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EXPLORING MARTIAN IMPACT CRATERS: WHAT THEY CAN REVEAL ABOUT THE SUBSURFACE AND WHY THEY ARE IMPORTANT FOR THE SEARCH FOR LIFE.

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Introduction: Impact craters are important targets for Mars exploration, especially craters of Noachian age, which record conditions on Early Mars. Smaller craters can also be used during missions to the planet as natural "drill holes" or excavation pits into the subsurface, and so can provide information and samples that would otherwise be inaccessible (e.g., [1]).

During the Noachian period impact cratering was the dominant geological process on Early Mars and on the contemporary Earth and Moon [2]; investigation of craters will inform our understanding of this geologic process and its effects on the water-bearing Martian crust at the time. Impact craters disturbed and heated this water-bearing crust, and likely initiated long-lived hydrothermal systems [3-5], which may have created some clement environments for life [6] and formed secondary minerals [7]. Also, impact-heat generated lakes may have formed [8]. Thus, Noachian impact craters are particularly important exploration targets, providing subsurface access, data on crucial geological processes, and warm, water-rich environments possibly conducive to life.

Hydrologic aspects and post impact mineralogy: For habitable conditions, one key aspect is the availability of water. Channel networks [e.g., 9,10], rampart craters [11], and hydous minerals [e.g., 12,13] are the most important sources of evidence for a water rich environment and crust in the Noachian. If the early Noachian did start out warm and wet, theoretical models of atmospheric evolution suggest that such conditions did not persist beyond the end of heavy bombardment [9,14]. With the transition to a colder climate, a freezing front developed in the planet's crust, creating a growing cold-trap for both atmospheric and subsurface H_2O – a region known as the cryosphere. Models show that the depth of the that cryosphere varies from about 2 km near the equator up to 6 km near the poles [15]. Below this cryosphere, a briny aquifer is expected, which can serve as a connection between individual sites of thermal anomalies such as impact craters or volcanoes. However, models for the post formation evolution evolution of large impact craters [5] indicate that the central region of a 100 km diameter crater initially is up to 900 °C hot, melting ice and extracting water from minerals. With time, a hydrothermal system eveloves that shows the most intense and longest activity between 300 and 100 °C. Temperatures decline with the isotherms moving inwards and downwards over about 300,000 years [5]. The change in temperature and water flow disturbs the thermochemical state of the pre-impact stratigraphy, causing alteration minerals to form. The main hydrous silicates expected to form from Martian rock chemistry at intermediate (150 °C) temperatures are chlorite, smectite (Mg-nontronite) and serpentine [7]. All the above results are obtained from models, but can be verified in terrestrial craters.

Ground truth on Earth and Mars: On Earth, there are a few large, complex impact craters that can be studied for their post-impact effects. Two prominent examples are Sudbury and Chixculub, for which the post-impact hydrothermal hydrology was calculated using the same model that was applied to the Martian case [16,17]. Mineralogic information for both craters comes from detailed investigations (e.g., Chicxulub [18-20], and Sudbury [21]). In both cases, a diversity of hydrothermal mineral assemblages is observed, also displaying a succession from high to lower temperatures. Another factor influencing the alteration assemblage is the chemical composition of the host rock. Clay minerals are thereby one key component in the alteration of impact crater lithologies [22]. Transferring this knowledge to Mars is not straightforward at this point in exploration, because the information obtained from Mars is not at the same level of detail as that for the Earth. However, several discoveries of hydrous silicates, especially nontronite and chlorite in central peaks and terrace zones of complex Noachian craters on Mars point at the potential of finding fossil hydrothermal systems and their alteration products in those craters. Currently the best examples come from an about 40 km diameter crater in Nili Fossae (17°N, 72°E), for which 15 % of smectite, and 20 % of pumpellyite are calculated in an plagioclase and pyroxene bearing rock [23], a 25 km crater west of Nili Fossae (20°N, 66°E), where analcime and chlorite/smectite have been found in the central uplift [13], and an about 60 km diameter crater in Cimmeria Terra (32°S, 141°E), where chlorite and either Al-clay or hydrous silicate have beend detected in the central uplift [24].

Impact craters and life: All craters with phyllosilicate evidence in their central peaks are in Noachian terrains. Not only was the Noachian the eon with water activity, the impact frequency was also very high during the Late Heavy Bombardment (e.g., [25]). This, in turn, may have caused extremely inhospitable conditions as a result of repeated sterilization of the surface (e.g., [26]). At the same time, an abundance of surface and subsurface habitats may have been created in the form of impact crater lakes (e.g., [8,27,28]), impact-induced hydrothermal systems (e.g., [3,29]), driven by impact-deposited heat and providing an incubator for organisms able to thrive in hot subsurface hydrothermal fluids [30,31]. While hydrology and mineralogy of post-impact systems are independent from surface temperature, connection of the individual sites by a deep aquifer may be critical for the emergence of life especially under cold surface conditions.

Exploring impact craters: The Martian crust in general and impact-generated strata in particular are diverse and extend to significant depths. To take the depth-dimension into account, many proposed Mars landers carry drills or excavation tools, but no spacecraft instruments are currently capable of accessing deeper than a decimeter or so. Therefore, using natural excavation of smaller craters superposed into the sites of interest, will allow access to the subsurface in question.

Gale crater and MSL. To study this using a well documented example, we chose ~150 km Gale crater in Elysium Planitia (4.49°S, 137.42°E), which is also one of the proposed landing sites for MSL. Gale has a complex history that starts with the target lithologies continues with the impact and its aftermath, followed by sedimentation and erosion, including one or more crater lakes [27,32,33]. Small craters have hit all zones of the crater including the crater ejecta, crater terrace zone, crater floor and the central mound, and thus excavated pre-impact target rocks, impact strata and post-impact sediments [15]. If MSL were to land in Gale, a succession of instruments could also be applied to investigate fresh, less dust covered young craters that expose strata of interest. Those instruments include the Mars Descent Imager to map the projected driving path upon landing, the imaging and analysis techniques on MSL's mast, which can operate from a distance; and finally, small craters and their ejecta can be contact sol targets with the rover stopping to analyse the rocks with its detailed mineralogic instrument suite. Each site will most likely display a variety of rocks. For example, a crater punched into crater floor material could have excavated lake sediments and melt sheet material. Therefore, each site will provide multiple options for geologic investigations and chances to find fossil habitats and their potential inhabitants.

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