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Groove formation on Phobos: Testing the Stickney ejecta emplacement model for a subset of the groove population

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ABSTRACT

Numerous theories have been proposed for the formation of grooves on Phobos, and no single explanation is likely to account fully for the wide variety of observed groove morphologies and orientations. One set of grooves is geographically associated with the impact crater Stickney. We test the hypothesis that these grooves were formed by clasts that were ejected from the Stickney crater interior at velocities such that they were able to slide, roll, and/or bounce to distances comparable to observed groove lengths (of the order of one-quarter of the circumference of Phobos), partly crushing the regolith and partly pushing it aside as they moved. We show that this mechanism is physically possible and is consistent with the sizes, shapes, lengths, linearity, and distribution of Stickney-related grooves for plausible values of the material properties of both the regolith and the ejecta clasts. Because the escape velocity from Phobos varies by more than a factor of two over the surface of the satellite, it is possible for ejecta clasts to leave the surface again after generating grooves. We make predictions for the surface characteristics and distributions of such grooves and their deposits on the basis of this model, and then compare them with remotely sensed observations of Phobos' grooves. We find that many of their characteristics can be accounted for by a model in which grooves are formed by rolling and bouncing boulders ejected from Stickney. As a further test of this hypothesis, we examine a wide range of lunar boulder tracks, and find that they have considerable similarities to grooves on Phobos in terms of morphology, structure, and relationships with underlying topography. We therefore find that the emplacement of very low-velocity ejecta associated with the Stickney cratering event is a candidate mechanism for the formation of grooves on Phobos. This model and these predictions can be further tested by analysis of high-resolution image data from current and upcoming missions to this and other small airless bodies.

1. Introduction

A variety of models has been proposed for the formation of the grooves and crater chains detected on Phobos by the Mariner 9 and Viking Orbiter missions (Thomas et al., 1979) (Fig. 1a–c). These include (1) original primary layering (Veverka and Duxbury, 1977), (2) drag forces generated during capture of the satellite (Pollack and Burns, 1977), (3) tidal distortion (Soter and Harris, 1977), (4) impact fracturing (Fujiwara and Asada, 1983), (5) impact fracturing accompanied by degassing, (6) impact fracturing accompanied by regolith drainage (Thomas et al., 1979), (7) impact fracturing followed by regolith drainage (Horstman and Melosh, 1989), (8) ejecta emplacement and secondary cratering associated with the Stickney event (Head and Cintala, 1979; Wilson and Head, 1989; Hamelin, 2011; Duxbury et al., 2010; Head and Wilson, 2010), (9) crater ejecta from Mars intersecting Phobos to form secondary chains (Murray, 2011; Murray et al., 1992, 1994, 2006; Murray and Iliffe, 1995, 2011; Murray and Heggie, 2014; Ramsley and Head, 2013a,b), and (10) a combination of several of these processes (Illes and Horvárth, 1980). Additional observations and interpretations have been reported from the Soviet Phobos, ESA Mars Express, and the NASA Viking and Mars Reconnaissance Orbiter missions (Avanesov et al. 1989, 1991; Duxbury and Veverka, 1979; Duxbury, 1989; Head, 1986; Murchie et al., 1991, 2013; Murray, 2010).

Two factors have motivated us to reassess theories for the origin of grooves on Phobos. First, ongoing analysis of high-resolution images of linear tracks on the Moon formed by rolling and bouncing boulders has shown that these features display many similarities to grooves on Phobos (compare Fig. 1a–e and Figs. 1 f–g and 13). Second, continued study of the formation of impact craters on very small airless bodies such as asteroids and the satellites of Mars underlines the unusual and often counterintuitive nature of the

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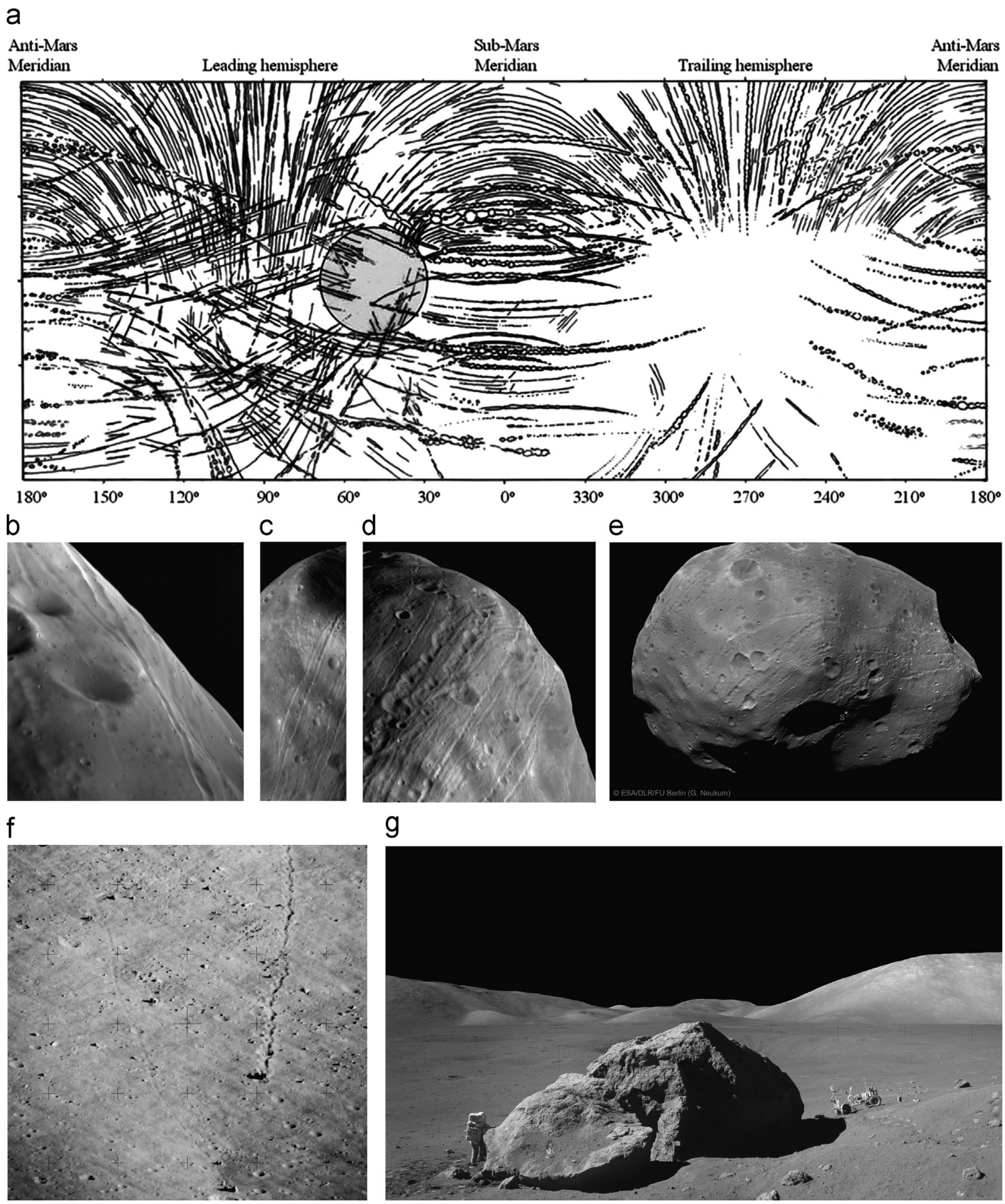

Fig. 1. Grooves on Phobos and comparisons with boulder tracks at the Apollo 17 landing site on the Moon. a) The distribution of grooves on the surface of Phobos (from Murray and Iliffe (2011)). b) An example of Class III grooves of Murchie et al. (1989) (Viking Orbiter image 244A08). c) Groove sets east of Stickney (portion of Viking Orbiter image 343A31). Grooves are ~100–200 m wide. d) Additional grooves east of Stickney; grooves are up to ~250 m wide (Viking Orbiter image 343A15). e) Characteristics of grooves in an image from the High Resolution Stereo Camera (HRSC) on board the European Space Agency Mars Express mission. The "S" on the rim of the crater at center marks the south pole. The large depression in the upper left is Stickney crater. A wide range of groove morphology and cross-cutting relationships is seen. Compare groove morphology on Phobos with the characteristics of boulder tracks on the Moon (Figs. 1f and g, and 13). f) Image showing two types of boulder tracks on the flanks of the North Massif, near the Apollo 17 landing site (AS-17–144-219910). The track on the left is about 7 m wide and the boulder diameter is about 8 m; the track on the right is about 10 m wide, and the boulder diameter is about 18 m (Mitchell et al., 1973). Note that the boulders have broken into a series of fragments near the end of their tracks. g) At Station 6 of the Apollo 17 landing site, Astronaut Harrison Schmitt explored an 18 m-wide boulder that broke into five pieces at the end of its track (Muehlberger et al., 1973).

cratering process, and the resulting ejecta emplacement patterns, there (e.g., Cintala et al., 1979; Asphaug and Melosh, 1993; Asphaug and Benz, 1994; Asphaug et al., 1998; Wilson and Keil, 2001; Holsapple et al., 2002; Scheeres et al., 2002). Impact craters on larger airless bodies, such as the Moon, are characterized by radial ejecta patterns, vast secondary crater fields, thick, areally extensive, radially textured ejecta deposits surrounding the crater rim crest, and large volumes of impact melt in crater interiors (Melosh, 1989; Stöffler et al., 2006; Hiesinger and Head, 2006). The ejection velocities of the vast majority of material forming such deposits on the Moon, however, exceed the escape velocities on asteroids and Phobos and Deimos, and thus leave these bodies (Cintala et al., 1979; Asphaug and Melosh, 1993; Asphaug et al., 1998; Scheeres et al., 2002; Buczkowski et al., 2012; Stickle et al., 2013; Bowling et al., 2013; Ivanov and Kamyshenkov, 2013). The only ejecta remaining on the impacted body in these cases are likely to be the least shocked materials excavated toward the end of the cratering event at very low energies (i.e., less than escape velocity).