IMPACT CRATER DEPOSITS IN THE MARTIAN HIGHLANDS.

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Introduction: The martian highlands of Noachis Terra (20-30°S, 20-50°E), Tyrrhena Terra (0-30°S, 50-100°E) and Terra Cimmeria (0-60°S, 120-170°E) preserve long and complex histories of degradation [e.g., 1-12], but the relative effects of such factors as fluvial, eolian, and mass wasting processes have not been well constrained. The effects of this degradation are best observed on large (D>10 km) impact craters that characterize the ancient highlands. Some craters exhibit distinct interior deposits, but precise origins of these deposits are enigmatic; infilling may occur by sedimentary (e.g., fluvial, lacustrine, eolian), mass wasting and (or) volcanic processes.

Analysis of Viking, MOC, THEMIS, MOLA, and TES data are allowing detailed characterizations of impact crater morphologies, geologies, erosional and depositional histories, and ages to be determined. This study intends to (a) characterize the complex geologic and geomorphic terrains found within highland craters, (b) determine the origin(s) and ages of floor deposits, and (c) investigate degradation processes that might have affected impact craters in these regions. Several studies [e.g., 13-17] have suggested that large impact craters on Mars may have contained standing bodies of water that could have been ideal environments for life to persist. Determining the nature of impact interior deposits will provide targets for future landing sites in order to identify sources of subsurface water as well as evaluate evidence for biologic activity.

Geology of Millochau: Millochau (21.4°S, 275°W; D=114 km; depth ~2.3 km) is a large, highly degraded Noachian-aged crater that displays a complex geology representative of many of the above-mentioned processes [18]. Due to its size, degree of modification, and age, the geologic record of Millochau spans a large part of martian history, recording changes in degradational style(s) and (or) climatic changes.

Millochau has no ejecta blanket, which has been eroded and (or) covered by local Late Noachian/Early Hesperian-aged plains material and younger eolian sediments [12]. Millochau's rim is quite discernible, but impact cratering and other processes have degraded portions of it. The northern and southern interior walls contain high concentrations of gullies and display the steepest slopes. Millochau does not have obvious inflow and outlet valleys, therefore any water entering Millochau traveled via gullies, through the subsurface, or by direct precipitation [18].

MOLA topography shows that Millochau contains an ~400-m-high 'plateau' that is bounded to the north and east by irregular depressions and slopes to the south and west where it grades into the surrounding floor materials [18]. The topographic expression of the plateau could reflect a buried crater structure; however, the plateau is offset to the northeast and is likely a secondary feature unrelated to the impact event that formed Millochau. Layering exposed along the northern and eastern scarp boundaries of the plateau, part of its southern boundary, and knobs within depressions display regular sequences (massive overlying thin) and morphologies that allow layers to be traced laterally for several kilometers in MOC images. Thin layers outcrop at the bases of knobs and on the floors of depressions typically form staircase-like patterns. Several valleys cut into the southern and northern edges of the plateau and are contained within plateau deposits. These valleys have uniform widths and depths from head to mouth, and display amphitheater-shaped heads consistent with formation primarily by groundwater sapping [18].

Millochau contains six distinct interior deposits: pitted, rugged, etched, dune and talus materials, and knobs [18]. Pitted material (Nmp) covers the plateau and shows a heavily pitted and cratered surface in MOC and THEMIS images. TES thermal inertia data show that Nmp ranges from ~275-350 $J/m^2Ks^{1/2}$, which corresponds to materials containing fine materials and (or) few rocks [19-22]. THEMIS images show Nmp to be bright during the day and dark at night, consistent with fine-grained deposits that heat up and cool down relatively quickly. The presence of many small (D<1 km) impact craters is similar to the plains surrounding Millochau and suggests these units may be similar in age [12]. Nmp could include sedimentary (fluvial, lacustrine or eolian) and volcanic (loosely consolidated pyroclastics) deposits [18]. Pits on the surface of Nmp could be poorly preserved impact craters, collapse features, and (or) eolian-modified depressions.

Rugged material (HNmr) displays a surface with a stucco-like texture and extends from the plateau to the base of Millochau's interior wall, sloping gradually toward the plateau at ~0.8° [18]. HNmr exhibits TES-derived thermal inertia values of ~400-500 $J/m^2Ks^{1/2}$, consistent with rocky and (or) coarse-grained materials or cemented fine materials [19-22]. THEMIS images show that HNmr is dark during the day and bright at night, suggesting this unit is composed of materials that retain heat. HNmr embays rim material, but the embayments are not pronounced. In some places, HNmr covers gullies incised within the interior wall; fluvial deposits are not visible at the mouths of these gullies indicating fluvial activity may have ended prior to emplacement. Alternatively, slope differences coupled with the potentially high porosity of HNmr may not have allowed valley incision. The outer edge of HNmr is buried by talus in the north, east and parts of the south, and by ejecta in the south and west. Most craters in HNmr are poorly preserved showing highly degraded rims and little to no ejecta. The precise nature of HNmr is unclear, but could include mass-wasted material, and (or) sedimentary (fluvial, playa or eolian), volcanic and impact related deposits [18].

Etched material (HNme), exposed within depressions that border the plateau, displays smooth, lineated, and irregular surface textures and encompasses surfaces not incorporated within other units mapped in Millochau [18]. In short, HNme is more of a geomorphic surface than a true geologic unit. Few fresh craters are observed within HNme; some exposures contain exhumed craters. Irregular and lineated etched material are interpreted to be exhumed crater interior deposits, most likely composed of the same materials as Nmp and HNmr. Lineated etched material displays some similarities to the positive and negative relief features that form the deltaic deposits observed in the crater northeast of Holden [23-25], but there is no indication of a distributary channel system within Millochau. Collapse of overlying materials and (or) erosion are believed to be the main processes exhuming these deposits [18]. Smooth etched material is believed to consist of eroded crater interior materials redistributed via fluvial and eolian processes and may be unconsolidated to loosely consolidated.

Knobs (Hk) are found within the depressions that border the plateau [18]. Most knobs are rounded and are found at elevations lower than the surface of the plateau, but some knobs are capped with Nmp suggesting they are outliers of the plateau. No knobs are visible within HNmr, which implies that if Nmp extended over most of Millochau's floor, it was completely removed from these distal areas. Alternatively, this could suggest that the extent of Nmp was not much greater than it is now.

A narrow band of material along the base of Millochau's interior wall, mapped as talus (AHt), most likely consists of sediments shed from the crater wall by rock slides and falls, eroded by fluvial processes and transported via gullies, or emplaced as other volatile-related mass movements [18]. AHt buries the outer edge of HNmr in many places along the base of Millochau's wall. The fronts of some talus deposits, especially in northeast Millochau, have very irregular edges and appear to have been eroded. Here, removal of talus has exposed underlying rugged material and numerous degraded impact craters. Several "ghost" craters are visible within this exposure of talus indicating the deposit may be relatively thin.

Dune material (Amd) occurs in isolated patches that fill low-lying parts of Nmp, HNmr, and HNme [18]. In MOC images these deposits are generally darker than the underlying materials, but in some MOC images very bright deposits, possibly frost, are found between dunes. The materials composing this unit form large sets of long- and short-wavelength dunes, similar to those described by [26,27]. Long-wavelength dunes (wavelengths ~40-170 m, avg. $\approx$ 70 m) are oriented east-west (long axis) and span the widths of the depressions in which they occur. Short-wavelength dunes (wavelengths ~10-30 m, avg. $\approx$ 20 m) occur between long-wavelength dunes and at the bases of knobs and the scarps. The orientations of short-wavelength dunes are strongly influenced by adjacent topography - they are oriented perpendicular to the knob, scarp or long-wavelength dune with the highest relief. MOC images show that most short-wavelength dunes superpose long-wavelength dunes indicating they are either younger and (or) more mobile. In MOC images, most impact craters observed in Amd are found between dunes and do not superpose duneforms. Amd is interpreted to consist of sediments eroded from other interior floor deposits, and crater wall and rim materials, and redistributed by eolian processes [18].

Conclusions: Impact craters such as Millochau are common throughout the highlands and range in size and preservation state. Some display distinct interior deposits. Significant coverage of Millochau by MOC and THEMIS images allowed its geology to be determined and features to be characterized [18] in relation to the surrounding highlands [12]. Analysis of Millochau has shown that a Noachian-aged crater underwent a significant amount of modification by erosion and deposition throughout Mars' history, which is exhibited by lack of an ejecta blanket, dissected rim materials, and layered floor deposits [18].

Ongoing work: Currently, large (D>10 km) impact craters in Tyrrhena Terra, Noachis Terra and Terra Cimmeria are being identified, their dimensions measured (e.g., diameter, depth, floor elevation) using MOLA, and their preservation states (e.g., "fresh", "degraded", "moderately degraded", "highly degraded", and "buried" or "exhumed"; morphologic definitions modified from [28 and 29]) characterized. Individual craters, such as Terby [30,31] (Tyrrhena Terra), Rabe and Proctor (Noachis Terra) and Gale [31] (Terra Cimmeria), that are well-covered by MOC, THEMIS and TES data may be mapped in detail, as done for Millochau [18], to determine if similar degradation styles are common among craters (such as by precipitation-driven processes or by a regional mantling unit that contributes mass-wasted material to crater floors) or differ from crater to crater, suggesting mostly localized processes were (are) active.

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