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Hydrodynamics of impact-induced tsunami over the Martian ocean

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ABSTRACT

Large bodies of liquid water ranging from lakes to oceans have been hypothesized to have occupied the surface of ancient Mars episodically. Such inferences have been founded largely on geomorphological observations of putative shoreline features during the period ranging from the 1980s to the early 2000s. High-resolution satellite images obtained during various Mars missions conducted since the early 2000s have enabled detailed sedimentological studies. One phenomenon that might leave sedimentological traces of the purported Martian paleo-oceans is a bolide impact and consequent generation of large tsunami waves. Numerical modeling of impact-induced tsunami waves on a hypothesized northern plains paleo-ocean was performed to elucidate their potential propagation characteristics on Mars, including the ranges of wave height and velocity. When considering a tsunami triggered by a 50 km-diameter impact cratering event, the offshore and shore-zone wave heights respectively reached 40–50 m and 120 m. In the same test scenario, the tsunami wave velocity reached 20 m/s near the crater and 16 m/s at the shore zone. The wave height and velocity in highly cratered regions, such as Arabia Terra, tend to be relatively low because tsunami inundation is diffused by impact crater rims existing along the tsunami passage.

1. Introduction

Mars is a dry and cold planet, but it has been argued that Mars was covered by large bodies of liquid water up to the size of an ocean once or multiple times (Lucchitta et al., 1986; Parker et al., 1989, 1993; Baker et al., 1991, 2000; Head et al., 1999; Clifford and Parker, 2001; Fairén et al., 2003; Dohm et al., 2009; Di Achille and Hynek, 2009; Parker et al., 2010). If the ocean indeed existed, it might mean that a wet and possibly warm climate prevailed on Mars. Subsequently, it changed to today's more desert-like climate (Clifford and Parker, 2001). The state of water on Mars, including whether it represents large bodies of water, also has a fundamental relevance to the question of life on Mars (Grotzinger, 2009). However, the existence of paleo-ocean has been a highly speculative and controversial topic because of the lack of convincing geomorphological or sedimentological traces of such an ocean (Section 2).

Tsunami waves induced by a bolide impact into an ocean would have strongly affected shorelines and sea floors. The resulting traces of such tsunamis might be useful for assessing the Mars paleo-ocean hypothesis (Section 2). Paleo-crater lakes on Mars, of which the existence is advocated based on various geological observations (e.g., Cabrol and Grin, 1999; Komatsu et al., 2009), might also have been affected by an impact and consequent tsunami, although they are not addressed in this paper.

Studies of the effects of bolide impacts into Martian oceans, however, have been scarce (Matsui et al., 2001; Dohm et al., 2009; Mahaney et al., 2010). Particularly, numerical modeling for understanding the propagation of an impact-induced tsunami on Mars has been conducted only by Matsui et al. (2001). In this work, discussion of the characteristics of tsunami waves and topographic control effects on tsunami propagation are limited to a few cases. Numerical modeling of a hypothetical impact-induced tsunami over the topography of the northern plains was performed to assess the possible extent of wave propagation and inundation. Results provide valuable information that is expected to facilitate the future search for possible Martian tsunami evidence.

2. Mars paleo-ocean hypothesis, and bolide impact into the ocean

Whether liquid water existed on Mars in the form of oceans has been debated for at least the past 30 years. In the late 1980s, the existence of a paleo-ocean was hypothesized from a geomorphological perspective using satellite images acquired by the Viking orbiters (Lucchitta et al., 1986; Parker et al., 1989, 1993).

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Parker et al. (1989) emphasized the study of a series of geomorphological features extending continuously between the northern lowlands and southern highlands, suggesting that they represent paleo-shorelines. Parker et al. (1993) identified seven geomorphological shoreline features, two paleo-shoreline candidates of which they traced along the entire dichotomy boundary, naming them Contact 1 and Contact 2. Differences in albedo and the presence of pingo-like- or tombolo-like features occurring around the shorelines were regarded as strong support for their interpretation (Parker et al., 1993), although these features might have resulted from other processes (eolian mantles, periglacial landforms, etc.). Scott et al. (1995) did not observe evidence for paleo-oceans, but they revealed various evidence pointing to possible paleo-lakes in the northern plains, as shown in a USGS map, which they interpreted as indicating either late-stage pondings or a diminished ocean. The "shorelines" mapped by Parker et al. (1993) were also interpreted as landforms generated without the existence of an ocean, such as in the case of an outward-directed emplacement of a viscous flow (Tanaka et al., 1997).

From the late 1990s to the early 2000s, high-resolution satellite images (meter to tens of meters/pixel) of Mars Orbiter Camera (MOC) and Thermal Emission Mars Image System (THEMIS), as well as Mars Orbiter Laser Altimeter (MOLA) topographic data were acquired. From MOC images, Malin and Edgett (1999) observed localities interpreted by Parker et al. (1989) to be a shoreline, concluding that the shoreline-like geomorphology in reality does not resemble true shorelines when observed with higher-resolution satellite images. Head et al. (1998, 1999) examined MOLA topographic data of Contact 1 and Contact 2. If Contact 1 and 2 features were indeed paleo-shorelines, then their elevations should be equipotential, assuming little post-ocean tectonic influence. According to them, although the elevation of Contact 1 has large variation and is difficult to interpret as a shoreline, Contact 2 is approximately equipotential, except for some regions affected by volcanic activity (i.e., Tharsis). They concluded that Contact 2 is indeed a paleo-shoreline.

In the 2000s, element-distribution data of the surface of Mars were acquired by the Gamma Ray Spectrometer (GRS) onboard Mars Odyssey. The distributions of elements such as K, Th, and Fe determined from the GRS data were interpreted as marking paleo-hydrologic activity including the existence of a paleo-ocean (Dohm et al., 2009). The distributions of these elements were concentrated on the northern plains with respect to the southern highlands. This situation might be explained if an ocean has existed, and these elements, dissolvable in liquid water, especially if acidic, had been transported from the southern highlands to northern lowlands. More recently, very high-resolution images (6 m/pixel and 25 cm/pixel respectively) have been acquired through the Context Camera (CTX) and the High Resolution Imaging Science Experiment (HiRISE) instrumentation onboard the Mars Reconnaissance Orbiter. They have enabled observations of the Martian surface at much greater detail than was previously possible. Di Achille and Hynek (2010) surveyed the spatial and topographic distributions of features interpreted as deltas using MOLA and CTX data. Both clustered along the purported paleo-shoreline (Contact 1), thereby corroborating the existence of a paleo-ocean.

Because of the high-resolution capacities of CTX and HiRISE, studies of a sedimentological nature, including detailed analysis of stratigraphy and large boulders, have become possible for Mars. McEwen et al. (2007) conducted a meter-scale boulder observation using HiRISE of the Vastitas Borealis Formation (VBF), which is widely distributed in the northern plains. VBF has been regarded as sediment deposited at the bottom of a sea composed of homogeneous sand (Kreslavsky and Head, 2002) or debris-flows deposit (Tanaka et al., 2001). HiRISE-based analysis has rebealed many meter-scale boulders scattered about the surface of the VBF, with no clear evidence of a sandy deposit. Therefore, McEwen et al. (2007) concluded that the VBF materials were not deposited at the bottom of sea, and that an ocean had never existed. However, also using CTX and HiRISE images, which cover parts of the proposed shorelines, Parker et al. (2010) reported evidence that supported the original interpretations of Parker et al. (1989). According to them, there are geomorphological features similar to those associated with terrestrial lakes, such as terraces (Fig. 1).

Some researchers argue that a terrestrial-analog approach for identifying shoreline features has limits (e.g., Ghatan and Zimbelman, 2006). The physical characteristics of a Martian paleo-ocean and its shorelines might differ from those of oceans on Earth because of several factors such as a lack of tidal activity (Dohm et al., 2009). Many researchers are therefore cautious about arguing the existence of paleo-oceans deduced solely from geomorphological features (Malin and Edgett, 1999). Additional problems in interpreting shoreline features are that the ocean might have been frozen. For that reason, the shorelines might not have been etched by wave action (Ghatan and Zimbelman, 2006). Alternatively, the spatial distribution of the ocean might have been limited (Rodríguez et al., 2010).

In the context of problems in interpreting shoreline features, finding evidence of other types for paleo-oceans based on cataclysmic processes has never been explored. It is therefore certainly worth investigation. A bolide impact into a Martian paleo-ocean is a candidate for the creation of such phenomena, which could induce large tsunami waves and thereby leave geomorphological landforms and/or sedimentological disturbances on the sea floor and shorelines (Matsui et al., 2001; Dohm et al., 2009; Mahaney et al., 2010). Even one impact might be sufficiently large to influence an ocean at a global scale (Dohm et al., 2009).

Ormö et al. (2004) estimated the possible number of bolide impacts into a Martian ocean during its estimated duration. The duration of the ocean is estimated as a range from 0.1 to 800 Myr. The minimum value was derived from the MEGAOUTFLO hypothesis (Baker et al., 1991, 2000), which assumes a Tharsis-driven flood inundation of the northern hemisphere and its consequent formation of a paleo-ocean. The maximum value was estimated from the model proposed by Fairén et al. (2003), similar to that of Baker et al. (2000) but with multiple flood episodes caused by episodic Tharsis-driven activity. According to Fairén et al. (2003), flood inundations occurred in the Noachian, Hesperian, and possibly the Amazonian based on a geologic mapping investigation.

The number of marine target craters was estimated as between 0–160 in the case of Contact 1, and as 1–1400 in the case of Contact 2 (Ormö et al., 2004). However, these numbers assume impactors that are sufficiently large to leave craters on the sea floor. Impactorswith diameter greater than 600 m were assumed

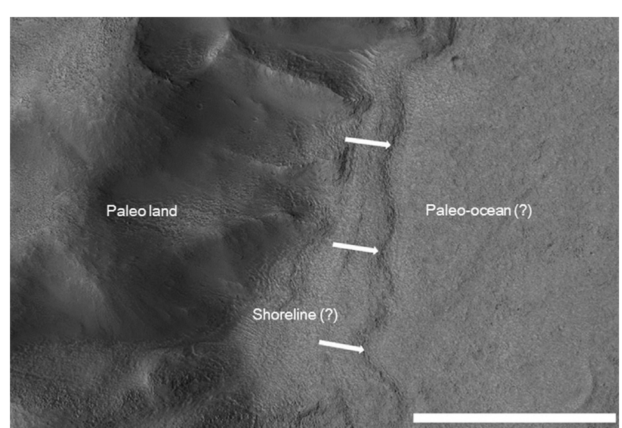

Fig. 1. Proposed shoreline on Mars (modified from Parker et al., 2010, Image: NASA/JPL/University of Arizona: PSP_009998_2165).