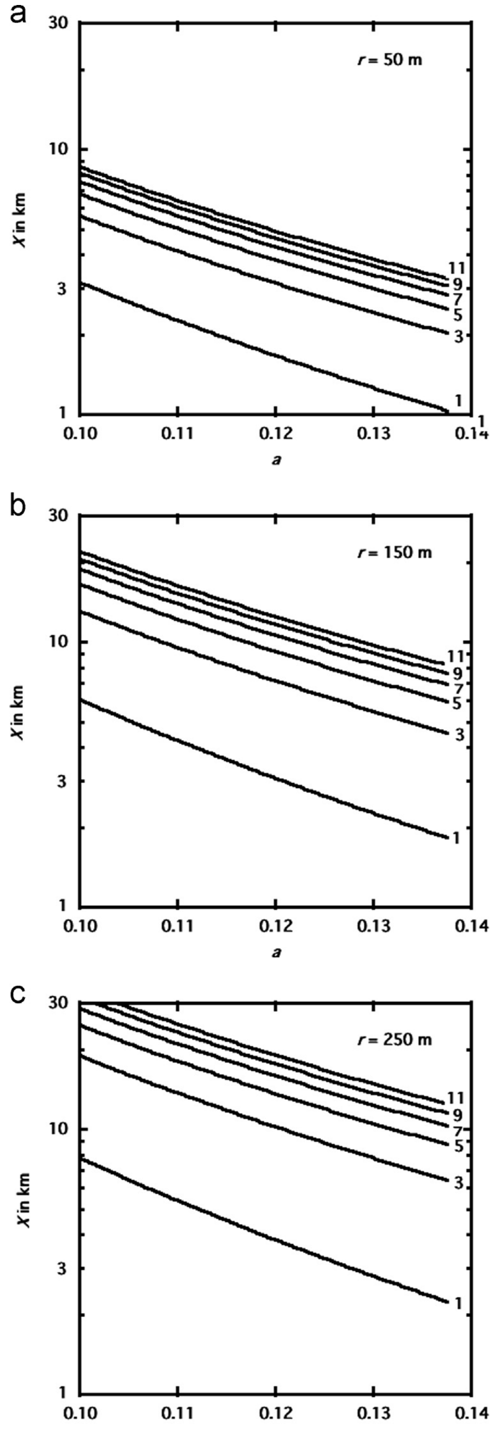

Fig. 5. The variation of boulder travel distance, X, as a function of a (boulder track depth–width aspect ratio) and initial speed, u_i (curves labeled 1, 3, 5, 7, 9, and 11 m s^{-1}), for clast radii of (a) 50 m, (b) 150 m, and (c) 250 m, calculated from Eq. (8) using a regolith density of 1000 kg m^{-3} and a clast density of 1800 kg m^{-3}.

not depend on the internal friction angle. Fig. 5(a–c) show X as a function of a for $r=50$, 150, and 250 m, respectively, for $u_i=1$, 3, 5, 7, 9, and 11 m s^{-1}. A regolith density, ρ_r, of 1000 kg m^{-3} and a boulder density, ρ_b, of 1800 kg m^{-3} were used in these calculations, and g was again taken as 5.7×10^{-3} m s^{-2}. Eq. (9) shows that X is directly proportional to ρ_b and inversely proportional to ρ_r. The influence of g is much less: a 20% decrease in g increases X by 4%, and vice versa. It is clear that horizontal travel distances, and hence groove lengths, in excess of 25 km (comparable with the greatest groove lengths observed on Phobos) can be generated by the near-horizontal ejection of large ($r > \sim 150$ m) boulders at close to escape velocity. Such clasts would produce relatively shallow grooves: the shapes of the curves in Fig. 5(a–c) imply that larger boulders should produce deeper grooves of a given length. Note also that the calculations underlying Fig. 5 assume that a boulder travels in such a way as to form a groove of a given constant depth. A bouncing boulder, or one of irregular shape that tumbles as it moves laterally, will not penetrate the regolith to the same depth at all points along its path, and so will travel farther for the same initial velocity. If we assume that a bouncing or tumbling boulder expends 50% less energy as it moves than a boulder that does not behave so, grooves 25 km long with the full range of observed depth-to-width ratios can readily be formed by boulders with radii of up to 150 m.

5. The fate of ejecta clasts

The above analysis demonstrates that clasts with radii of the order of 100 m ejected from Stickney at speeds near the local escape velocity of Phobos, and on paths almost parallel to the local horizontal, can readily produce grooves of the observed widths, depths, and lengths. There are at least two possible outcomes for the ejecta clasts that form such grooves. Either they remain in a similar gravity field and their velocity decreases monotonically with distance, finally coming to rest at the end of the groove, or clasts traverse down a gravity gradient, gaining kinetic energy, and reach escape velocity after forming a groove (Fig. 2). Under the first scenario, clasts that have diameters of within about a factor of two of observed groove width should come to rest at the ends of the grooves. If such clasts survive subsequent micrometeorite bombardment over their lifetime, at least some should be observable. No clasts in the 100 m diameter range are visible at the ends of grooves in the currently available image coverage; this may be due to the ancient age (several billion years) attributed to Stickney (Soter and Harris, 1977; Thomas and Veverka, 1980; Schmedemann et al., 2013; Basilevsky et al., 2014). Indeed, the lack of observable boulders at the ends of grooves has been used as evidence against a groove origin by the mechanism we investigate here (Thomas et al., 1979). However, the clasts may have broken into smaller fragments toward the ends of their traverses (a phenomenon seen commonly in boulder tracks on the Moon: Mitchell et al., 1973) (Fig. 1f–g), or they may have been broken and reduced in size by micrometeorite bombardment subsequent to their emplacement (Basilevsky et al., 2013). Clasts up to 150–200 m in diameter are present on Phobos, with several 30–60 m boulders being observed on the rim of Stickney (Lee et al., 1986). Furthermore, recent high-resolution image data have revealed the presence of abundant blocks and boulders on Phobos (Kuzmin et al., 2003). If rolling and bouncing boulders formed the grooves and came to rest at the end of the groove, then, they either: 1) broke up there into fragments below the limits of resolution due to their traverse (Basilevsky et al., 2014) and/or 2) were broken down and degraded beyond the limits of resolution by subsequent impact bombardment (Basilevsky et al., 2013). A variant of this second scenario is that the boulders were composed of icy blocks (Hamelin, 2011), interpreted to reside in the interior of Phobos on the basis of its low density (Andert et al., 2010; Rosenblatt, 2011; Rosenblatt et al., 2011).

We now consider the second possible fate of ejecta clasts (traversing down a gravity gradient, gaining energy from the gravity field, and reaching escape velocity after forming a groove; see Fig. 2) by considering in more detail the behavior of a boulder starting close to Stickney and moving eastward along the equator of Phobos. As discussed by Thomas (1993), the unusual