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Crater degradation in the Noachian highlands of Mars: Assessing the hypothesis of regional snow and ice deposits on a cold and icy early Mars

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ABSTRACT

The presence of valley networks and the highly degraded state of Noachian highland craters has led to the interpretation that Mars was once warmer and wetter. Recent climate models have suggested, however, that the extremely cold climate in the Noachian would be unlikely to support liquid water precipitation. The presence of a thicker atmosphere thermally coupled to the surface is predicted instead to concentrate surface snow and ice deposits in the higher-altitude southern highlands, producing a Late Noachian Icy Highlands (LNIH) characterized by hundreds of meters of relatively continuous ice cover. In this study we test this hypothesis by reevaluating the degradation state of Noachian highland craters to assess whether their degradation state might be attained in such a cold and icy climate. We review the characteristics of Amazonian-aged impact craters hypothesized to form in surface snow and ice layers (excess ejecta, EE; double-layered ejecta, DLE; and pedestal, Pd, craters) to provide the potential initial conditions of craters forming in Late Noachian surface snow and ice layers. We then examine modification processes active in the Amazonian that may have played a role in crater degradation in the Late Noachian. In addition, we examine the potential morphometric effects of impacting into a thick surface ice deposit, and the potential erosive effects of backwasting, top-down melting, basal ice melting, and atmospheric warming pulses on the morphology of Noachian highland craters. We find that several aspects of the highly degraded state of Noachian craters could be accounted for in the context of a cold and icy climate, and we outline further tests of the hypothesis.

1. Introduction

The presence of a faint young sun (Newman and Rood, 1977; Gough, 1981) has led to the supposition that early Mars was cold, with mean annual temperatures well below freezing (e.g., Kasting, 1991; Haberle et al., 1993; Carr and Head, 2003; Gaidos and Marion, 2003; von Paris et al., 2014). The presence of valley networks (Carr and Clow, 1981; Hynek et al., 2010), the degraded state of Noachian highland craters (Mangold et al., 2012), and the relationship of increasing surface age with elevation in Noachian terrains (Craddock and Maxwell, 1993; Irwin et al., 2013), however, has led previous investigators to suggest that the martian climate in the Noachian (> ~3.6 Ga; Hartmann, 2005; Werner and Tanaka, 2011) was warm and wet, and that liquid water precipitation (rainfall) and surface runoff is the most likely cause of fluvial activity and crater degradation (Craddock and Maxwell, 1993; Craddock et al., 1997; Hynek and Phillips, 2001; Craddock and Howard, 2002; Irwin et al., 2005a, b; Howard et al., 2005; Hoke and Hynek, 2009; Hynek et al., 2010; Hoke et al., 2011), although snow precipitation and subsequent melting has not been ruled out (Howard et al., 2005).

Recent climate models, however, have shown that climatic conditions in the Late Noachian (~3.6 to 3.8 Ga; Hartmann, 2005; Werner and Tanaka, 2011) may not have been able to support liquid water precipitation (Wordsworth et al., 2013), and that regional snow and ice deposits, much like those inferred to be present at various latitudes in the Amazonian (Head et al., 2003, 2005, 2006a, b, 2010), could have been pervasive in the Late Noachian southern highlands (Head and Marchant, 2014; Fastook and Head, 2015). The models show that even a slight increase in atmospheric pressure enables the martian atmosphere to thermally couple to the surface (Forget et al., 2013; Wordsworth et al., 2013; Scanlon et al., 2013), a scenario in which the Noachian highlands acts as a cold trap and preferentially accumulates atmospheric snow and ice deposits (Fastook et al., 2012; Head and Marchant, 2014). This set of cold and icy conditions is known as the Late Noachian Icy Highlands (LNIH) scenario (Wordsworth

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et al., 2013; Head, 2013). Concentrating the current Amazonian ice supply from the polar caps above an equilibrium line altitude (ELA) of 1 km, is volumetrically equivalent to a thickness of ~280 m of ice concentrated in the southern highlands (Head and Marchant, 2014; Fastook and Head, 2015), although this estimate may be significantly underestimated based on the unknown quantity of water lost from Mars since the late Noachian (Jakosky et al., 1994; Kass and Yung, 1999; Hodges, 2002; Greenwood et al., 2008; Andrews-Hanna and Lewis, 2011; Carr and Head, 2014).

Wordsworth et al. (2015) further conducted a variety of 3D global climate models of both warm/wet and cold/icy scenarios. In order to produce warm/wet conditions, they artificially increased the solar flux. In this case, Wordsworth et al. (2015) found poor correlation between the zones predicted to exhibit liquid water precipitation and those which host the valley networks (e.g., Hynek et al., 2010). In contrast, the models which assumed nominal cold Late Noachian conditions (mean annual temperature of 225.5 K) showed that the regions with high valley network densities correlated much better with zones predicted to accumulate snow (Wordsworth et al., 2015). Thus, the LNIH model appears robust enough to be further tested.

In this paper, we examine modes of crater modification expected in the LNIH scenario for comparison with the observed degraded morphology of Noachian highland craters. Our aim is not to prove or disprove conclusively whether the LNIH early Mars climate model is correct or not; rather, we provide observational tests of the climate model of Wordsworth et al. (2013) using one geologic line of evidence, the morphology and degradation state of Noachian highland craters, noting that future work is required to test whether other features of the Late Noachian are consistent with such a model. We first outline and document the set of morphologic features and morphometric associations that characterize impact craters formed in the Noachian highlands (Section 2). Next, we look to the nature of impact craters formed in snow and ice in the later, Amazonian period of the history of Mars as a guide to candidate formation and degradation processes that might have operated in a LNIH climate scenario (Section 3). We then use these characteristics and guidelines to assess candidate processes that might have operated during both crater formation and later modification of Noachian craters (Sections 4–6). Finally, we examine these candidate characteristics and processes to assess whether they can successfully explain the characteristics of Noachian highland craters (Section 7). We find that several aspects of Late Noachian crater degradation states, commonly thought to be explained by "warm and wet" climatic conditions, are also consistent with formation and modification in the context of Late Noachian icy highland climate conditions. We conclude with suggestions for further tests and investigations.

2. Characteristics and degradation state of Noachian craters

Martian Noachian highland craters differ markedly from fresh martian craters (Table 1; Fig. 1 through 4) in that they are highly degraded (Craddock and Maxwell, 1990, 1993; Craddock et al., 1997; Craddock and Howard, 2002; Forsberg-Taylor et al., 2004; Mangold et al., 2012). Noachian highland craters exhibit subdued crater rims when compared with fresh craters (Craddock and Maxwell, 1993; Craddock et al., 1997; Craddock and Howard, 2002). Craddock et al. (1997) compared the morphometry of fresh and degraded crater rim heights and found that the least squares fit for rim heights of degraded craters was systematically lower than fresh craters by factors of ~3 to ~10, and that many degraded craters lacked any observable rim topography. These results highlight the importance of either significant and pervasive

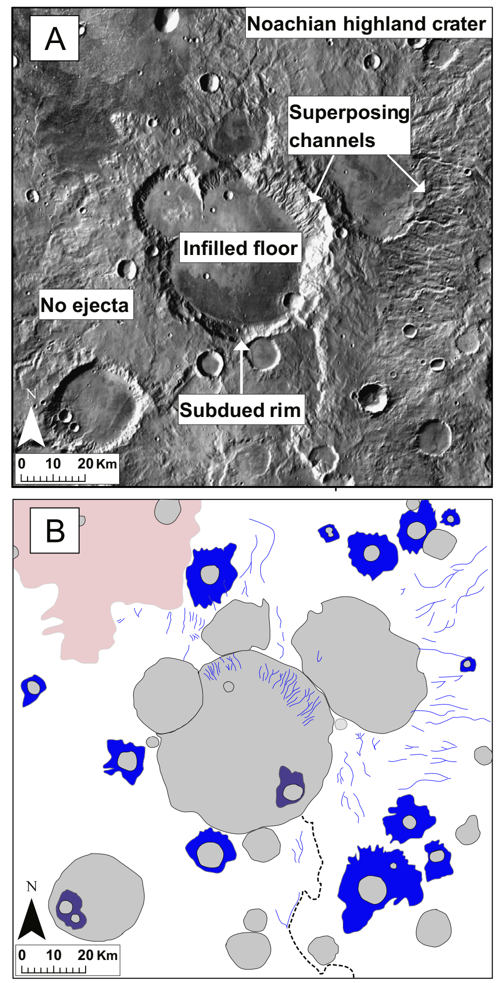

Fig. 1. Map views illustrating typical degraded Noachian highland crater characteristics. (A) Map view of a 55 km diameter Noachian highland crater and characteristics (149°E, 36°S, THEMIS daytime mosaic). (B) Sketch map of (A) (Key: craters (gray), ejecta (blue), fluvial channels (blue lines), and plateau contact (dashed black line), low-lying region (red)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Characteristics of Noachian highland craters.

Morphological characteristics of Noachian highland craters	Reference
Subdued rims	Craddock and Maxwell (1993), Craddock et al. (1997), Craddock and Howard (2002)
Shallow, flat floors	Craddock and Maxwell (1993), Craddock et al. (1997), Craddock and Howard (2002)
Superposing channels on crater wall interior and within 2*R* from the rim	Masursky et al. (1977), Craddock and Maxwell (1993), Craddock et al. (1997), Craddock and Howard (2002), Mangold et al. (2012)
Absence of ejecta deposits and secondary craters	Craddock and Maxwell (1993), Craddock et al. (1997), Craddock and Howard (2002), Mangold et al. (2012)
Paucity of small craters (< ~10 to 20 km diameter)	McGill and Wise (1972), Jones (1974), Craddock and Maxwell (1990)