VOLATILE-RICH UPPER CRUST OF MARS CONSTRUCTED DURING THE IMPACT CATACLYSM

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1. Introduction/Overview: Escarpments along Noachian cratered plateaus that form the margins of the outflow channels, chasmata and chaotic terrains [1] commonly display layered sequences appearing to contain populations of buried impact craters [2,3]. We refer to these materials as the Noachian Basal Layered Unit (NBLU), which resides stratigraphically at the base of the Hesperian and above the Noachian or pre-Noachian basement. The NBLU, in places several kilometers thick, is interpreted to consist of intercalated sedimentary rocks, impact breccia, volcanic rocks, and in some regions, volatile condensation deposits. The NBLU was produced during an early period in Martian history characterized by elevated erosional/depositional rates and frequent impacts [3-5]. Destabilized zones of the NBLU are thought to have led to subsidence, collapse and outflow activity in eastern circum Chryse and fretted canyon development in northern Arabia Terra. Elsewhere, stable remnants may exist still today [6].

This model explains the extreme volatile enrichment of the NBLU [7]. The uniqueness of this stratigraphic unit and the prevailing conditions during its formation are best explained in the context of cataclysmic bombardment [8]. Variations in regional geothermal gradient may have led to complex upper crustal chemical zonation and heterogeneous regional resurfacing by mechanical and chemical weathering, clastic and chemical deposition, and volatile sublimation processes.

2. Evidence for volatile enrichment within the NBLU

Rodriguez et al [6] propose that the Noachian highland plateau situated north of the Aureum Chaos, east of the Hydraotes chaos, and south of the Hydaspis chaos forms part of the NBLU. This region shows evidence for extensive crustal subsidence and collapse that has been attributed to the partial loss of massive deposits of subsurface volatiles and entrained debris [6]. Enhanced and preferential surface subsidence and collapse over and nearby shallow buried impact craters indicates that buried impact craters represent volatile enriched zones within the cryosphere and that the loss of subsurface volatiles utilized their tectonic fabrics [3]. The northern margin of Arabia Terra also seems to be volatile enriched. Fretted canyons, lineated valley fill, and lobate debris aprons are interpreted as due to ductile failure and creep of the crust itself in response to crustal heating [7]; this creep is similar to but distinct from Earth-style climate-driven glacial flow.

3. NBLU volatile integration and time of formation

Key issues that we seek to explain include: (1) How did the NBLU become highly enriched in volatiles? (2) When did the NBLU form? We present a geologic scenario that involves the two following stages:

A. Pre-cataclysm phase: This stage consisted of several subphases, the record of which appears to be largely lost but can be deduced in broad outlines: (A1) Primordial outgassing attending accretion and core-mantle-crust differentiation. (A2) A poorly defined period of several hundred million years characterized by high heat flow, igneous activity, tectonism (possible plate tectonics), impacts, and perhaps fluvial, lacustrine, glacial, permafrost, and eolian processes [9]. Resurfacing during this period eroded and altered the original crystalline basement, and resultant deposits may form the deep crust beneath the NBLU.

B. Impact cataclysm phase (3.8-3.9 Ga) [7]. The following general subphases occurred. (B1) Giant basin-forming impact phase (Hellas, Argyre, Chryse, Utopia, Isidis, etc.): each major impact and myriads of lesser ones evaporated crustal volatiles (including H_2O, CO_2, SO_2, Na, Cl, P) into a transient hot atmosphere. Related intra-basin basaltic volcanism may have also added greenhouse gases to the atmosphere [9]. (B2) Volatile deluge phase: a relatively rapid condensation sequence caused by transient atmospheric collapse following individual giant basin-forming impacts and/or major volcanic outbursts. This stage caused rapid erosion and deposition [4-5] and volatile saturation of the surficial porous materials, especially in crater lake basins. It is uncertain whether the deluge was a single catastrophic, brief event for each large impact, or whether a longer period (perhaps millennia) of intense hydrologic cycling occurred; heavy erosion seems to favor the latter. Rapid atmospheric cooling attended atmospheric collapse. (B3) Possible intra-cataclysmic episodes of climate that was cooling but warmer than at present. A global hydrologic cycle and related erosional and sedimentary processes occurred, prone to modulation by annual and obliquity cycles, before complete dissipation of the transient atmosphere between major impacts. (B4) Possible cryogenic phase: completion of atmospheric collapse and solidification of liquid volatiles during transition to cold conditions [11] before the next major impact or volcanic outburst. (B5) Burial phase: repetition of stages B1-B4 caused burial where impact ejecta, eolian, alluvial, debris flow, lacustrine, and volcanic deposits accumulated within ancient paleobasins that may have sourced from surrounding topographically higher regions, such as paleo-orogenic complexes, plateaus, rims of craters or basins, and volcanic edifices [6]. Burial led to partial thawing at depth, including eutectic and peritectic melting and recrystallization of salt and ice assemblages and dissociation of clathrates. Polar condensation, glaciation, and burial of ice sheets added to the richness of crustal volatile heterogeneity in the NBLU.

4. NLBU preservation and disturbances

NBLU would have included a chemically and lithologically heterogeneous sequence. Subsequent Martian geology and climate history, according to this model, is substantially the story of how the NBLU has been disturbed by changes in pressure and/or bottom→up and top→down heating [7,10]. The degree of terrain disruption by heat flow can be categorized according the types of geothermal gradients as deduced from geologic mapping [e.g., 1]. Zones of low geothermal gradient: complete preservation of NBLU (e.g., parts of Noachis Terra). Zones of moderate geothermal gradient: thermokarst development, crustal subsidence, incipient chaos development, fretted canyon formation and crustal creep (e.g., Arabia Terra). Zones of high geothermal gradient: chaotic terrain and outflow channels (e.g., circum-Chryse channels and chaos), and in some region, volcano-permafrost interaction [10].

5. Compositional volatile fractionation within NLBU

Several phases and subphases involve thermal evolution of the NBLU such that key freezing and melting transitions are crossed. We know from recent spacecraft exploration that the Martian upper crust in some regions is heavily impregnated by ice and salts (especially sulfate hydrates, such as jarosite, kieserite, hexahydrite, epsomite, and gypsum). These ices and volatile-rich minerals were incorporated as major crust-forming minerals in the NBLU. Aqueous chemistry that originally produced the salts of Mars may have occurred during the cataclysm, or the cataclysm may have merely reworked salts produced during the pre-Noachian hydrological regime. The salt hydrates, ice and other volatiles of the upper crust have not remained entirely stable everywhere. The destabilization of these materials explains much Martian geology during the post-cataclysms eras.

Remnants of NBLU should preserve evidence of intense remobilization and fractionation of volatiles and water-soluble substances. During the impact cataclysm, local hydrothermal systems established mainly by impact heating induced local transfer of brines; temperature gradients in the crust would have caused leaching and zone refining, fractional partial melting, and fractional crystallization in briny aquifers and in icy veins and dikes. Climatic excursions related to outgassing caused by major impact events would have caused transient conditions whereby evaporative and partially frozen lakes and evaporative pumping of soils would have fractionated salts. Crater-fill lake sediment sequences, impact ejecta, debris flows, intercrater plains, impact brecciated zones, and volcanic systems would have become sites for subsurface migration and freeze-induced fractionation of volatile ices, gases, and salts. Surficial freezing and drying of lakes and brine-saturated sediments and solid/liquid equilibria in the crust would have driven local fractionation. Local hydrothermal systems established at impact craters and volcanoes would have produced concentric zonations of salt and ice assemblages. Aqueous chemical differentiation would have produced secondary layering and discomformable ice and salt structures.

6. Testable predictions

Relatively undisturbed sections of the NBLU are predicted to contain, besides igneous rocks and impact breccias, intercalated sedimentary rock strata (and impact ejecta clasts of these) and lenses, layers, veins, nodules, and dikes of water ice, other molecular ices, clathrates, hydrated acids and salts, and organic compounds.

Exploratory validation of this model may be achievable among deposits associated with buried craters. The volatiles should exhibit a coherent nature, such as a physical structure of icy/salty veins and dikes consistent with operation of a hydrologic system; these networks of ices and salts should exhibit systematic changes in salt mineral hydration state and changes in composition attributable to freezing and/or evaporative sequences. In addition, if the crust has remained cold, potassic and rubidium bearing salts should be isotopically datable and should yield ages consistent with the cataclysm. Stable isotopes in ices and aqueous precipitates should indicate coherent isotopic fractionations, such as systematic changes with radial distance from craters.

7. References. [1] Rotto, S. and K.L. Tanaka, 1995, Geologic/Geomorphic map of the Chryse Planitia region, *USGS Misc. Inv. Ser. Map*, 1:5M. [3] Rodriguez et al., (2005) *J. Geophys. Res. 110,* E06003. [4] Howard, A. D., et al., 2005, *J. Geophys. Res. 110*, E12S14, doi:10.1029/2005JE02459. [5] Irwin, R.P., III, et al., 2005, *J. Geophys. Res.* 110, E12S15, doi:10.1029/2005JE002460. [6] Rodriguez, A.P. et al., (2005), *Icarus, 175*, 36-57. [7] Kargel, J.S., 2004, *Mars: A Warmer Wetter Planet*, Praxis Springer. [8] Strom, R.G. et al., 2005, *Science*, *309*, 1847. [9] Baker, V.R., et al., 2000, *Lunar Planet. Sci. XXXI*, Abstract # 1863. [10] Kargel, J.S. 2006, other abstract, this volume. [11] Clifford, S.M., 1993, *J. Geophys. Res.*, **98**, 10,973-11,016.