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Hypervelocity impacts in the laboratory on hot rock targets

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Abstract

The variation of impact crater size in rock has been investigated as a function of target temperature in the range 150 K – 1150 K. Three rock types were used: limestone, sandstone and basalt. A total of thirty impacts were observed, at a typical impact speed of 5 km s^{-1} with a 0.8 mm diameter stainless steel spherical projectile. The three rocks behaved in two ways. The craters in limestone and sandstone initially grew in size, until a maximum was reached at around 500 K. Crater size then fell again as temperature increased further. For basalt however, crater size fell as temperature increased, reaching a constant level above 800 K. This strongly suggests that crater sizes seen in experiments on Earth, should not be taken as typical, rather they are a function of rock temperature. It proved difficult to relate crater size to target strength, as data in the literature on rock strength vs. temperature were in some cases contradictory.

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Keywords: Rocks, cratering, temperature, impacts

1. Introduction

The study of impact cratering on rocks is of crucial importance for understanding the evolution of rocky bodies in the Solar System. There are many works on the subject, with key publications summarising past work including [1, 2]. However, when conducting laboratory experiments, most work is done at room temperature. Whilst this may be

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appropriate for impact events on Earth (mean surface temperature 291 K), in the context of the broader Solar System this is clearly not appropriate. For example, the mean surface temperature on Venus is 735 K, Mars has a mean of 213 K with a range of 73 K, and Mercury ranges from 723 K in direct sunlight, to 103 K in deep shadowed regions. Given this wide range of temperatures on just the rocky planets, the question arises as to how this may influence cratering efficiency. At low temperatures does increased brittleness change things, or at high temperatures does increasing plasticity alter the response to impacts?

2. Method

The work reported herein used three types of rock samples: limestone (a sedimentary rock), sandstone (a fine grained rock) and basalt (a typical volcanic rock). These represent a range of rock types, with differing properties. Previous studies have been done as to their low strain rate strength as a function of temperature, see [3, 4, 5] and Fig. 1. There are clearly significant strength variations over the temperature range of interest here.

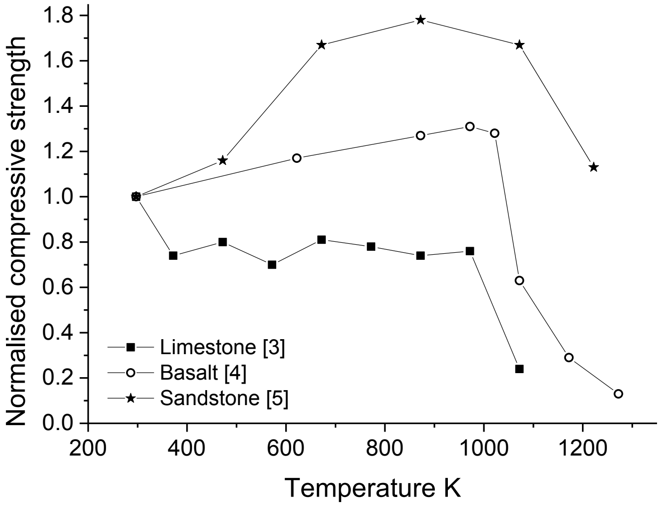
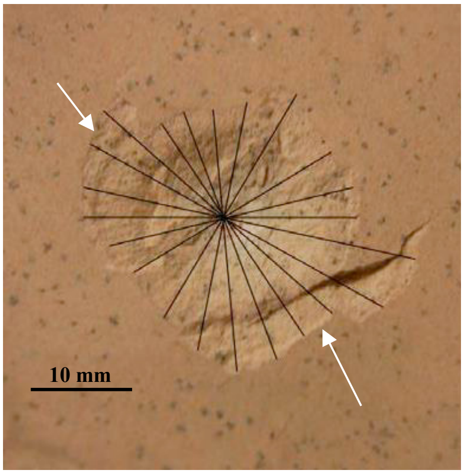


Fig.1. Normalised compressive strength of rock vs. temperature.

In the present work, we sourced basalt from Ruddons Point in Fife Scotland, Ancaster Hard White limestone from Lincolnshire and Beestone Red sandstone from Cumbria (all in the UK). The Ancaster Hard White Limestone is a Jurassic limestone which is cream white with pink variations, its density was 2.3 g cm^{-3} and it had a compressive strength of 25 MPa. The Beestone Red Sandstone is a fine-grained sandstone from the Triassic period with a compressive strength (dry) of 115 MPa.

The rock samples were cooled using a liquid nitrogen refrigerator and left for several hours at the desired temperature before use. When removed from the refrigerator they were kept in a LN_2 cooled bath before actual use as targets in our gun. The heated samples were heated in situ in the gun, in a specially constructed holder with built in heating elements.

The impacts took place in our in-house two stage light gas gun [6]. This uses hydrogen gas (compressed in the first stage), to accelerate a sabot to high speed. The (split) sabot is discarded in flight and the projectile proceeds alone to the target chamber. Here we used 0.8 mm diameter spheres of 420 stainless steel. The typical impact speed



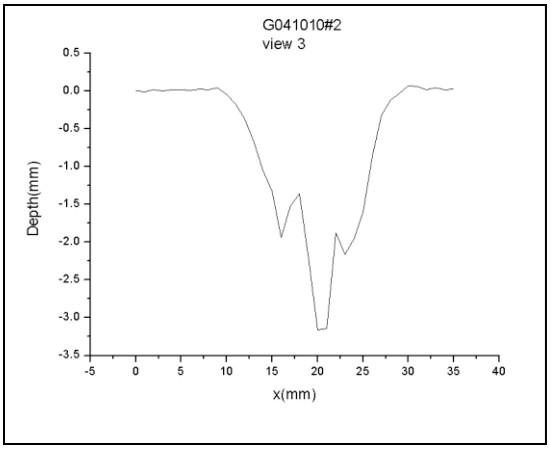
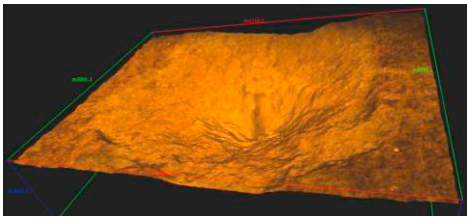


Fig. 2. (Left) Impact in limestone. The black lines across the crater show various diameters used as measurements and which were averaged to give a mean diameter. The scale bar (bottom left) is 10 mm. Note the features marked with arrows, which show spall outside the main crater and which distort the estimate of the mean crater diameter. (Right) A depth profile across a sandstone crater, showing a deep central pit with a terrace around it.



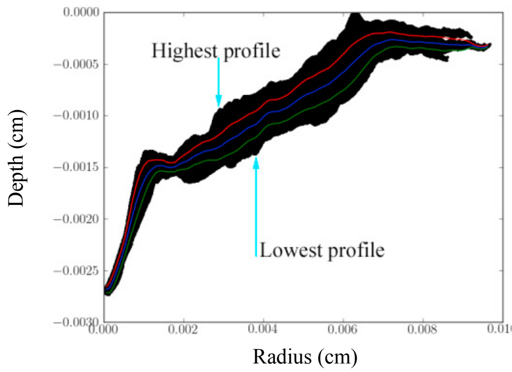


Fig. 3. (Left) An inclined image if a sandstone crater (793 K). (Right) An automated set of crater profiles for the crater. The black region shows the full range of all profiles swept out in a 360° rotation around the crater centered on deepest point. The highest and lowest profile are marked. The central blue line in the black region is the mean depth profile, with the red and green lines the 1σ deviations.

was 5 km s^{-1}, and was measured in each shot to within ±1%. The target chamber was held at a vacuum of ~0.2 mbar during each shot.

This work featured 30 impact experiments; 11 on limestone (mean speed 5.07±0.26 km s^{-1}), 11 on sandstone (mean speed 5.11±0.27 km s^{-1}) and 8 on basalt (mean speed 5.02±0.14 km s^{-1}). Target temperature was measured in-situ in the gun and ranged from 150 to 1180 K. After impact, the targets were removed from the gun and measured. Several techniques were used to measure crater, depth, diameter and volume. Initially calipers were used to find diameters on pairs of orthogonal axes. Depth gauges were then used to find crater depth. The volume was found by in-filling the craters with fine glass beads. Separately we also took 3D images of the craters to make stereo reconstructions of the full shape. These reconstructions also provided measures of the depth, diameter and volume, and it is these, more accurate values which are used in the analysis presented here.

Before proceeding to a presentation of the full results, we show typical results to illustrate the main features of the data. In Fig. 2 we show an impact in the limestone. Given the unequal spallation around the main crater, estimates of the crater diameter and volume will be too large in this case. Similarly, in cases where there is incomplete spallation, these measures will be too small. Effects like this introduce scatter into the data which is seen in the full results. The crater depth however is not influenced by these effects. In Fig. 3 an inclined image is shown which is used to make a stereo reconstruction of a crater. Also in Fig. 3, we show a radial depth profile obtained from a 3D reconstruction of a crater. In the example in Fig. 3, the set of all possible radial crater profiles has been rotated into a single plane and superimposed. The deep central pit in the middle of this crater is visible, as is shallow region around it (traditionally held to arise from late stage spallation).

3. Results: Crater Dimensions

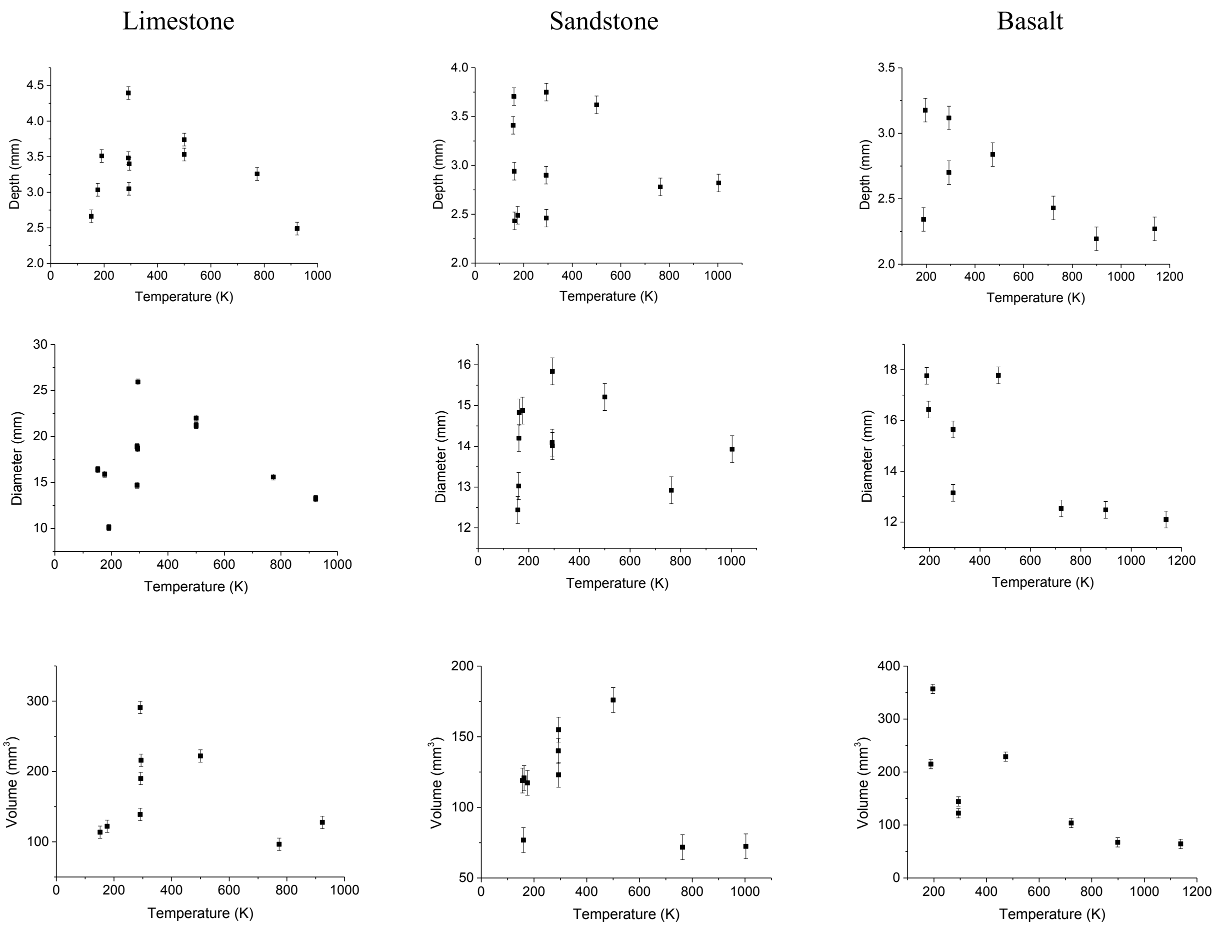


Fig. 4. Crater depth, diameter and volumes vs temperature for limestone, sandstone and basalt.

For the limestone data in Fig. 4 there appears to be an initial increase in depth, diameter and volume as temperature increases from 150 K up to around 500 K. The three parameters then all appear to start falling again as temperature increases further. The result is that crater size (depth, diameter and volume) appears the same at both room temperature and 900 K, but has increased by x1.5 (depth), x2.25 (diameter) and x2.25 (volume) at intermediate temperatures.

A broadly similar behavior is observed for the sandstone data in Fig. 4. There again appears to be an initial increase in depth, diameter and volume as temperature increases. But this time the increase is quicker, and appears to peak at around 300 K, before broadly maintaining crater size until 500 K, after which it falls back to its original size around 800 K. The peak increase in crater size was x1.5 (depth), x1.25 (diameter) and x2.3 (volume).

The basalt samples displayed a different behavior to the other rocks in Fig. 4. Here crater depth, diameter and volume all fall as temperature is raised. The fall appears to follow an exponential-like decay and flattens off by around 800K. The total decrease in crater size was roughly x1.5 (depth), x1.5 (diameter) and x6 (volume).

The three rock types thus displayed two types of behavior, with the limestone and sandstone showing one type (an initial rise, and then a near equal fall, in crater dimensions as temperature increases), whilst basalt craters decrease in size.

4. Results: Crater Shape

Using the data from the 3D reconstructions, it is possible to see how crater shape changes with temperature. In Fig. 5 we show radial profiles for all three types of target. In each case we show typical profiles at a range of temperatures. For limestone the deep central pit is present at all temperatures. It however becomes more pronounced as temperature rises, then at the highest temperatures the central pit starts to broaden in to the wider crater. In sandstone, the central pit becomes narrower and deeper as temperature increases. By contrast, in basalt, the central pit/shallow spall zone pattern was less pronounced at room temperature than in the other two samples, with no pronounced shallow spall zone around it. The central pit appearance then almost disappears as temperature increases, with a near linear variation of depth with radius at the higher temperatures.

5. Discussion

The overall shape of the craters is mostly (basalt excepted) dominated by two features, a deep central pit and a broader surrounding shallow spallation region. This is typical of impacts in brittle materials in the strength dominated regime. Extensive literature exists on this, and, for example, experiments on rocks in the same facility show how craters grow with impact speed and angle of incidence [7]. Indeed, this behavior is general for brittle materials, not just rock, and can also be seen in glass, e.g. [8], and ice, e.g. [9]. In ice, the change in crater size has been reported over the temperature range (100 – 253 K) [10]. What is reported in [10] is that in ice, the central pit and wide (shallow) spall zone shape is seen at 253 K, but this progressively disappears as temperature is lowered, resulting at 100 K in a broad shallow crater, with only a vestigial central pit. It was reported by [11] that the strength of polycrystalline ice increases as temperature is lowered, suggesting that the absence of a pit is related to increasing strength. The strength of ice varies by a factor of 2 over the temperature range 81 K to 255 K [12], which leads to a change of x1.6 in crater depth for example. This change in crater size with a modest change in target strength, is on the same scale as observed here for the rock targets as they undergo similar proportional changes in strength.

The uniaxial compressive strengths from the literature shown vs. temperature in Fig. 1, do not cover the same temperature range as here, as they start at room temperature. In general however, they suggest basalt and sandstone are undergoing an initial strengthening as temperature increases above room temperature, and after a critical temperature, they start to soften again. Limestone by contrast initially weakens, then maintains a constant strength until around 1000K when it suddenly weakens significantly. If crater size is related directly to compressive strength, then only none of our samples follows a behaviour which tracks that indicated by the compressive strength. For limestone, the strength falls initially as temperature increases to 400 K, but is then roughly constant up to 1000 K. This would explain the increase in crater sizes as temperature increases up to 500 K, but not the subsequent fall. In the case of sandstone, we would expect that as the strength increases with temperature above room temperature, the crater should become smaller – this is the opposite of what is observed. Basalt could be taken as behaving as expected, the basalt strength increases with temperature, and crater size falls. It is only above 1000 K that strength falls, and the behaviour here merits further investigation. But it is clear that in general, the overall pattern in the data for the three rock types used here does not track the compressive strengths given in Fig. 1.

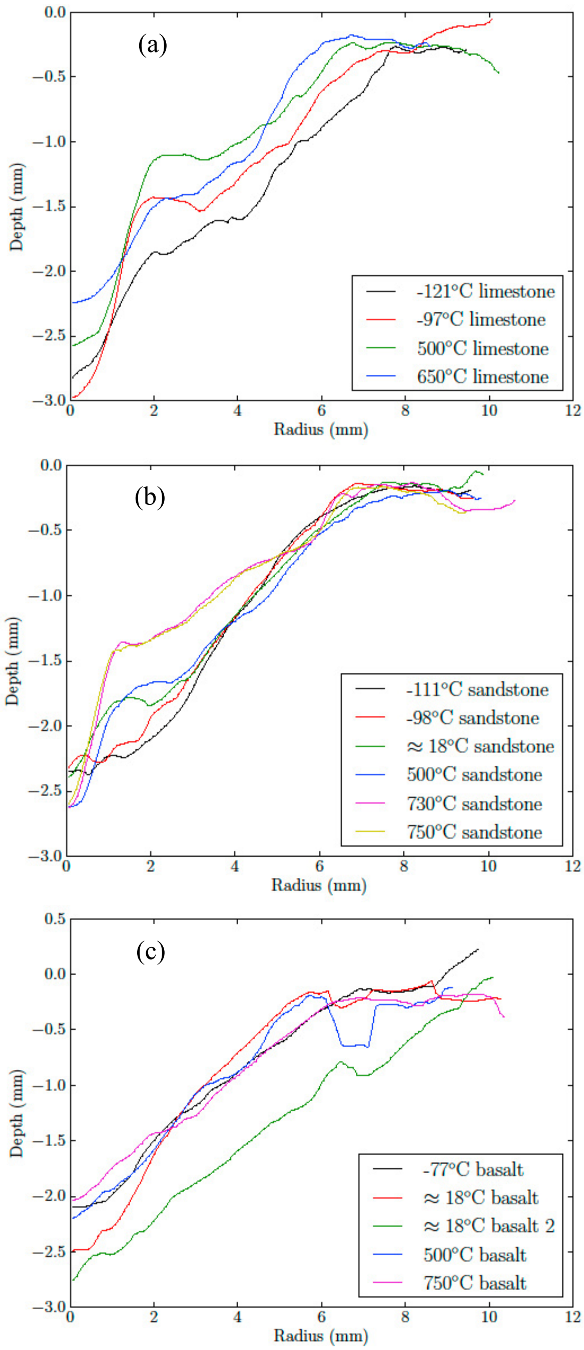


Fig. 5. Radial depth profiles for craters in (a) limestone, (b) sandstone and (c) basalt vs. rock temperature.

It is reasonable to ask if crater size should track strength. Scaling of crater sizes is often described by π-group scaling [1, 13, 14]. This consists of forming dimensionless parameters out of the key variables in the process. In impact cratering it is possible to form a group π_D, which is a linear function of crater diameter, and another, π_3, which depends linearly on, amongst other variables, target strength. In the strength dominated regime, π_D should depend on π_3 inversely to some power which is determined experimentally. This is widely found to be the case. Therefore, as rock strength changes, we should see crater diameter for example vary inversely to some power, which is suggested for rock in Table 7.1 of [1] to be 0.28. So we may expect that if strength varied by a factor of say 1.6 to 1.8 (as it does for sandstone in Fig. 1.), we might find a variation in crater diameter of 14 – 16%. This is slightly smaller than found here but is of similar magnitude.

It was noted by [5] that not all previous compressive strength measurements in the literature are consistent. For example, as shown in Fig. 1, reference [5] found for sandstone an increase in compressive strength with rising temperature (with a maximum at 900 K), followed by a reduction at higher temperatures. Other workers however, found that either there was no initial increase with strength as temperature rose [15], or indeed even a weakening [16]. The issue seems to lie in the exact composition of the samples. Such extreme variability inside one rock type may well prevent any attempt to use literature data for strength to compare to experimental cratering results. The solution would appear to be to do temperature related uniaxial compressive strength tests on samples of the same rocks used in the impact studies. This was not possible here, as our strength rig is neither heated nor cooled.

Regarding the overall crater shape, we note that basalt has a less pronounced central pit surrounded by wider spall zone shape that the other rocks. It is reported by [17], that in high speed impacts (i.e., processes at high strain rates such as the impacts here), basalt behaves as an elastic-plastic material and not as a purely brittle material. This may explain the difference between the basalt and other rock type used here.

6. Conclusions

We have investigated the change in impact crater shape as a function of temperature (range 150 – 1150 K) for three types of rock. We do not find that the variation in crater size tracked the rock strengths given in the literature. For limestone and sandstone, crater size initially grows (to a peak at around 500 K), and then falls again. For basalt by contrast, the crater dimensions fall in an exponential like fashion continually from 150 K upwards. This clearly suggests that rock crater sizes in lab experiments are a function of temperature and cannot be extrapolated to other bodies without taking into account the ambient temperature. However, given the failure of the results to track published temperature related rock strengths, it is not immediately clear how such an adjustment be made.

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