The character of the ejecta forming the major circum-crater deposits on the Moon is thus not a good indicator of what to expect on bodies such as Phobos. Instead, one needs to consider the nature and fate of only the small percentage of ejecta that remains below the escape velocity of Phobos. This improved conceptual understanding of the cratering process on small, airless bodies shows that ejecta from Stickney-sized craters will look and behave very differently from the extensive ejecta deposits on the Moon, with emphasis on the low-velocity emplacement of blocks in a manner perhaps similar to that which forms tracks from rolling and bouncing blocks observed on the Moon (Figs. 1f and g and 13). The sizes of clasts that constitute late-stage ejecta from impacts are a function of the complex interplay between the distribution of fractures in the near-surface and sub-surface layers, the nature of the regolith and its thickness, and whether the interiors of such bodies are bedrock or rubble piles. Empirically, however, clasts as large as 200 m in diameter have been observed on Deimos, and clasts up to 150–200 m in diameter have been documented on Phobos, with several 30–60 m-diameter boulders observed on the rim of Stickney (Lee et al., 1986) from Viking data. Furthermore, over 2000 substantial blocks (the largest being ~85 m across) have been identified in Mars Global Surveyor Mars Orbiter Camera data (Thomas et al., 2000; Basilevsky et al., 2014).

The current global map of grooves on Phobos (Murray and Iliffe, 2011) is shown in Fig. 1a. Murchie et al. (1989) showed that the grooves mapped in an earlier study by Thomas et al. (1979) can be divided into three major classes on the basis of morphology. In this paper, we consider the origin of some grooves in these classes (primarily those in Classes II and III of Murchie et al. (1989)), many of which are geographically associated with the Stickney impact crater. Class II grooves consist of closely spaced or coalescing pits whose centers fall within a curvilinear band generally several hundred meters wide and from 2 to 30 km long, whereas Class III grooves are linear chains of coalesced pits, and are predominantly 80–200 m wide, 5–20 m deep, and up to 10 km long (Fig. 1a–e).

We explore the consequences of assuming that these grooves were formed by hectometer-scale ejecta clasts that left Stickney at velocities such that they were able to roll or bounce to distances of the order of one quarter the circumference of Phobos, partly crushing the regolith and partly pushing it aside as they moved (Fig. 1). Using basic soil mechanics relationships together with estimates of regolith material properties, we calculate the range of sizes of the boulders responsible for the observed grooves under such a sencario. We then consider the motions of clasts ejected from the 10- km-diameter Stickney crater at velocities just below that of the escape velocity in the Phobos environment. We show that groove formation by these clasts is physically possible and that the sizes, shapes, lengths, linearities, and distribution of the grooves are consistent with plausible values of the material properties of both the regolith and the ejecta clasts. We also show that there are two principal outcomes for these clasts: 1) some will be abraded and diminished in size during their traverse before coming to rest, whereas 2) some will leave the surface again after generating grooves because the escape velocity of Phobos varies by more than a factor of two over its surface. On the basis of our analysis, we are able to make some deductions about the internal structure of Phobos on the 100- m scale in the vicinity of Stickney, and about the applicability of this process in general to small airless bodies (Chapman, 2002; Sullivan et al., 2002; Fraeman et al., 2013) and small satellites (Morrison et al., 2009).

2. Primary crater ejecta on Phobos

The distribution around a primary impact crater of material forming the equivalent of an ejecta blanket/deposit and secondary crater field on a small body like Phobos will be very different from the corresponding distribution on a more massive (i.e., higher-gravity) body (e.g., Cintala et al., 1979; Asphaug et al., 1998; Melosh, 1989; Banaszkiewicz and Ip, 1991; Asphaug and Melosh, 1993; Thomas, 1998; Holsapple et al., 2002; Richardson, 2011). Ejecta deposits on Phobos will be largely composed of material that would have remained in the crater rim unit on bodies such as the Earth and Moon, since most of the material from the transient crater cavity is ejected with velocities at least as great as the escape velocity from Phobos, and much of it exceeds the escape velocity of the Phobos–Mars system itself. The paths of all primary crater ejecta clasts produced on Phobos must be therefore considered in terms of the total gravity field of both Phobos and Mars (e.g., Dobrovolskis and Burns, 1980; Davis et al., 1981; Banaszkiewicz and Ip, 1991). In this respect we draw a distinction between *super-orbital*, *orbital*, and *sub-orbital* ejecta (Fig. 2).

Ejecta leaving at very high velocities (*super-orbital* ejecta) may be regarded as part of the general Solar System meteoroid flux, and can be neglected in terms of future impacts with Phobos. Ejecta leaving the surface of Phobos at speeds greater than the moon's escape velocity (3–8 m s^{-1}, depending on position on the surface and the direction of launch: Housen and Davis, 1978; Dobrovolskis and Burns, 1980), but less than the escape velocity from the Mars system (a few km s^{-1}), are termed *orbital*. These clasts are potentially capable of re-impacting the surface of Phobos at speeds similar to those at which they were launched and at elevations to the horizontal of c. 45°, thus producing craters with a wide range of sizes, some of which are indistinguishable from primary impact craters. *Sub-orbital* clasts are those ejected at speeds below the escape velocity of Phobos alone. Such clasts are launched from near the edge of the crater cavity (Fig. 2). They are excavated by stress waves with small stress amplitudes and stress gradients, and so will tend to be relatively coarse, more coherent than clasts ejected at greater velocities, and launched at low speeds and at low elevation angles (relative to horizontal). There are likely to be very strong correlations between the sizes and the horizontal and vertical velocity components, respectively, of such ejecta clasts.

For example, our calculations show that clasts of the order of a few tens of meters in diameter may re-impact the surface of Phobos at ranges of a few to 20 km from where they were ejected. If such clasts disturb 10 times their own mass of the surface on impact they may excavate secondary features up to 100 m in size (e.g., Oberbeck, 1975). The peak stress induced in such an impacting clast will be ~10^4 Pa, and it will not survive the re-impact intact unless its yield strength is greater than this value. Most consolidated silicate rocks have yield strengths in the range of a

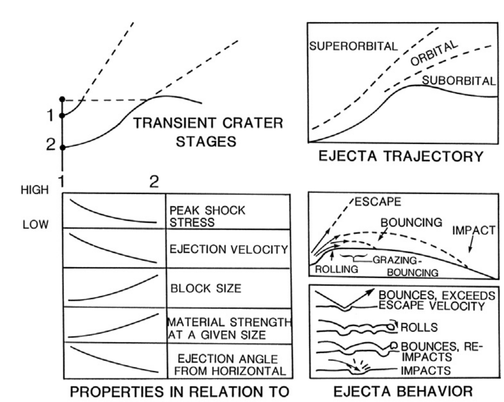

Fig. 2. Schematic diagram of the trajectories of super-orbital, orbital, and sub-orbital ejecta from a large crater on Phobos, and the geometry of the interaction of a horizontally moving spherical ejecta clast with the regolith surface on Phobos. Also shown schematically transient crater stages and various ejecta properties in relation to position in the transient cavity and crater.