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Hypervelocity impact fragmentation of basalt and shale projectiles

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ABSTRACT

Results are presented for the fragmentation of projectiles in laboratory experiments. 1.5 mm cubes and spheres of basalt and shale were impacted onto water at normal incidence and speeds from 0.39 to 6.13 km s^{-1}; corresponding to peak shock pressures 0.7–32 GPa. Projectile fragments were collected and measured (over 100,000 fragments in some impacts, at sizes down to 10 µm). Power laws were fitted to the cumulative fragment size distributions and the evolution of the exponent vs. impact speed and peak shock pressure found. The gradient of each of these power laws increased with increasing impact speed/peak shock pressure. The percentage of the projectiles recovered in the impacts was found and used to estimate projectile remnant survival in different solar system impact scenarios at the mean impact speed appropriate to that scenario. For Pluto, the Moon and in the asteroid belt approximately 55%, 40% and 15%, respectively, of an impactor could survive and be recovered at an impact site. Finally, the catastrophic disruption energy densities of basalt and shale were measured and found to be 24×10^4 J kg^{-1} and 9×10^4 J kg^{-1}, respectively, a factor of ~2.5 difference. These corresponded to peak shock pressures of 1 to 1.5 GPa (basalt), and 0.8 GPa (shale). This is for near normal-incidence impacts where tensile strength is dominant. For shallow angle impacts we suggest shear effects dominate, resulting in lower critical energy densities and peak shock pressures. We also determine a method to ascertain information about fragment sizes in solar system impact events using a known size of impactor. The results are used to predict projectile fragments sizes for the Veneneia and Rheasilvia crater forming impacts on Vesta, and similar impacts on Ceres.

1. Introduction

Impacts in excess of a few km s^{-1} are deemed hypervelocity impacts, and have long been studied as a major evolution process for solar system bodies and surfaces. Here on Earth the mean impact speed is usually given as around 20 km s^{-1} (Steel, 1998; Jeffers et al., 2001). However, the mean speed of impacts varies depending on their location within the Solar System. For example, the mean impact speed in the asteroid belt is approximately 5 km s^{-1} (Bottke et al., 1994), with the exact speed depending on the exact conditions, e.g. the mean impact speed on Vesta is estimated as 4.75 km s^{-1} (Reddy et al., 2012). Lower impact speeds (0.5–1 km s^{-1}) are expected for Kuiper Belt objects in the outer Solar System (Zahnle et al., 2003). However, if a body is a satellite of a planet, there will also be a contribution to the mean impact speed from the gravitational attraction of the larger nearby planet. Hence the satellites of Jupiter and Saturn will have mean impact speeds that increase the closer they are to the parent planet (e.g., see Zahne et al., 2003; Burchell et al., 2005). There are even more specific, niche examples, of impacts, such as that of terrestrial material ejected after impacts on Earth, which then impacts the Moon. Such impacts have speed ranges which need to be found for that specific example (e.g., see Armstrong, 2010, who gives the mode speed for terrestrial ejecta on the Moon as approximately 2.8 km s^{-1}).

There has been significant research into impact cratering events and the resulting ejecta. A typical recent summary of impact related research can be found in Osinski and Pierazzo (2013) and references therein. What is sometimes overlooked however is that projectile material itself may survive the impact (albeit in modified and/or heavily fragmented form). There has long been discussion of this, albeit less than that for other aspects of impacts. For example, early work by Gault and Heitowit (1963) looked to see how the kinetic energy of the projectile was partitioned during an impact, and estimated that the projectile internal energy (the waste heat) was 6% (of the projectile's kinetic energy) for sand and between 4% and 12% for basalt. Later, Gault and Wedekind (1978) discussed projectile ricochet in shallow angle impacts in the laboratory, as well as the energy density (Q_p^*) needed to fragment alu-

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minium and basalt projectiles in an impact. Note that this concept of Q_p^* is similar to that of the critical energy density needed in an impact to disrupt a target (Q^*). Thus it is the energy density (kinetic energy divided by mass) which, on average, results in the largest surviving fragment possessing half the original mass of the parent body (here the projectile). The presence of the subscript p indicates that the projectile alone is being considered, and thus $Q_p^* = ½v^2$. This approach is extended in Schultz and Gault (1990a), who considered in detail the break-up of projectiles in such impacts. In that work, Schultz and Gault reported firing aluminium and basalt spheres at targets of mostly steel, but with examples of water and aluminium targets as well. The impacts covered a speed range of 0.4 to 5.3 km s^{-1}, and were at very shallow angles of incidence (30° from the horizontal or less). Projectile disruption was reported, with significant fragments of the impactor recovered post-shot (over 50% in some cases). Where projectile ricochet was reported, in some cases the incident projectile was effectively intact after the impact. Studies of shallow angle ricochet have also been reported for basalt targets covered with sand (Burchell et al., 2010, 2015). As well as observing intact ricochet, they also reported very little reduction in outgoing speed compared to the incident speed. Separate studies have also considered projectile fragmentation during penetration of thin plates (e.g. Piekutowski, 1995). Schultz and Gault (1984) also considered how projectile fragmentation can influence crater morphology. They showed that when the impact induced shock pressures exceeded the dynamic strength of the projectile, cratering efficiency was reduced. Since this occurs at modest impact speeds (less than a few km s^{-1}), extrapolation of low speed data to higher speed examples in the Solar System may not be effective.

Previous work in the laboratory which has observed projectile fragmentation also includes impacts into metal targets at speeds of up to 5 or 6 km s^{-1} (which can involve shock pressures of 80 to over 100 GPa). Examples of this include Hernandez et al. (2006) for metal projectiles, and Burchell et al. (2008) for mineralic impactors. Despite the extreme shocks, in the latter example, post-impact fragments of the mineral projectiles retained sufficient internal structure to have recognisable Raman spectra. Recently, studies of Raman spectra from olivine grains after impacts at speeds up to 6 km s^{-1}, do however show some subtle changes in peak positions. This suggests that some fine changes in structure may be occurring due to the shock during impact (Foster et al., 2013; Harriss and Burchell, 2016).

In addition, Nagaoka et al. (2014) fired millimetre-sized pyrophyllite and basalt projectiles onto regolith-like sand targets at velocities up to 960 m s^{-1}. They determined Q_p^* to be $(4.5 \pm 1.1) \times 10^4$ for pyrophyllite and $(9.0 \pm 1.9) \times 10^4$ J kg^{-1} for basalt projectiles (Nagaoka et al., 2014). They also found that destruction of rock projectiles occurred when the peak pressure was approximately ten times the tensile strength of the rocks (Nagaoka et al., 2014). Recently, Avdellidou et al. (2016) fired forsterite olivine and synthetic basalt projectiles onto low porosity ($<10\%$) pure water–ice targets at speeds between 0.38 and 3.50 km s^{-1}. From this, the estimated implanted mass on the target body was found to be a few percent of the initial projectile mass. Furthermore, they found an order of magnitude difference for Q_p^*, between the olivine ($Q_p^* = 7.07 \times 10^5$ J kg^{-1}) and basalt ($Q_p^* = 2.31 \times 10^6$ J kg^{-1}). However, they found that the two projectile materials had very similar fragment size frequency distributions (Avdellidou et al., 2016).

As well as laboratory experiments, there is extensive evidence for projectile survival in Solar System impact events. For example, projectile fragments have been recovered at 13 terrestrial impact sites including Barringer, Morokweng and Chicxulub craters (see Table 15.1, Goderis et al., 2013, and references therein). Furthermore, analysis of Apollo era lunar samples shows that projectile fragments from impacts early in the Moon's history can be found within the lunar regolith (e.g. Joy et al., 2012, and references therein). Schultz and Crawford (2016) have suggested that the high meteoritic component found in samples returned from the Apollo 16 landing site may arise from ejecta from the impact which formed the Imbrium basin on the Moon. As well as projectile material being mixed within the lunar regolith, Yue et al. (2013) used numerical models to show that for vertical impact velocities below 12 km s^{-1}, projectile material may survive the impact and be found in the central peak of the final crater. There are also suggestions by Reddy et al. (2012) that the dark material on Asteroid (4) Vesta could be of exogenic origin. This is based on the observation that the majority of spectra of the dark material are similar to carbonaceous chondrite meteorites, indicating mixing of such impactors with materials indigenous to Vesta. Relating to this observation, Daly and Schultz (2013, 2014, 2015a, 2015b, 2016) have conducted hypervelocity impact experiments in order to explain the implantation of an impactor onto Vestan regolith, and also the surface of Ceres. They fired basalt and aluminium spherical projectiles, approximately 6.35 mm in diameter, onto pumice and highly porous ice targets at speeds between 4.5 and 5.0 km s^{-1}. Surviving projectile fragments ranged from approximately <105 μm to 5 mm. Based on their results, it was inferred that both Vesta and Ceres should have significant levels of exogenic material delivered via impacts.

In parallel to this, renewed interest in the distribution of organic (and possibly even biological material) around the Solar System as contents of small rocky bodies etc., has led to a steady increase in the number of laboratory studies into the survival of projectiles. For example, the survival of biomarkers in projectile fragments in hypervelocity experiments has been studied (e.g., see Bowden et al., 2008; Parnell et al., 2010; Burchell et al., 2014a). Furthermore, even the survival of diatom fossils in projectile fragments has been demonstrated in laboratory experiments (Burchell et al., 2014b, 2017). This indicates that not only can projectile fragments survive after impact, they can deliver a wide variety of materials to the target bodies.

The subsurface regions at man-made impact sites should also contain impactor material. For example, consider the crater on comet 9P/Tempel-1 arising from the Deep Impact Mission (Schultz et al., 2013). This mission consisted of a 363 kg impactor (of which 49% was porous copper) impacting the comet nucleus at 10.3 km s^{-1} (A' Hearn et al., 2005; Veverka et al., 2013). In laboratory impacts onto ice targets at speeds up to 6.3 km s^{-1}, it has been shown that fragments of copper projectiles can survive at the impact site (McDermott et al., 2016). Extrapolating to the Deep Impact case, McDermott et al. (2016) predict the survival of between 8% and 15% of the copper projectile at the impact site. In that study, McDermott et al. (2016) also reported extensively on the progressive stages of disruption undergone by copper projectiles for impacts involving shock pressures up to 50 GPa, including providing size distributions of the fragments. Using high porosity targets, Avdellidou et al. (2017), have shown that whilst, in general, projectile fragment survival increases with increasing target porosity, this is not the case when target mineral grain size exceeds projectile size.

Given the growing interest in emplacement of projectile material onto targets after impact we have conducted a series of impacts in the laboratory, recovering the projectile material after impact. Here we look at the fragmentation of basalt and shale projectiles in normal incidence impacts at speeds from 0.39 to 6.13 km s^{-1}. The targets were water, a homogeneous target which is easily modelled and from which the projectile fragments can be readily recovered. We find Q_p^* and fragment size distributions, and compare to previous work. We also determine the possible sizes