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Topography of the Deuteronilus contact on Mars: Evidence for an ancient water/mud ocean and long-wavelength topographic readjustments

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ABSTRACT

In this paper, we present the results of our detailed study of morphology, topography, and age of the Deuteronilus contact that outlines Vastitas Borealis Formation (VBF) in the northern plains and the Isidis Planitia unit. The Deuteronilus contact represents a sharp and distinct geological boundary that can be traced continuously for many hundreds to thousands of kilometers. In the northern plains, segments of the Deuteronilus contact occur at two distinct topographic levels. In the northern plains, the long-wavelength topography of the Deuteronilus contact occur at two distinct topographic levels. In the Tempe, Chryse, Acidalia, and Cydonia-Deuteronilus regions (the total length is ~14,000 km), the contact is at the mean elevation of about −3.92 km (the decile range is 180 m, from −4.01 km to −3.83 km). In the Pyramus-Astapus, Utopia, and Western Elysium regions (the total length is ~7700 km), the mean elevation of the contact is about −3.58 km (the decile range is 270 m, from −3.73 km to −3.46 km). These levels to large extent (but not completely) correspond to the model geoids that may have been characterized the shape of Mars at the time of the VBF emplacement. Largest deviations of the actual topographic position of the contact from the model geoids occur in the Tantalus and Phlegra regions where the deviations are due to the post-VBF changes of the regional topography. The fact that the model geoids satisfactory describe the shape of the largest portion of the contact provides additional evidence for both the emplacement of the VBF edges near an equipotential surface and for relative stability of the shape of Mars during a long time interval of about 3.6 Ga. Within the northern plains in the Tempe Terra, Acidalia Planitia, Cydonia-Deuteronilus, Pyramus-Astapus, and the southern Utopia regions, the absolute model ages of the VBF surface near the Deuteronilus contact are tightly clustered around the age of ~3.6 Ga, which we interpret as the age of the VBF emplacement. The surface of the VBF-like Isidis Planitia unit is distinctly younger, ~3.50 ± 0.01 Ga, which suggests that this unit formed independently. Neither volcanic nor glacial modes of emplacement are consistent with the topographic configuration and the shape of the Deuteronilus contact within both the northern plains and in Isidis Planitia. The broad flooding and formation of extensive water/mud reservoirs remains to be the most plausible mode of formation of the VBF in the northern plains and the VBF-like unit on the floor of the Isidis basin.

1. Introduction

The hypothesis of the existence of a large water reservoir (an ocean) within the northern lowlands of the planet is one of the most intriguing open questions of the Martian geology (e.g., Parker et al., 1989, 1993, 2010; Head et al., 1998, 1999; Clifford and Parker, 2001; Carr and Head, 2003; Tanaka et al., 2003, 2005). If it existed, the ocean-sized body of water thousands of kilometers wide may have seriously influenced the climate/atmospheric conditions on Mars (e.g., Baker et al., 1991; Villanueva et al., 2015) and leaved recognizable evidence of its presence in the geological record of the planet (Parker et al., 1989, 1993; Malin and Edgett, 1999; Boyce et al., 2005; Rodriguez et al., 2016).

The Vastitas Borealis Formation (VBF) is among the most widespread units on Mars that covers the majority of the northern plains (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987). Although the VBF shows a range of morphologies, they are so different from the surrounding terrains that collectively define a single unit (e.g., Tanaka et al., 2005). The dimensions of the VBF occurrence (~4500 × 6500 km) and its relative morphological homogeneity suggest that this unit is the best candidate to represent remnants of the former ocean (Parker et al., 1989, 1993, 2010; Head et al., 1999; Kreslavsky and Head, 2002; Carr and Head, 2003).

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The characteristic features of the VBF surface are consistent with the interpretation of this unit as a residue of a standing body of water/ice. These features include thumbprint terrains (e.g., Carr and Schaber, 1977; Lucchitta, 1981; Grizzaffi and Schultz, 1989; Hiesinger et al., 2009), giant polygons (e.g., Lucchitta, 1981; McGill and Hills, 1992; Hiesinger and Head, 2000), and assemblages of low sinuous/curvilinear ridges that resemble moraines and eskers (e.g., Kargel et al., 1995). Impact craters with rampart- and pancake-like ejecta and low depth/diameter ratio (Mouginis-Mark, 1979, 1987; Barlow et al., 2000; Boyce et al., 2005; Komatsu et al., 2007) strongly suggest that the target materials of the VBF were rich in volatiles. The progressive changes from craters with rampart ejecta near the edges of the VBF to the pancake-like ejecta toward the VBF interiors suggests increasing amounts of volatiles in the target materials (Ivanov et al., 2014, 2015). The pitted cones in Acidalia and Chryse Planitiae that are interpreted as possible mud volcanoes (Farrand et al., 2005; Oehler and Allen, 2010; Komatsu et al., 2012) and mudflows in Acidalia and Utopia Planitiae (Ivanov et al., 2014, 2015) provide additional evidence for the possible water-related nature (including the ocean hypothesis) of the VBF. Heavily degraded/buried (ghost) craters (Carr, 1981; McGill, 1986; Head et al., 2002) occur within the northern plains in Utopia and Acidalia Planitiae. The morphology and topographic characteristics of these features have been interpreted as evidence of compaction of possibly sedimentary materials of the VBF against the rims of buried craters (e.g., Buczkowski and McGill, 2002; Buczkowski and Cooke, 2004; Buczkowski et al., 2012).

Although most researchers agree upon the water-related nature of the VBF, the proposed modes of its emplacement vary. The VBF may represent sediments either eroded from the uplands, or carried out from the outflow channels, or both (e.g., Jöns, 1985; Tanaka et al., 2001, 2005), or the VBF materials may have been deposited from the single standing body of water (e.g., Parker et al., 1989, 1993, 2010; Kreslavsky and Head, 2002).

In spite of the growing body of evidence supporting the ocean-related nature of the VBF, inspection of MOC high-resolution images showed little evidence in support for the coastal landforms (Malin and Edgett, 1999, 2001; Ghatan and Zimbelman, 2006) along the boundaries interpreted by Parker et al. (1989, 1993) as possible shorelines of the putative ocean. The existence of specific coastal landforms, however, would require wave action, which is less likely under the present climatic conditions (Ghatan and Zimbelman, 2006). However, the amount of the sedimentary load, the environmental conditions (the lack, partial, or complete coverage by ice), and lifetime of the ocean are poorly known, all resulting in large uncertainties of the expected morphologic characteristics of the landforms related to the potential coastal processes. For example, large standing bodies of water may have been almost immediately covered by ice if a cold climate dominated the Hesperian (Kreslavsky and Head, 2002). The freezing would prevent the wave-cut and the other types of erosional activity along the shorelines. Instead, the depositional processes may have been dominated during evolution of water bodies and the lobes of VBF, which are likely related to deposition of material, may represent coastal landforms on Mars (Erkeling et al., 2014).

One of the most important and testable predictions of the ocean hypothesis is the topographic position of its possible shoreline that must occur at a single topographic level of the paleo-equipotential surface (Head et al., 1998, 1999). If the VBF represents remnants of the ocean and its boundary corresponds to the ocean shoreline, this boundary should follow approximately the same contour line around the northern lowlands. In the papers by Head et al. (1998, 1999) were presented the first results of investigation of the topographic configuration of the Deuteronilus contact. Results of these studies were based on a limited number of MOLA orbits that crossed the Deuteronilus contact, 11 and 1191, respectively (Head et al., 1998, 1999). Thus, the knowledge of the Martian topography at that time was insufficient to adequately reconstruct topography of a long geologic boundary such as the Deuteronilus contact.

The Deuteronilus contact (Parker et al., 1989, 1993; Clifford and Parker, 2001) is the most extensive and traceable boundary of the VBF with the surrounding terrains. It was mapped in many regions of the northern plains and proposed to be one of the shorelines of the putative ocean (Parker et al., 1993, 2010; Clifford and Parker, 2001). The contact can be traced continuously for many hundreds to a few thousands of kilometers (Fig. 3). In the northern plains, the contact is prominent from ~264°E eastward to ~132°E and between 170 and 184°E where the younger units do not overlay the VBF (Tanaka et al., 2005). In Isidis Planitia, the contact is prominent everywhere along the edges of the basin floor except for the transition to the Syrtis Major volcanic plateau (Erkeling et al., 2012, 2014; Ivanov et al., 2012).

What is the topographic configuration of the Deuteronilus contact? Does the contact occur at the same topographic level or show multiple levels? Do the local short-wavelength (tens of kilometers) topographic features control configuration of the contact? What are the long-wavelength (hundreds of kilometers) characteristics of the contact and what regional-scale features they may correspond to? Do the absolute model age estimates of the VBF surface cluster around some specific value or do they show broad variations?

These questions are of key importance in testing the hypothesis of the ocean in the northern lowlands of Mars. In our study, we address them by detailed mapping of the position of the Deuteronilus contact within the northern plains and in Isidis Planitia using the latest data provided by Thermal Emission Imaging System, THEMIS (Christensen et al., 2004), gapless THEMIS-IR day-and nighttime mosaics (USGS version 12.0, spatial resolution is 100 m/px). In places where the location of the contact was unclear, we used contiguous mosaics of high-resolution images provided by Context Camera, CTX, spatial resolution is ~6 m/px, (Malin et al., 2007). To assess the topographic variations along the mapped segments of the Deuteronilus contact, we used Mars Orbiter Laser Altimeter, MOLA (Smith et al., 2001), gridded topographic data (spatial resolution is 128 px/degree) and individual MOLA profiles.

In our study, we pursued the following goals. (1) To trace and map the Deuteronilus contact as precisely and continuously as possible. (2) To assess the types of relationships of the VBF with the surrounding terrains. (3) To estimate the absolute model ages of the surface of the VBF near the contact in different regions. (4) To construct topographic profiles along the mapped segments of the boundary and reconstruct the topographic profile for the entire Deuteronilus contact both in the northern plains and in Isidis Planitia. The results of our study allow addressing the problem of the topographic configuration of the edges of the VBF and the relative and absolute model ages of the VBF and its marginal portions. In particular, the location and amplitude of the long-wavelength topographic variations of the Deuteronilus contact (Head et al., 1998, 1999; Carr and Head, 2003) are important. Do these variations contradict the hypothesis that the contact represent a shoreline? Do they correspond to a configuration of the ancient geoid (Perron et al., 2007)? Do they reflect the long-wavelength topographic readjustment after removal of a load of large masses of ice in the northern plains? What are the absolute model age estimates throughout the VBF? Are they clustering near some specific age or do they show a wide range of ages? These results are crucial parameters in testing the models of the mode of emplacement of the VBF and, thus, in addressing the problem of the northern ancient ocean on Mars.

2. Definition of the Deuteronilus contact, data, and methods

The Deuteronilus contact (Clifford and Parker, 2001) represents one of the most extensive geological boundaries on Mars that usually consists of broad (a few tens of kilometers wide) lobes (Fig. 1) oriented toward the cratered uplands (Parker et al., 1989, 1993). In many areas of the northern plains, the Deuteronilus contact corresponds to the southern edges of the Vastitas Borealis Formation (VBF), as it was mapped on the basis of either Viking images (Scott and Tanaka, 1986; Tanaka and Scott, 1987; Greeley and Guest, 1987), or the MOLA gridded topography (Head