IMPACT CRATERS AS PROBES TO INVESTIGATE THE UPPER CRUSTAL HYDROUS MINERALOGY ON MARS

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Introduction: The advent of orbital infrared hyper-spectroscopy imaging backed by in-situ measurements from the Mars Exploration Rovers (e.g. 1) has greatly enhanced our comprehension of past wet environments on Mars. Proof of globally distributed and diverse aqueous settings has been found based on mineralogy data provided by OMEGA and CRISM (2,3). To date, over a dozen type of diverse hydrated minerals have been found (e.g. 4), including phyllosilicates and sulfates, in equally diverse geological settings.

Global mapping of localized hydrated deposits on Mars (5) reveal that the dominant species are mixed layered Fe-Mg rich smectites/chlorites, and are found mostly (>60%) associated with crater impact structures.

Craters are a key geological process which has been active throughout the planet's history, particularly during the Noachian bombardment. Energy from impacts can excavate crustal material at great depths (6) and may also trigger hydrothermal systems in water-bearing subsurface (7). While surface erosion and tectonic features such as fossae can provide insight into the sub-surface, craters are a more widely distributed process which allows to probe the sub-surface at various depths depending on the crater size.

Recent observations of hydrated minerals including the metamorphic phyllosilicate prehnite excavated from under the northern plains of Mars (8) and at proximity to the Argyre basin (9) lead us to consider that some parts of the southern and northern Noachian crust could have been altered in depth due to chemically active fluids. Various low grade hydrated metamorphic assemblages are expected to be excavated in craters large enough to have penetrated the crust and vary vertically as a function of depth. As demonstrated in (5,10), the Terra Tyrrhena region shows the presence of numerous hydrated minerals very often associated with craters. We here present a systematic study of the mineralogy and setting of hydrated deposits found in close association with craters in this region.

Crater sample and sample selection: We selected 79 craters in the greater Terra Tyrrhena region of Mars ranging from ~200m to 81km in diameter. We investigate the evolution of hydrated mineral composition in the central peak, inner walls and ejecta as a function of crater size. The enquiry is two-fold: we build statistics on the entire sample and keep a subset of 18 smaller craters (D<4.4km) to investigate a shallow sub-surface layer of Fe-Mg phyllosilicates. This layer has been detected in Terra Tyrrhena (fig. 3) and other regions of Mars (e.g. 11) and is not related to in-depth alteration of the crust, but is of relevance to test the excavation models for Martian craters (6,12) necessary to constrain the burial depth of the excavated minerals. This subset sample was selected based on the mineralogy (Fe-Mg phyllosilicates), and presence of preserved ejecta. For maximum accuracy, we selected sites where both the floor, rim and ejecta are visible in a single CRISM observation.

Craters larger than 5km are discarded in the subset sample as the field of view is too narrow to map the ejecta composition up to several crater radii. Larger craters also intrinsically have a smaller fraction of sub-surface layer material in the ejecta so detections are more difficult and may be contaminated by deeply excavated minerals. Craters smaller than 0.2km are also discarded due to lack in spatial resolution.

Our results may be biased by variability in crustal thickness and local surface morphology. To limit these biases we discard any small (~<10km) crater overlying Noachian ranges or larger crater floors, inner walls and ejecta as they sample different crustal thicknesses or may not access the crust. Mineralogy in larger craters will be less dependent on the impact site as the bulk of the material excavated will not bear material from the surface structure.

Impact-induced hydrothermal systems may cause phyllosilicate formation in the central uplift and floor of craters ~>10km (7,13). This formation pathway needs to be taken into account while interpreting the crater composition statistics.

Method: Data analysis follows a standard procedure described in (14). Spectral criteria are derived and mapped over imagery data for context. We identified Fe-Mg smectites, Al-smectites akin to montmorillonite and illite, kaolin-class minerals, chlorites, low-grade metamorphic mineral prehnite, zeolites and hydrated basaltic glass or opaline silica. For the main sample, we build a histogram of the number of occurrences of each mineral phase as a function of crater diameter (fig. 1). For the subset sample (D<4.4km), we plot the Fe-Mg smectite criterion as a function of distance to crater center in radii (fig. 2).

Sub-sample: results: These small craters have simple morphologies with no to very few central structures and no inner ring. They excavate crustal material up to a maximum depth of about D/10 (6), hence ~< 500m. For each observation, the Fe-Mg smectite criterion (2.3 µm spectral shoulder depth) was plotted as a function of distance to center in radii. In fig. 2 is plotted the median value of the criterion for craters with D<1.5km (red) and D>1.5km (black). All craters exhibit a similar behaviour: low value in the crater floor, peak value near the rim (dashed line) and a smoothly decreasing value in the ejecta. Smaller craters (red) have peak values in the outer rim and ejecta, visual inspection of these craters at the CRISM <30m/pix resolution does not reveal a layer exposed in the inner walls. Larger craters all have an exposed sub-surface layer, coinciding with the peak value (black) just under 1 radius. Both crater ranges exhibit a drop in the criterion at about 1.5 radii followed by a shoulder to about 2 radii. The Fe-Mg smectite profiles in fig. 2

reveal that smaller craters (D~<1.5 km) do not exhibit an inner layer, but excavate the same minerals in the ejecta, indicating that they likely penetrated the layer. Therefore the layer is no deeper than ~150m. The drop at 1.5 radii for both crater ranges may correspond to the proximal ejecta which comprises of more deeply buried material than the distal ejecta. This would be consistent with visual observation of a single 10s to 100s meters thick Fe-Mg bearing layer which does not extend downwards (e.g. in fig. 3). More definite interpretations of these results require comparison with excavation models (6,12).

Large sample: results: Central uplifts are a poor indicator of buried structure as they are only present in craters larger than ~8km on Mars, hence in the same size range where impact-induced hydrothermal alteration can take place, and which is strongest in the uplift. Statistics for the central uplifts show an evolution of the mineral assemblage with craters size (fig. 1a). Larger craters (>20km) have larger occurrences of Fe-Mg smectites and zeolites and lower ones for chlorite. Hydrated glass/opaline silica is not found in the smaller craters. Prehnite is equally found as small outcrops in uplifts of all-sized craters. Mineralogy of the ejecta is a better tool as hydrothermal alteration could occur for very large (D~>150km) only (7). The most striking trend is the dominance of Fe-Mg smectites in craters <5km (fig. 1b), which are then replaced by chlorites and zeolites in larger craters. Craters >5km all have about the same mineral assemblages in their ejecta. The 'bump' in chlorite occurrence for craters 10-20km is difficult to explain, as is the presence in almost constant proportion of prehnite at all sizes.

Discussion: Assuming a geothermally-driven vertical mineral structure in the upper crust, we expect shallow material to bear low temperature and pressure phases such as Al and Fe-Mg smectites, sequentially replaced with increasing depth by interstratified smectite/chlorite, vermiculite/chlorite and chlorite (very low-grade metamorphism). At greater depth, low-grade metamorphic prehnite is found. Zeolites occur on Earth at a wide range of pressure and temperature, but are typically found at a temperature and depth greater than that of smectites, and down to low-grade facies.

Observations of the mineral assemblages in the ejecta of craters ranging 0.2-81km are in good agreement with the excavation scenario. Craters larger than ~5km excavate higher grade minerals. Prehnite is however not expected in craters ~<5km as they do not excavate deep enough within the crust to access this high-temperature phase nor may they trigger hydrothermal systems hot enough. This may be the result of crustal thickness and composition variability. Interpretation of the central uplifts results is somewhat trickier. The large occurrences of smectites found in larger crater uplifts is opposite to what is expected. One explanation could be that these smectites formed under hydrothermal systems. Careful examination of uplift morphologies and comparison with mineral assemblages predicted in hydrothermal systems (13,15) are necessary. Hydrated glass/opaline silica in larger craters also point towards hydrothermal alteration in the uplift.

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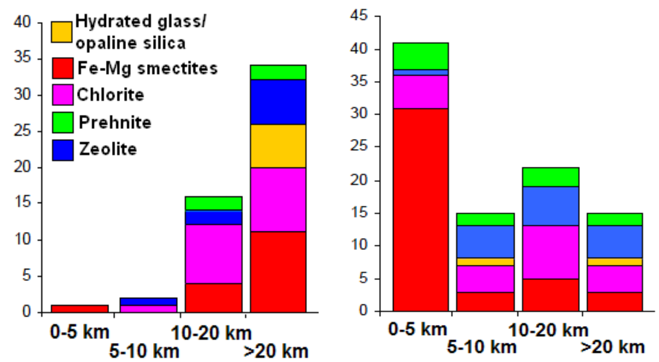

Figure 1. Occurrences of hydrated minerals in crater central uplifts (a: left) and ejecta (b: right) as a function of crater diameter (79-crater sample).

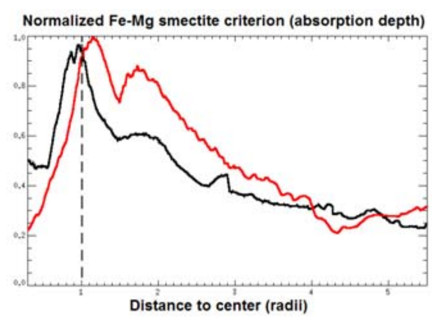

Figure 2. Median Fe-Mg criterion strength as a function of distance to crater center in units of radii. Red: craters D<1.5 km. Black: craters D>1.5km.

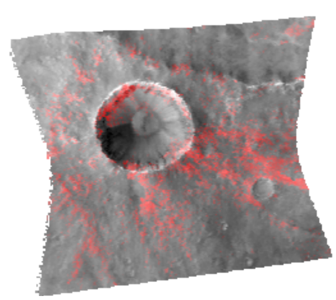

Figure 3. Example of crater in Terra Tyrrhena showing Fe-Mg phyllosilicates (red) in ejecta and exposed in a shallow layer within the inner walls