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Winds, waves and shorelines from ancient martian seas

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ABSTRACT

We consider under what environmental conditions water waves (and thus eventually shorelines) should be expected to be produced on hypothetical ancient martian seas and lakes. For winds and atmospheric pressures that are too small, no waves should be expected, and thus no shorelines. If the winds and atmospheric pressure are above some threshold, then waves can be formed, and shorelines are possible. We establish these criteria separating conditions under which waves will or will not form on an ancient martian open body of water. We consider not only atmospheric pressure and wind, but also temperature and salinity, but find these latter effects to be secondary. The normal criterion for the onset of water waves under terrestrial conditions is extended to recognize the greater atmospheric viscous boundary layer depth for low atmospheric pressures. We used terrestrial wave models to predict the wave environment expected for reasonable ranges of atmospheric pressure and wind for end-member cases of ocean salinity. These models were modified only to reflect the different fluids considered at Mars, the different martian surface gravity, and the varying atmospheric pressure, wind and fetch. The models were favorably validated against one another, and also against experiments conducted in a wave tank in a pressure controlled wind tunnel (NASA Ames MARSWIT). We conclude that if wave-cut shorelines can be confirmed on Mars, this can constrain the range of possible atmospheric pressures and wind speeds that could have existed when the open water was present on Mars.

1. Introduction

Mariner 9 images first showed geomorphological evidence that water has shaped the martian surface in prominent outflow channels and valley networks, but the final fate of this water has been debated ever since, and is still unresolved. There has been analysis, discussion, and speculation that water responsible for carving channels eventually accumulated, perhaps repeatedly, in relatively large bodies of open or ice-covered water (ponds, lakes, oceans) early in martian geologic history. However, the evidence for standing bodies of water on Mars, whether open or ice-covered, has been circumstantial and controversial. Ocean shoreline morphologies proposed from analysis of Viking Orbiter data were evaluated later with higher resolution Mars Global Surveyor (MGS) imaging and altimetry data, with equivocal results. Smaller bodies of water, especially within large, older impact craters, have also been proposed. The Curiosity Mars Rover was sent to Gale crater, just such an environment, to better understand the geologic history of water on Mars. Not long after landing, it discovered unambiguous evidence of sediments created by flowing surface water (Williams et al., 2013). Determining the fate of flowing water is central to understanding how much water existed, and how long it remained at the surface, with direct implications for the possibility of life developing on the planet. One of the key components of the debate concerning whether water accumulated in standing bodies has been whether ancient shoreline erosion features are still evident. Something that so far has been unrecognized in the debate over these features (or the significance of their absence, in places where other geomorphological evidence is suggestive of standing water) is the following question: Is the expectation of shoreline erosional features a physically reasonable concept?

Terrestrial seas modify their shorelines through the action of wind-driven water waves, as well as tides, tsunamis and the effects of thermal expansion or wind traction on ice sheets. All of these phenomena except tides (because Mars lacks a large moon like Earth's Moon) could also occur on ancient martian seas, creating shorelines. A careful examination of each of these may allow limits to be placed on the ancient martian environmental conditions if evidence of their action can be definitively identified. If no shorelines are ever found, an examination of the ability of various size

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shorelines to persist to the present may still allow us to establish limits of the environmental conditions that existed on ancient Mars. The full scope of what can be learned from the current presence or absence of ancient shorelines on Mars is beyond the scope of this work. The magnitude of tsunami waves on ancient Mars was examined by Iijima et al. (2014). Here, we ask under what conditions could wind-driven open-water waves have formed on ancient Mars, leaving the other aspects of the problem to later work.

Evaluating the physics of wind waves in a low-pressure atmosphere affecting a water surface is not a simple exercise of extrapolation from terrestrial experience to very different martian conditions of lower gravity and significantly lower atmospheric pressure. Clearly, reducing the surface pressure to very low values will reduce the capability of the atmosphere to generate waves on a liquid water surface. The pressure at which these atmospheric stresses become insignificant is not yet well understood, but is certainly amenable to investigation. Today, Mars' atmospheric pressure is small (about 0.5% of Earth sea level pressure), but its value in the past is not well constrained. Using models of water waves, we explore the wave conditions that would have occurred on the downwind shores of ancient martian seas subjected to carbon dioxide atmospheres with different surface winds and densities.

Wave formation is fundamental to understanding the potential of shoreline formation. This paper focuses on wave formation under possible conditions on ancient Mars. Section 2 begins by summarizing the present evidence for fossil shorelines on Mars. Section 3 describes wind-wave formation on Earth, the relevant physics of water waves, the two wave-growth models used in this study, and outlines the transition to theoretical martian conditions. Section 4 describes how we validated our generalized wave-growth models against wind-tunnel/wave-tank experimental data under conditions approaching those on Mars. In Section 5, we report the results of the model simulations for a wide range of assumed martian atmospheric and oceanic conditions. Finally, in Section 6, we summarize our results and their implications for constraining conditions on ancient Mars.

2. Background – Evidence for fossil shorelines

The notion that Mars once had flowing water on its surface is long-standing, and recent results have strengthened this viewpoint immensely. The earliest evidence to suggest this were the Mariner 9 images of outflow channels with streamlined islands within them and debris aprons at their ends. Using Viking images, Parker et al. (1989, 1993) identified several geomorphologically distinct levels in the northern lowlands, which they proposed were shorelines of an ancient sea. In addition to the proposed shoreline features, Parker et al. also noted that the debris deposits changed character near these same levels at the mouths of the channels, consistent with a change from sub-aerial to sub-aqueous deposition.

The Mars Orbiter Laser Altimeter (MOLA) instrument on MGS provided well-controlled geopotential heights of features on Mars' surface. Head et al. (1998, 1999) and Ivanov and Head (2001) examined Parker et al.'s shoreline features and found that one of their contacts ('contact 2') was at a nearly constant elevation, supporting the argument that it represents an ancient shoreline. They also noted that the circum-Chryse Channel termini all fall within 18 m vertically of one another. However, there were definite differences from an equipotential surface on contact 2, and Parker et al.'s other proposed shorelines were even farther from an equipotential surface. Some of these problems might be explained by tectonic changes since the sea disappeared, isostatic changes from volcanic loading (e.g., Head et al., 1998), the removal of the water itself (Leverington and Ghent, 2004) or true polar wander (Perron et al., 2007).

Malin and Edgett (1999) used MGS Mars Orbiter Camera (MOC) images to examine Parker et al.'s proposed shorelines at higher resolution than was possible with Viking images. They found no evidence to support the hypothesis that ancient shorelines had been preserved, but recognized that identifying shorelines from orbit may be difficult. Carr and Head (2003) synthesized much of the preceding work and concluded that the evidence for Parker et al.'s proposed shorelines was small, but that other lines of evidence strongly support an ancient sea in the northern lowlands of Mars. In particular, the character of the Vastitas Borealis Formation, a veneer covering most of the northern lowlands, is most consistent with sub-aqueous sedimentation of debris transported from the southern highlands to the northern lowlands in the catastrophic floods that carved the outflow channels, and presumably once formed a sea in the northern lowlands.

Most recently, the Spirit and Opportunity rovers identified mineralogy at both landing sites suggesting evaporite minerals. This suggests plentiful ground-water, if not surface waters. Additionally, the hematite-enriched 'blueberries' found at the Opportunity site are believed to be hematite concretions, aided in their formation by significant ground water. The Mars Exploration Rover's (MER's) most compelling evidence is the cross-bedded sediments found in the Eagle and Endurance craters by the Opportunity rover (Squyres et al., 2004). These cross-bedded sediments are most consistent with deposition in a stream-flow environment, i.e., running water at the surface of Mars (Grotzinger et al., 2005). These observations are bolstered by the even more recent discovery by the Curiosity rover of definitive identification of stream-bed deposited gravels (Williams et al., 2013). The evidence for shorelines is still uncertain, with some studies producing no evidence for shorelines (e.g., Ghatan and Zimbelman, 2006), and others finding further evidence of shorelines (e.g., Webb, 2004; Di Achille et al., 2007; de Pablo and Pacifici, 2008; Di Achille et al., 2009; Di Achille and Hynek, 2010; Erkeling et al., 2012). Ghatan and Zimbelman (2006) found no shorelines, but recognize that this could have been due to a lack of waves on an ancient sea. Irwin and Zimbelman (2012) compared terrestrial paleo-shoreline indicators to what we might expect to find at Mars, and concluded that only highly degraded shoreline indicators would be likely to be found on Mars, even if shorelines were once robust. Kraal et al. (2006) argue that ancient lakes would be unlikely to have sufficient time to incise a shoreline into bedrock, even with waves of terrestrial strength, however this only addresses bedrock-incised shorelines, while other landforms could still produce and possibly retain shorelines. Although the debate is still uncertain, it places increasing pressure and interest on resolving the possibilities of standing water at the martian surface in some locations, for some periods of time.

A key unresolved question is how to reconcile the marginal evidence for shorelines with other evidence pointing to a sea in the martian northern plains in the past. The absence of ancient, preserved shorelines may not be evidence that a sea did not once exist on Mars. Rather, if a sea ever did exist, it may be that atmospheric and other environmental conditions might have been unfavorable for creation of prominent, robust shoreline morphologies. These issues also apply to ponds and lakes proposed for smaller basins, e.g., provided by impact craters in the southern highlands. Our target in this paper is to clarify if wind waves are indeed possible in atmospheric conditions substantially different from the ones we are used to on Earth. Principally, the atmospheric pressure is a key variable in influencing the ability of the atmosphere to transfer energy to the sea, which eventually is then deposited on the shoreline. Without this energy transfer, there would be no erosional/depositional shoreline, even in the presence of a sea.