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EVIDENCE FOR IMPACT-INDUCED HYDROTHERMAL CLAY MINERAL FORMATION AT ENDEAVOUR CRATER, MARS.

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Introduction: Over 13 years after landing at Meridiani Planum and in her 10th extended mission, Mars Exploration Rover Opportunity continues to explore the rim of ~22 km diameter Endeavour crater [1]. The rim exposes material that is older than the S-rich, layered sedimentary rock covering the Meridiani plains and filling much of the interior of Endeavour. Clay mineral exposures at the rim have been observed from orbit [2,3] and confirmed on the ground [4-6]. Clay minerals are thought to indicate wet, generally habitable environmental conditions more suitable to life than the S-rich, acidic waters responsible for the Meridiani sedimentary rocks. However, in order to assess the habitability of the past environment recorded by the Endeavour rim rocks it is important to understand how the clay minerals formed. Do they represent the conditions prior to impact; or do they result from impact-induced hydrothermal activity; or both? Here we present evidence that at least some of the observed clay mineral assemblages formed as a result of impact-induced hydrothermal alteration.

Results and Discussion

Geologic setting. Endeavour is a ~22 km diameter Noachian impact crater (Fig. 1). It is mostly filled with the S-rich sedimentary rock of the Hesperian Burns formation, which covers the Meridiani plains. Burns formation rocks have buried the potential central uplift as well as large tracts of the crater rim. Only isolated segments of the rim protrude through the Burns formation. Of these, Opportunty investigated Cape York, Murray Ridge, and Cape Tribulation at the western edge of the crater (Fig. 1). The rim is mostly made up of the clast-bearing Shoemaker formation impact breccia. The oldest stratigraphic unit so far is the Matijevic formation, which has to date only been observed at Cape York and is thought to predate the formation of Endeavour. Finding more of Matjevic formation or a lower stratigraphic unit is one of Opportunity's 10th extended mission goals.

Description of the observed clay mineral assemblages. Orbital detections of clay minerals at distinct locations at the Endeavour crater rim reveal Fe^{3+} and Mg smectites [2,3]. Unfortunately, Opportunity's mineralogical instrument were no longer operating, and these smectites had to be located on the ground on the basis of APXS-derived geochemical data alone [4-6]. Yet, the ground observations revealed a more complex clay mineral story by identifying Al-rich clays not observed from orbit [4-6]. These are associated with fracture fills and zones and suggest multiple episodes of aqueous alteration at Endeavour [6].

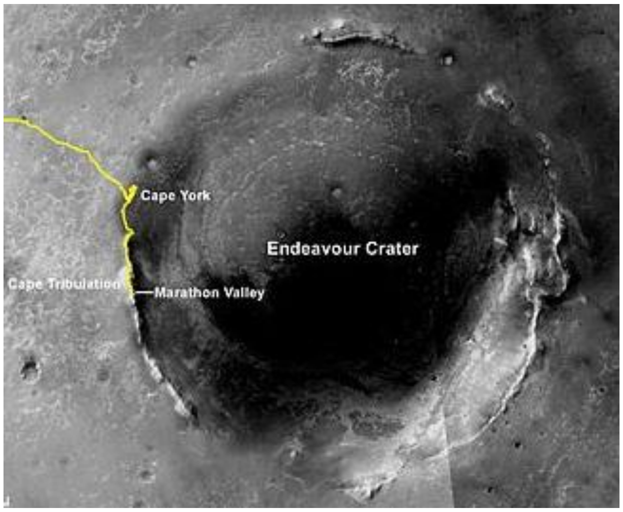

Fig. 1. *MRO-CTX image of ~22 km diameter Endeavour crater. The yellow line indicates Opportunity's traverse. Image credit: NASA/JPL-Caltech/MSSS/NMMNHS.*

At Cape York, clay minerals are found within the Matijevic formation. The Fe^{3+}-smectites seen from orbit are associated with veneers on the ground. The chemical composition of these veneers, enriched in elements mobile under aqueous conditions, and their Pancam 13f spectral features are consistent with clay minerals [4]. The boxwork fracture fills in distinct locations within the Matijevic formation on the other hand are enriched in Al and Si with a composition indicating montmorillonite [5].

In Marathon valley at Cape Tribulation, Mg-Fe smectites as seen from orbit appear to result from near-isochemcial weathering of Shoemaker formation impact breccia on the valley floor [6]. Curvilinear fracture zones dubbed red zones due to their appearance in false color Pancam images, are again enriched in Al and Si and depleted in Fe, suggesting Al-rich clays.

Evidence for impact-induced hydrothermal clay mineral formation. The observed clay mineral occurrence may be excavated by or produced as a result of the Endeavour impact. A case for the former can be made for Matijevic formation, but the latter cannot be excluded. Marathon valley clays are more likely to have formed as a result of the impact. Clay minerals can form through a number of alteration processes ranging from surface/near-surface weathering via hydrothermal alteration to diagenetic, metamorphic, and magmatic processes [7]. The clay mineralogy and geochemistry, their facies and abundance, and accompanying minerals can help to distinguish between the different settings of formation.

Clay minerals are the main alteration product in a wide range of Martian rocks when exposed to hot, circumneutral fluids. The case documented in most mineralogical detail are the nakhlite Martian meteorites, where alteration phases have been found. First described as 'iddingsite' [8], they are patches of complex mineral mixtures [9]. Most recently, detailed mineralogical analysis [10,11] led to the distinction of a carbonate – clay – gel succession that varies within the nakhlite pile. Changela and Bridges [10] concluded that these mineral associatons formed by post-impact hydrothermal processes. Modeling of this mineral succession [12] showed that an intitially hot fluid cooled to about 50 °C at the time of clay formation.

While very well documented mineralogically, the meteorites lack the geologic context, which is available from orbit [e.g., 13-15]. Unfortunately, from orbit, only mineral occurrences, but no detailed mineral assemblages can be observed. Nevertheless, combining these observations with thermochemical modeling allows for general predictions of the mineral assemblages expected. Nontronite and chlorite are among the main phases expected [16-18].

Studying Endeavour Crater allows us to put orbital observations of clay minerals in context with the detailed stratigraphy and geologic context only possible from rover observation. The clay minerals observed at Marathon valley, but also within the Matijevic formation are consistent with impact-induced hydrothermal formation in the way that they occur as fracture fills within breccia and/or as low abundance alteration rinds on mineral grains (near-isochemical weathering of Shoemaker rocks); they occur beneath the rim and were likely exposed by erosion; and relevant accompanying minerals such as sulfates and potentially silica and zeolites were found in close proximity [7].

Reaction of the local country rock with a hot, dilute brine, similar to the work of [16] and using their 'adapted water' starting fluid, results in chlorite formation (Fig. 2), which is likely representative of the deeper subsurface circulating system. Fig. 2 shows chlorite to be dominating over a wide range of W/R (10 to 10000), which is assumed to be the hydrothermal W/R range. At high W/R (above 1600) chlorite is accompanied by Fe-oxides (hematite/magnetite), and below W/R 1600 quartz is the second most abundant mineral in the assemblage. Pyrite occurs at all W/R, indicating reducing conditions in the precipitate. At Cape York and Marathon Valley, more complex clay formation is observed indicating mineral assemblage formation in a cooling and changing environment, more comparable to the scenario described for the nakhlite meteorites [10,12].

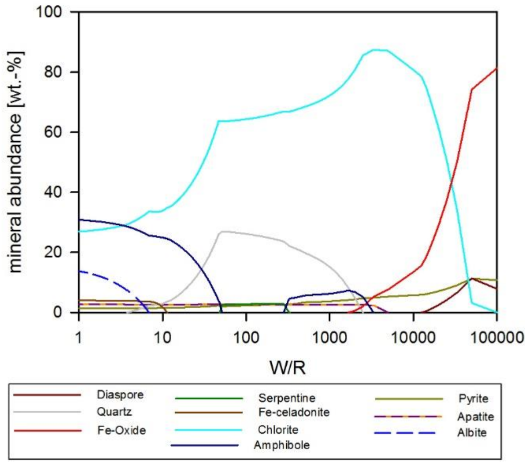

Fig. 2. *Model results for water rock interaction of a rock of „Chester Lake Clast“ [19] composition with a diluted neutral fluid at 150 °C at 110 bar.*

Conclusions: The geologic setting of the clays within the breccia is a strong indication of the impact-generated nature of at least a fraction of those clays. Their complex nature hints at high water to rock ratios (montmorrilonite-compositions) in fracture zones and a cooling and/or multi-step scenario rather than a one-step, isochemical alteration. Modeling those is currently under way.

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