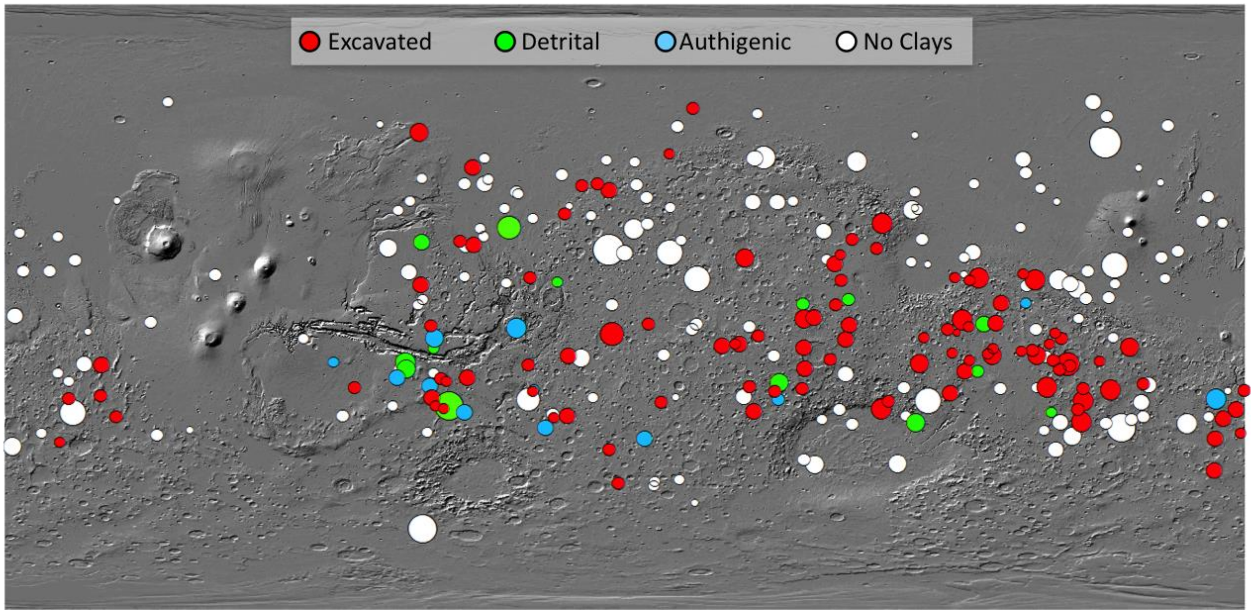

Figure 1. Global map of clay detections near crater central peaks, color-coded by inferred origin and with circles scaled to crater size.