**Chicxulub-and Gale-like Nicholson Impact.** James M. Dohm[1], Wolfgang Fink[2], Jean-Pierre Williams[3], William C. Mahaney[4], Justin C. Ferris[5], Robert C. Anderson[6], [1]Exploration Institute, [2]Visual and Autonomous Exploration Systems Research Laboratory, University of Arizona, [3]Department of Earth, Planetary, and Space Sciences, University of California, [4]Quaternary Surveys, Ontario, Canada, and Department of Geography, York University, [5]Bureau of Land Management, [6]NASA/Jet Propulsion Laboratory/California Institute of Technology, james.m.dohm@explorationinstitute.com.

**Introduction:** Significant evidence indicates that the northern plains of Mars were inundated by oceans at least during the Late Noachian/Early Hesperian and Late Hesperian/Early Amazonian [1,2]. During these ocean phases, impact craters formed. In particular, Gale (**Fig. 1** [3]) and Nicholson impacts are interpreted to have impacted into half ocean and half land, similar to Chicxulub on Earth, which was devastating on environmental and life conditions.

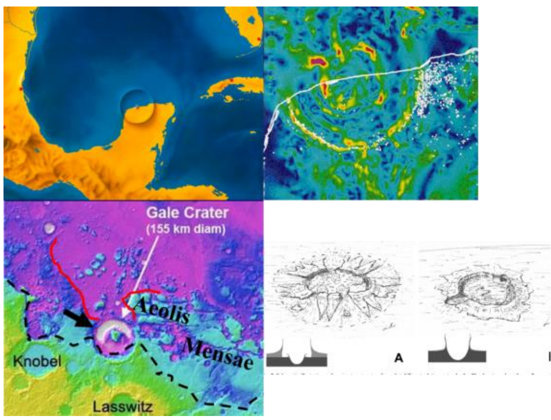


**Fig. 1.** After [3], Chicxulub shown impacting half on the Yucatan Peninsula and in the ocean (i.e., ~half ocean and ~half land), by Pearson Prentice Hall (top left) and through a gravity map (top right) based from [4], similar to what we interpret for the Gale impact event (i.e., ~half ocean/water-enriched ignimbrite and half land; bottom left). Schematic illustrations of marine-target craters (bottom right) interpreted to have occurred on Mars and formed at different relative water depths by [5] with the seafloor craters after early modification (e.g., the collapse of the water cavity).

**Gale Crater**: Based on orbital and field information from MSL Curiosity, [3] proposed the following sequence of events to explain the formation of Aeolis Mons (informally known as Mount Sharp; for brevity hereafter, Mt. Sharp) and a collection of anomalous features (i.e., geologic, geomorphologic, mineralogic, elemental, and geophysical), as follows (from Late Noachian-Early Hesperian to Amazonian including prevailing activity):

1) Magmatic-driven activity during the late Noachian-early Hesperian, particularly at Tharsis, included outgassing and extensive flooding. The flooding included the early dissection of the circum-Chryse and informally named northwestern slope valleys (NSVs) and associated inundation of the northern plains basin, referred to as "Shoreline 1" or "Contact 1" [1,2]. The outflow channel floodwaters rafted the pumice/ignimbrite-composing Medusae Fossae Formation (MFF) material (e.g., [6]), which was emplaced along the southern margin of the newly formed 'Shoreline 1' ocean and the dichotomy boundary onlapping the extremely ancient crustal basement/protolith of Terra Cimmeria [7].

2) During the Late Noachian-Early Hesperian, a Gale Crater-forming bolide impacted the dichotomy boundary, affecting both the Terra Cimmeria basement/protolith materials and the ocean water and associated ignimbrite deposits (MFF materials) along the ocean's margin (i.e., ~half ocean and ~half land). The impact generated enormous pressure/heat, intensive hydrothermal activity, deformation of a major geological contact (i.e., the dichotomy boundary), and tremendous diagenesis/dispersal of the target materials. This included significant modification of Medusae Fossae Formation (MFF) materials directly to the north through an impact-generated tsunami and possible snow-ice sheet melt and hydrological activity from the cratered highlands to the south.

3) Directly following the impact and outward push of water and target materials regarding Sequence 2, collapse and inwards slump of Aeolis Mensae-composing MFF material is proposed to have occurred in addition to (prior/simultaneously) a water resurge. The Aeolis Mensae material, which occurs directly north of the Gale Crater, was degraded, including the development of erosional scarps, as well as the northern crater rim (**Fig. 1**). Such a resurgence of ocean water and target material back into the impact crater has been observed for terrestrial impacts into oceans, including Chicxulub (ocean/continent [8]).

4) Gale impact-driven hydrothermal activity and the injection of elemental-rich hydrothermal materials (including significant silica-enriched fluids largely derived from crustal basement/protolith materials) into the basin infill producing dikes and veins, especially concentrated in what is the remaining differentially eroded materials that compose Mt. Sharp. A central dome with a system of radiating mineralized dikes and veins underpin and buttress remaining Mt. Sharp materials.

5) Continued impact-driven hydrothermal activity resulted in further diagenesis and breakdown of the impact-reworked ignimbrite and basement/protolith

materials into disaggregated sediments due to inherent chemical and mechanical instabilities. Ensuing differential erosion resulted in present day Mt. Sharp, which approximates the height of the southern rim of Gale Crater, indicative of Gale being infilled by slump and resurge deposits; Mt. Sharp being preserved due to concentrated impact-forming hydrothermal veins and dikes and a possible underpinning dome, with the remaining ignimbrite and basement/protolith infill differentially removed over time, exposing the crater rim and floor.

6) Through time (i.e., Hesperian into Amazonian), climate perturbations likely due to magmatic activity such as associated with the development of Martian volcanic provinces such as Tharsis resulted in the modification of Gale Crater including degradation of Mt. Sharp. This included additional post-impact flooding and inundation of the northern plains (especially in the case of late Hesperian/early Amazonian Tharsis-driven activity and associated transient hydrological cycling [9,10]. This activity also contributed to the development of lake (s) in the Gale Crater basin, as well as fluvial and alluvial fans, such as the formation of Peace Vallis (MSL landing site), groundwater, and ice-related manifestations, all of which contributed to further modification of Gale Crater, Mt. Sharp, and surroundings.

7) Prevailing aeolian activity and gravity-driven flows continue to etch Mt. Sharp, redistributing ignimbrite material (with smaller amounts of impact-related basement/protolith fragments) along the basal margin of the mount, accompanied by dune formation.

**Nicholson Crater**: A distinct mesa, similar to that of Mt. Sharp, occurs within the Nicholson impact crater. Nicholson formed along the dichotomy boundary, where removal and dissection of MFF and northern plains materials prevail (**Figs. 2,3**). Here, we propose that the Nicholson impact occurred into ~half ocean and ~half land, similar to Gale-Mars and Chicxulub-Earth.

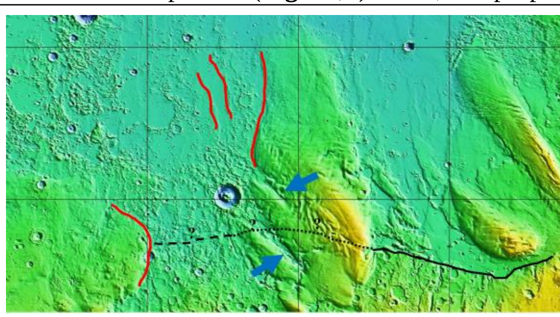

**Fig. 2.** Nicholson Crater (central part of the figure) formed along the dichotomy boundary (solid, dotted-buried, and dashed-approximated black line) with distinctive disruption of MFF (Eumenides Dorsa; blue arrows) and northern plains materials including in the form of erosional scarps (red lines) interpreted here to result from and impact into half ocean and half land, similar to the Chicxulub-Earth and Gale impacts, which included tsunami/slump resurgence [3]).

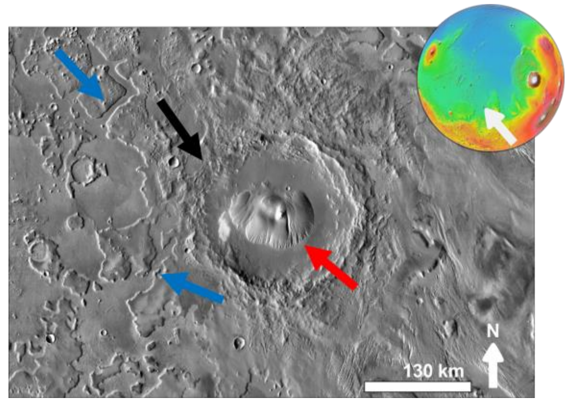


**Fig. 3.** Nicholson Crater, with distinctive: Mt. Sharp-like mesa (red arrow), channel that dissects the northwestern rim (black arrow), and channels that dissect northern plains (blue arrows), all of which are interpreted here to result from and impact into half ocean/half land, similar to the Chicxulub impact, which included tsunami/slump resurgence similar to that interpreted for the Gale impact and associated Mt. Sharp [3]).

**Chicxulub Crater:** The Chicxulub impact event occurred on the dichotomy boundary between the Yucatan peninsula and the Gulf of Mexico (**Fig. 1,** top); more specifically, the event occurred on the continental shelf along the peninsula (water depth ranging from ~2km on the northeast side vs. ~100m to the southwest) [11] underlain by carbonate and granite-composing continental crust) nearly 66 Ma (e.g., [8,11]). Furthermore, the ~200 km-diameter Chicxulub impact crater formed from an impact of comparable energy to that which formed the ~154 km-diameter Gale impact crater, estimated to have been ~$4.5\times10^{22}$J – ~$1.5\times10^{25}$J, or $7\times10^{8}$ – $239\times10^{9}$ Hiroshima A-bombs) [3].

**Summary**: Gale and Nicholson impact craters are included in a growing list of features supportive of ancient oceans on Mars.

**References:** [1] Fairén A.G. et al. (2003) Icarus 165, 53–67. [2] Dohm J.M. et al. (2009) Planet Spa Sci 57, 664–684 [3] Dohm, J.M., et al. (2022) Icarus 390, 115306. [4] Hildebrand. A. et al. (1998) Geol Soc. London, Spec. Pub. DOI:10.1144/GSL.SP.1998.140.01.12. [5] Ormö, J. et al. (2004) Meteoritics & Planet. Sci. 39, 333-346. [6] Mouginis-Mark, P. (2021) Eos. Retrieved 2021-06-26. [7] Anderson, R.C. et al. (2022) Icarus 387, 115170. [8] Ormö, J. et al. (2021) Earth and Planetary Science Letters 564, 116915. [9] Dohm, J.M. et al. (2001a) JGR 106, 32,942–32,958. [10] Dohm, J.M. et al. (2001b) JGR 102, 12,301-12,314. [11] Gulick, S.P.S. et al. (2008) Nat. Geosci. 1, 131–135.