of the forward velocity of a clast and the local slopes it encounters is such that the track it would make would deviate laterally from its original trajectory by no more than a few meters. The general linear cross-cutting relationship of grooves and preexisting craters has been cited as evidence for their internal or fracture origin (Thomas, 1978; Thomas et al., 1979), but rolling and bouncing ejecta can also produce such relationships. As rolling and bouncing boulders decrease to very low velocities near the end of their traverse, they would be more likely to respond to local slopes and gravity gradients: note how lunar boulder tracks become slightly more sinuous near their termina in Fig. 1f–g (see also Fig. 13). However, the greater velocity of boulders ejected from Stickney, compared with that characteristic downslope movement of boulders in the lunar gravity field, means that lateral deviations of boulders at the end of grooves on Phobos are less likely to be prominent. Indeed, the morphology at the end of many Phobos grooves (Fig. 12b–d) is more consistent with predictions of boulders actually reaching local escape velocities and leaving the surface of Phobos.

5) *Spatial distribution of grooves*: As discussed above, any preexisting structural or stratigraphic fabric will tend to dictate the exit directions of large boulders from the crater cavity, in contrast to the more radially symmetrical, shock-dominated distribution of ejecta leaving the cavity at earlier stages. Therefore, boulders ejected from Stickney in the terminal stages of the cratering event at very low velocities could easily produce distinctive, non-symmetrical ejecta patterns that reflect substrate heterogeneities (structural, compositional, physical properties, presence of ice, etc.), such as is seen for the vast majority of craters that excavate below homogeneous soil layers on planets and other satellites. Furthermore, variations in impact angle and azimuth could also introduce linearities and heterogeneities. On Phobos, Class III grooves that are associated geographically with Stickney are not radially arrayed around that crater (Fig. 1a), and some intersect Stickney at oblique angles. Although this has been cited as evidence for a fracture origin for the grooves (Thomas, 1978; Thomas et al., 1979), non-radial ejection of low-velocity boulders could also explain these orientations.

7. Characteristics of lunar boulder tracks and comparison with Phobos grooves

7.1. Lunar boulder tracks

In the previous section, we argue that many of the characteristics of the types of grooves observed on Phobos can be accounted for by the model developed in Sections 3–5, whereby grooves on the Moon formed by rolling and bouncing boulders. As a further test of this hypothesis, we now examine a wide range of lunar boulder tracks, features known to be formed by the dislodgement, lateral transport, and bouncing, skipping, and rolling behavior of large ejected blocks as they descend downslope, before finally coming to rest. Specifically, we assess these lunar examples because of the similarity of some Phobos grooves to boulder tracks and inferred boulder behavior at the Apollo 17 landing site (Fig. 1f–g). We compare the lunar boulder tracks with observed Phobos grooves in terms of morphology, structure, and the relationships with underlying topography (e.g., parameters such as groove width, width-to depth ratio, linearity, chains of isolated craters, chains of connected craters, linear grooves with associated pits, changes in morphology with distance, groove linearity with distance, map patterns, etc.).

A wide range of track characteristics in planetary regoliths produced by rolling and bouncing boulders can be seen on the flanks of massifs at the edge of the Imbrium impact basin that are part of the Alpine Valley, a broad trough oriented radially to the Imbrium basin (Fig. 13). Rocks near the top of the massifs have been dislodged and have rolled and bounced downslope on regolith that has formed on the slopes of the massifs in the almost 4 Ga since the formation of the Imbrium basin. This environment is similar to the boulder exposures at the top of the Taurus–Littrow North Massif, a mountainous part of the radial Taurus–Littrow Valley at the edge of the Serenitatis basin. Here, the Apollo 17 mission landed and photographed boulder tracks down the flank of the massif, and the boulders at the base were sampled by the Apollo 17 crew (Schmitt and Cernan, 1973) (Fig. 1f–g).

In the Alpine Valley example (Fig. 13), boulders have traveled up to distances of about 1300 m from their origin in a several-hundred-meter-wide boulder outcrop, moving downslope across typical cratered and textured regolith to their final resting place. In the area of detailed analysis (Fig. 13b and c), more than a dozen well preserved tracks are seen, almost all of which have boulders at their termini. A sampling of the diameters of these remnant boulders (Fig. 13d) show that they range from a few meters up to ~11 m in size. Boulder tracks show a wide range of morphologies between individual tracks and along-track within individual examples. They also display varying states of age-related degradation, cross-cutting and superposition relationships, and relationships to both preexisting features, such as impact craters, and impact craters formed subsequently. Here we describe these relationships as a basis for assessing the origin of grooves on Phobos as having formed by rolling and bouncing boulders. Boulder tracks in this area are numbered 1–14 for reference (Fig. 13c).

1) *General characteristics of boulder tracks*: Boulder tracks can be generally characterized as long, continuous, often straight, beaded to linear troughs (e.g., tracks 4 and 7). Linearity can change slightly along-track with some curvilinear or mildly sinuous planforms (tracks 5 and 10), but sharp deviations in trough strike are not observed, even where pre-existing topography is encountered. The maximum observed deviation from linearity occurs at the ends of some boulder tracks in the last few percent of the boulder track length (e.g., tracks 1, 5, and 6); here, frictional forces have reduced forward velocity sufficiently so that the boulder responds to local slopes as it comes to a stop. Along-strike boulder track widths do not vary substantially (i.e., by no more than a factor of ~2). Track widths are typically somewhat less than the widths of boulders found at individual track termini, but in some cases towards the end of the tracks, trough widths approach the diameter of the boulder. In one case (the 10.5 m-diameter boulder in track 4: Fig. 13d), the trough width increases slightly along its last ~70 m, with distinct raised levees along the trough margins likely formed by regolith displaced laterally from beneath the boulder to its sides. In this case, the repetitive pit-like patterns over most of the track suggest bouncing and rolling; in the last ~70 m, the boulder may have become oriented with its long axis normal to the track, the rolling around this axis producing the wider track as it came to rest.
2) *Along-track changes in morphology*: Variations in the beaded nature of individual boulder tracks are clearly related to two factors: 1) the nature of the boulder encounter with the regolith, and 2) the shape of the boulder itself. In the proximal parts of the boulder tracks (Fig. 13: tracks 10, 12, and 13), the tracks are composed of elongated beads completely separated from one another along-track or, in some examples, connected by a narrow trough. In the medial and distal portions of these