Shot to pieces and shocked to the core

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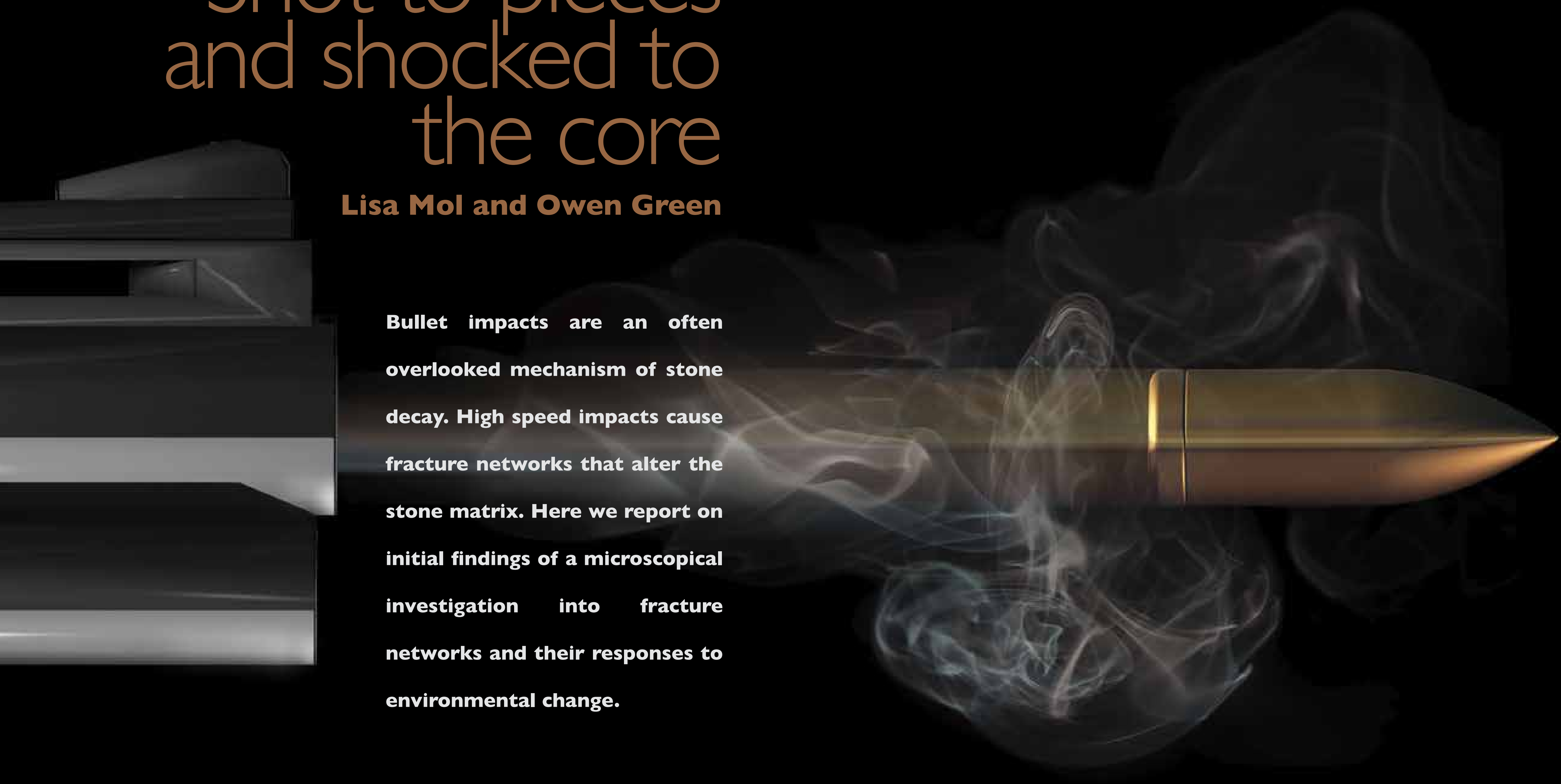

Bullet impacts are an often overlooked mechanism of stone decay. High speed impacts cause fracture networks that alter the stone matrix. Here we report on initial findings of a microscopical investigation into fracture networks and their responses to environmental change.

Figure 1: Close up of Tate Britain in London, exhibiting damage from WWII

Introduction

Widespread destruction of heritage is occasionally documented in the media, especially when high-profile structures are involved such as the Buddhas of Bamiyan, caught in the cross-fire or deliberately targeted to eradicate the cultural and religious identity of the opposition. Traces of damage are visible, even within the UK. One of the major problems is that we simply do not know the long-term implications of damage such as bullet and shrapnel impacts.

Figure 3: Close-up of WWII bullet impact on the Main Building, Cardiff University, illustrating the complex interaction of the direct impact zone and the fracturing of the surrounding stone

One of the issues is that damaged heritage can take on a new role as heritage in itself, cancelling out the options of complete repair or demolition of the structure. This memorialisation of conflict through preservation of atrocity sites can aid unification of the survivors of conflict or continue to create divisions through constant reminders of events

Figure 2: Close up of Cardiff University Main Building façade with air-raid damage inflicted during WWII

past (see Tunbridge and Ashworth; 1996 for more information). We need to know how to either repair or obscure the impact area and how to consolidate the fracture network to avoid rapid deterioration.

Microscopy enables us to observe these impacts in significant detail; we know that quartz can exhibit features induced through high impact (so called 'shocked' quartz, resulting when quartz crystals are impacted by a high velocity object such as a meteor, but the assumed threshold for this phenomena is 8.5km/s (Amor, K. Pers. Comm 26/11/2013). At speeds of 200-500 m/s a lead bullet would not have enough energy to create shocked quartz (for example Blenkinsop, 2002 p.80; Bohor *et al*, 1984; Kieffer, 1971; Seyedolali *et al,* 1997). We therefore investigate if the restrictions put on the theory of shocked quartz are indeed correct or if this phenomenon can be found in lower impact sites. In addition, we investigated whether clay cementation is affected by such impact and show evidence of 'remoulding' to accommodate a shift in crystal location.

Methodology

Sample type

Blocks of a well-consolidated, homogeneous medium grained sandstone (from the Huesca Province, northeast Spain) were shot at with .22 calibre lead bullets from a distance of 20m. A consolidant was applied to half the samples to test whether or not the elasticity of the surface

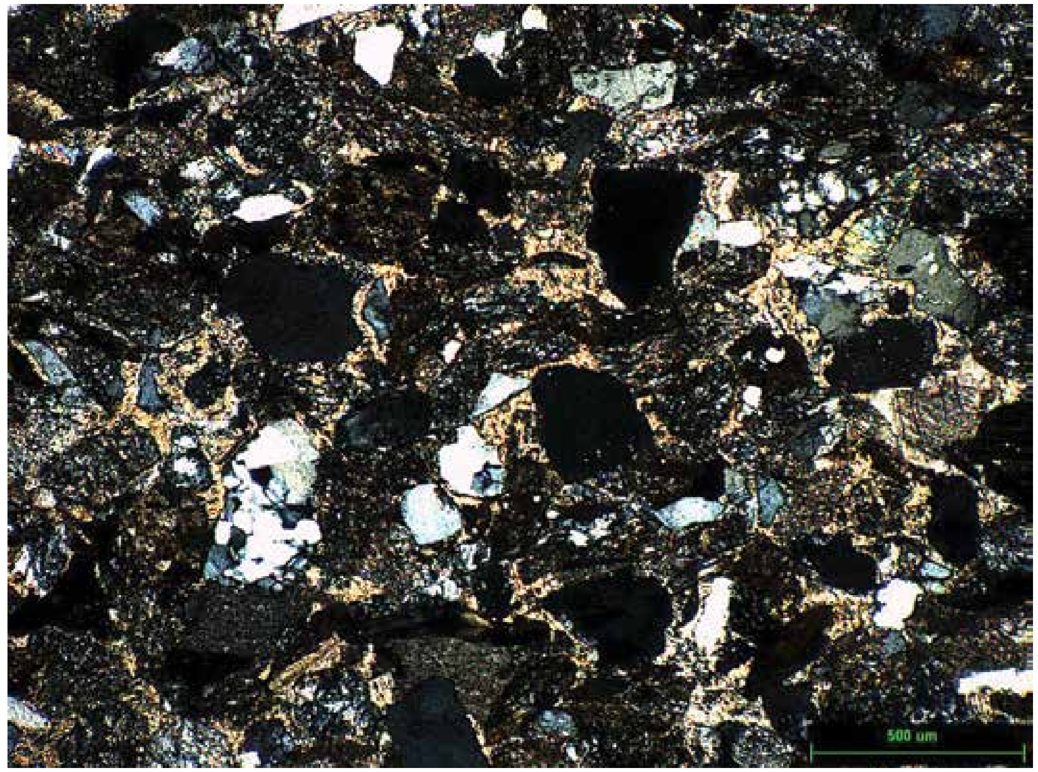

Figure 4: Petrographic thin section of sample 1, a non-treated and intact sample. The clay cementation is clearly visible around the crystals

Figure 5: Application of the Wacker treatment

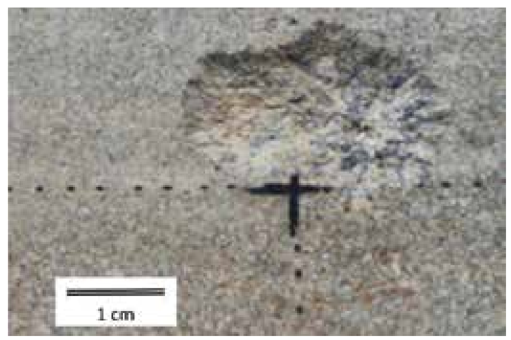

Figure 6: Close-up photo of the impact of the bullet on sample 3

Figure 7: Scan of impact zone of sample 3 (same as Figure 3), scanned using a Mephisto EOS 3D Scanner

influences the nature and extent of the fracture network. The created fracture networks and grain matrix damage were investigated using microscopy.

Consolidation

The consolidant Wacker SILRES BS OH100 was applied to half the samples, as a means of mimicking a hardened weathered surface crust, which is frequently seen on freshly cut building stone exposed to the natural elements.

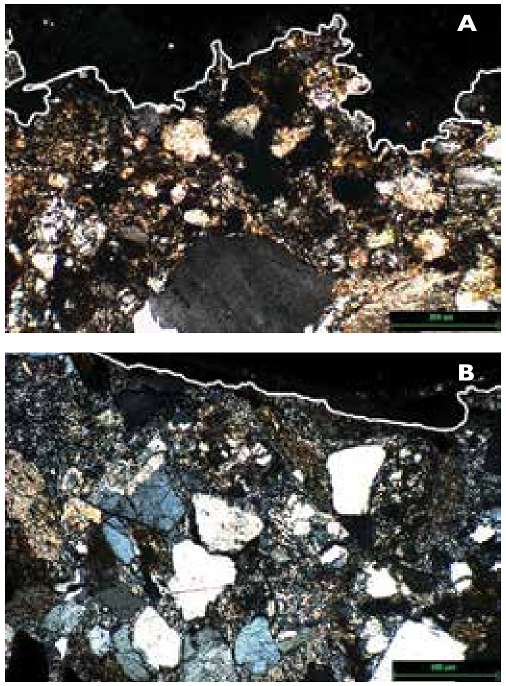

Figure 8: (A) Non-consolidated impact area (x4). (B) Consolidated impact area (x4). White line has been added to emphasise shape of impact area

Bullet impact sample creation

Samples 2-4 and 6-8 were taken to the Witney Rifle Club (Oxfordshire, UK). Samples 1 (not Wacker-treated) and 5 (Wacker treated) were retained as control samples. The lead-based bullets caused relatively little loss of surface material, yet their impact is visually noticeable as shown in figures 6 and 7.

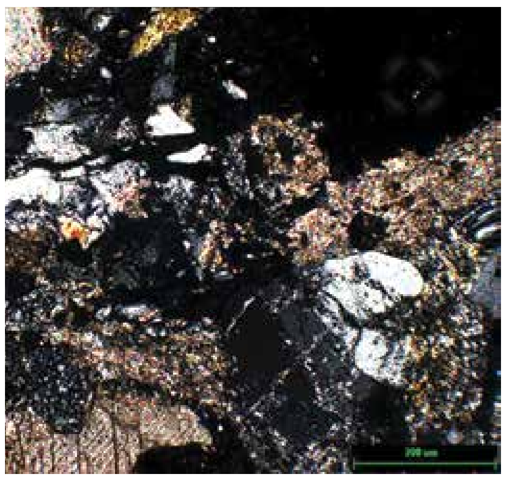

Figure 9: Part of the impact area of sample 2

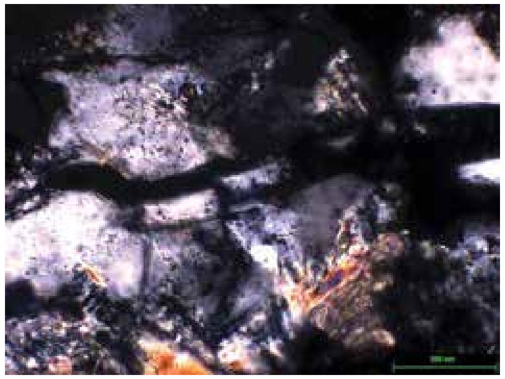

Figure 10: Close up of the fragmented and separated quartz found in the impact zone of sample 2

XRD analysis

Phase Found	Percentage
Quartz	48
Gypsum	17
Calcite	13
Muscovite	13
Kaolinite	6
Clinochlore	3

Table 1: Results of XRD analysis

As table 1 shows this type of sandstone consists largely of quartz and calcite crystals, but the cementation of the crystals consists largely of clay forming minerals, most noticeably kaolinite and muscovite.

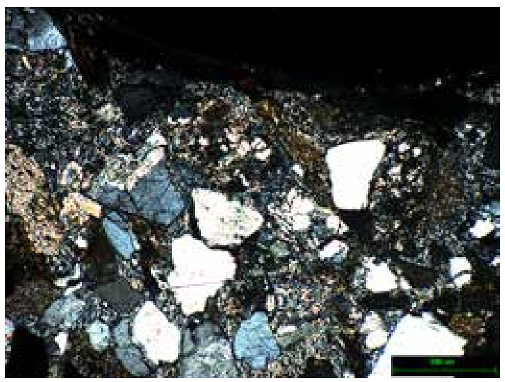

Figure 11: Impact area in a consolidated surface

Results

Impact area development

Impacts areas created in non-consolidated stone are far more 'jagged', (Figure 8(A)) in contrast to

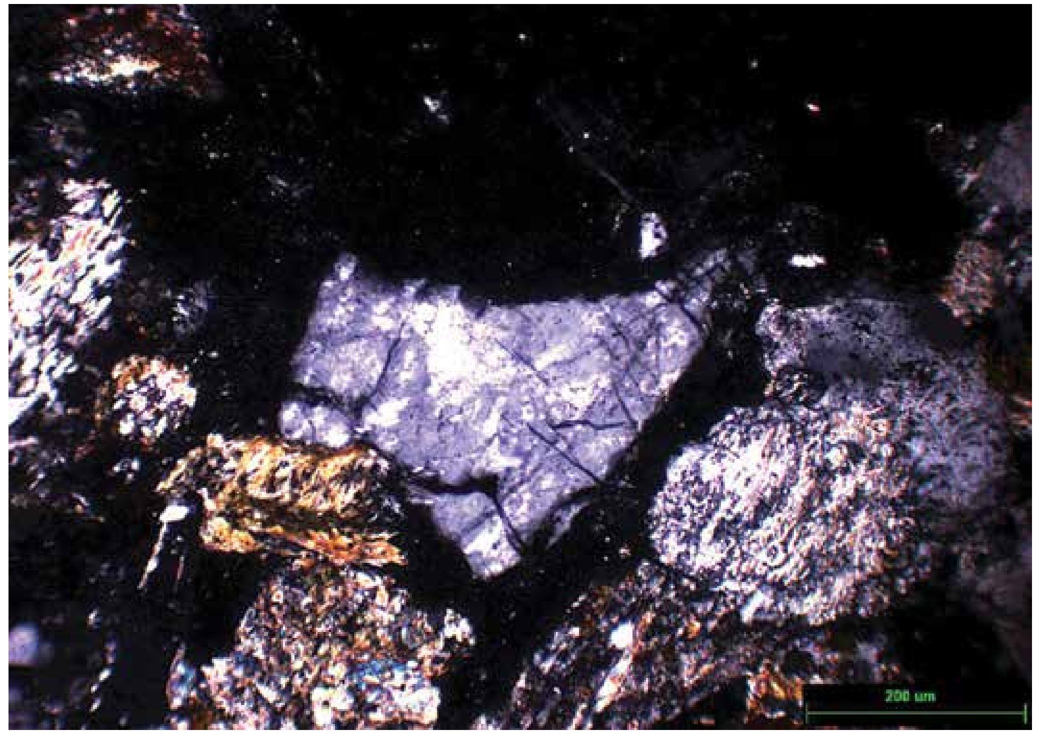

Figure 12: Sample 3 exhibits a fracture network pattern directly adjacent to the point of impact

the consolidated stone where the impact created a shallower and smooth curve (Figure 8(B)). This implies that the consolidant provides a measure of protection to the sub-surface; resulting in fracture between the consolidated layer and the subsurface. In non-consolidated samples no such boundary exists and instead the fracture lines exploit pre-existing weaknesses in the material such as around grains in particularly porous areas.

Quartz fragmentation

Experiments revealed that the quartz grains within the impact zone showed fracturing. Figure 9 illustrates the fractures observed in the impact zone of sample 2 which was not treated with a consolidant. The absence of this surface support has resulted in the separation of the quartz fragment along the fracture line.

The bullet impacted in the area directly to the right of the fractured quartz, indicating that the fracture and subsequent separation of the crystal is the result of the shockwaves generated at impact travelling sideways through the near-surface of the stone sample. The absence of a consolidant, and therefore a higher relative elasticity of the surface, facilitates sideways movement of the crystals. This type of separation was not observed in the samples treated with consolidant (Figure 11). This observation supports the notion that the nature of a micro-fracture network created upon impact is as dependent on the state of the material pre-impact as it is on the type of impact.

Shocked quartz?

While the heat generated by the impact of the .22 bullets is not sufficient to create a large scale

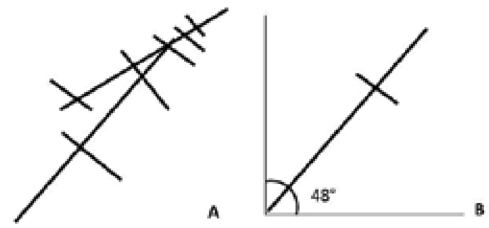

Figure 13: (A) Schematic representation of the fracture network visible in sample 3. (B) Schematic representation of average angle of fractures

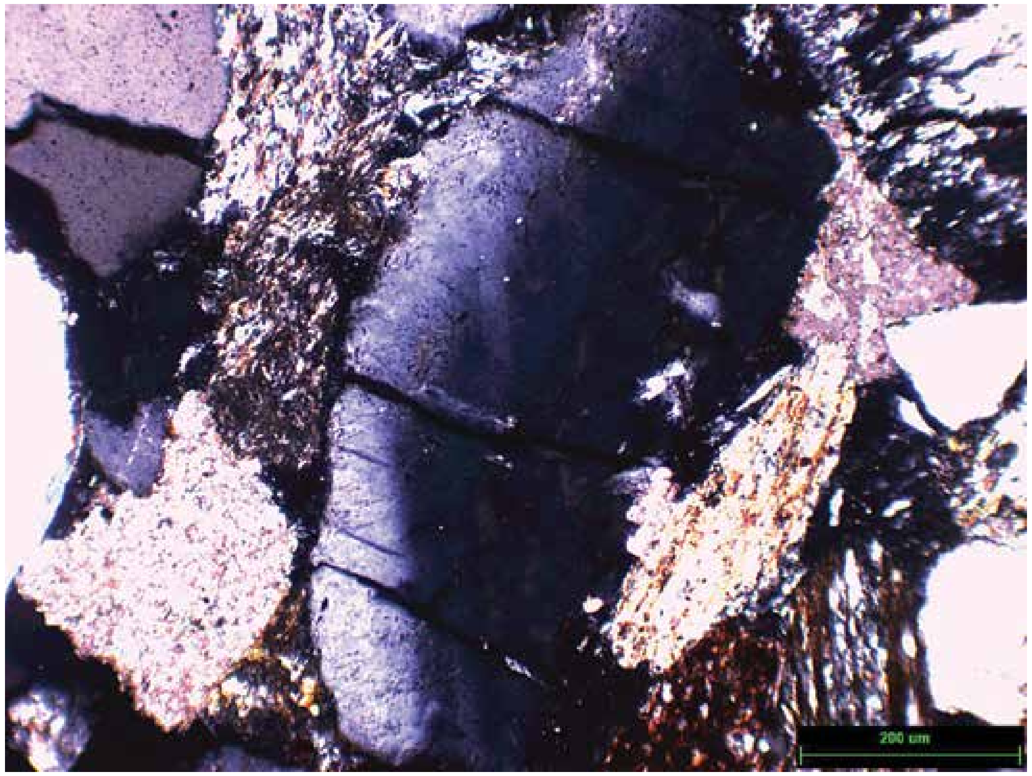

Figure 14: Sample 3, example of grain bruising and parallel fracture networks which were observed in sample 3 around the zone of impact

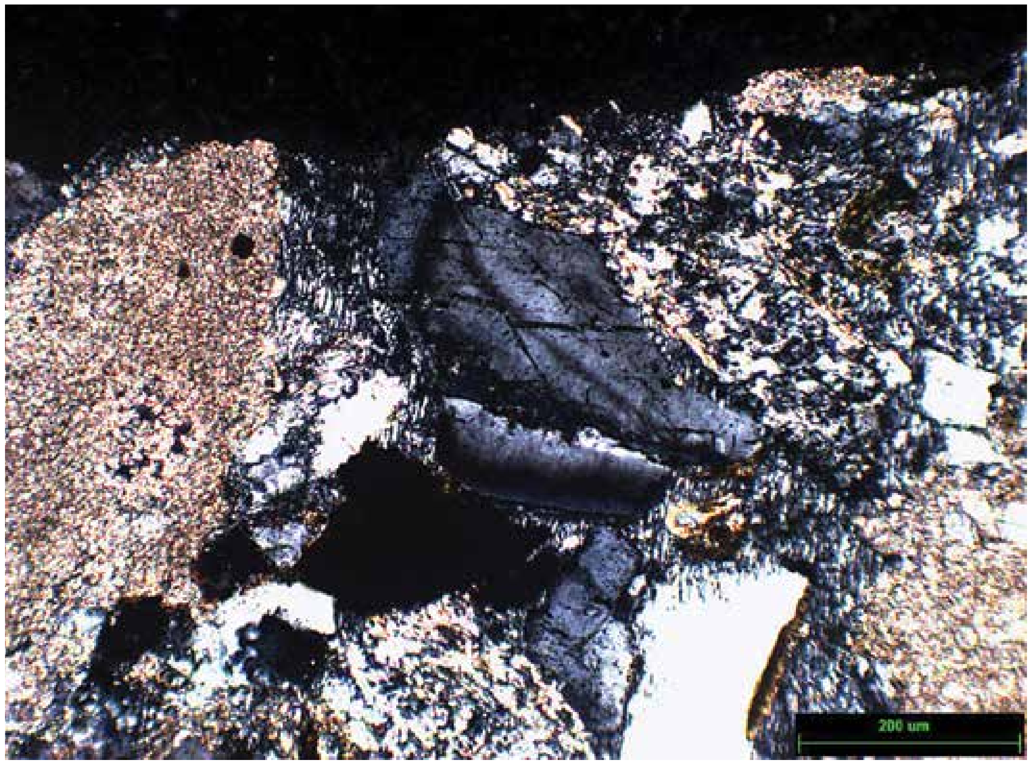

Figure 15: Sample 6 showing a parallel fracture network, similar to those found in the non-consolidated samples

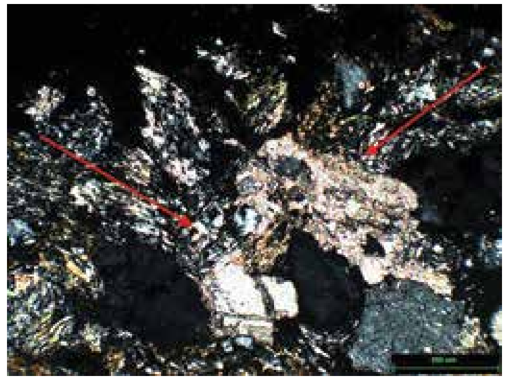

Figure 16: Sample 4 illustrates the realignment of clay minerals in relation to the central bullet impact area (between the two arrows). The arrows indicate the realignment of clay minerals, a feature not visible in the non-impacted sample (cf Figure 4)

deformation, this research aims to establish if there is an intermediate stage of shocked quartz where the tell-tale geometric micro-fracture network is visible but the partial melting of the minerals is absent. Our observations indicate that these small projectile impacts are capable of fractures which mimic shocked quartz (Figure 12) but show no evidence of (partial) mineral melting.

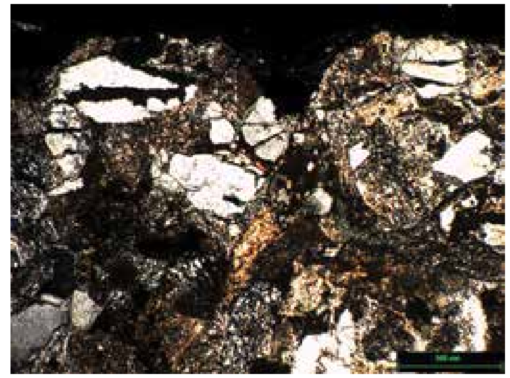

Figure 17: Impact area of sample 7 illustrating lead residues on the surface. The residues become more obvious when viewed using plane polarised light

This sample also exhibits 'bruising' where part of the grain appears to have been reduced in refractive index (also noted by Fratanduono *et al* (2011) in shocked quartz), resulting partial discolouration as observed using cross-polarised light. This discolouration was not observed in grains outside of the direct impact area, indicating that this 'bruising' is closely connected to the shock generated on impact.

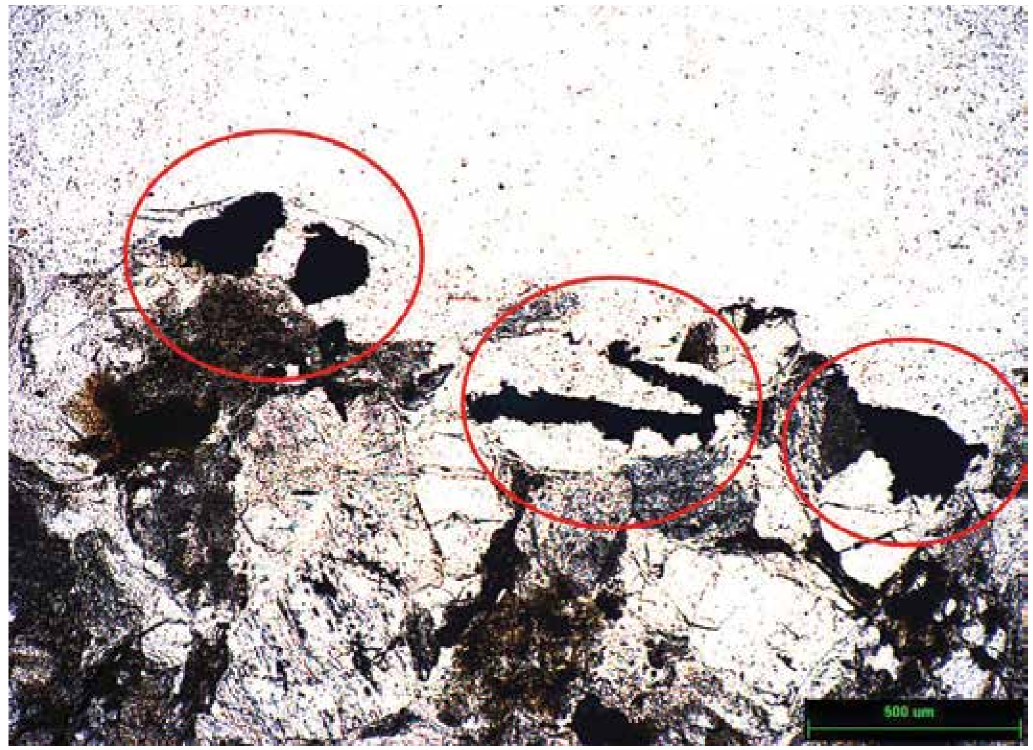

Figure 18: Plane polarised image of the impact area of sample 7, showing lead intrusions into the surface (black areas). The lead has not only deposited on the surface (right hand side) but also within the grains (middle and left)

Figure 19: Close up of the centre section of the lead intrusions into the surface of sample 7 where the lead intrusion has taken advantage of a pre-existing weakness in the grain and has fractured the grain, intruding not only through the centre but also into crevices extending from the centre fracture

The above examples are observed in non-consolidated material. In consolidated material (samples 5-8) similar fractures were observed, implying that even though impact area development may differ the subsurface effects of the impact are identical.

Realignment of the clay matrix

Deformation of the clay (muscovite/kaolinite) cementation indicates a realignment of the general matrix in response to the shock generated on impact.

The reconfiguration of the clay could have long-term implications for the response of the stone to environmental change; as cementation appears to have become compressed potentially lowering the permeability of the stone around the impact area. The relatively high percentage of clay minerals (muscovite 13% and kaolinite 6%) facilitates this compressive cementation. However, further research is required to establish any movement of moisture within the impact areas.

Deposition of lead on and within the surface

Another noticeable difference post-impact is the deposition of metals (lead) on and within the surface. The bullets used were strong enough to impact the surface but weak enough to lose their integral form upon impact, leaving behind a thin film of lead in some areas (Figure 17).

SEM analysis was carried out to focus on the lead deposits using an ESEM FEG. The microscope is a Veeco FEI (Philips) XL30 ESEM (Environmental Scanning Electron Microscope) FEG (Field Emission Gun). We observed that the deposits were indeed lead which adhered themselves within the surface of the impact zone.

Discussion and conclusion

There are similarities between shocked quartz and the impact of bullet holes.

Microscope analysis indicates that bullet impacts alter the substrate significantly, both through removal of material and alteration of the grains within the direct impact area.

Deformation of the primary texture is noticeable and results in the formation of fractures and compaction within the impact area.

The presence of kaolinite facilitates the compaction of the impact area, potentially hampering internal moisture flows. A long-term impact of this could be the development of weak areas around the impact zone where fractures facilitates more rapid through-flow of moisture, accelerating deterioration over a larger area. However, more research will be needed before firm conclusions can be drawn.

The shocked quartz comparison does indeed have some merit, when taking into account the reduced temperature impact compared to meteorite impacts. Evidence of parallel fracture networks and discolouration of the individual minerals points towards alteration associated with shock and heat generation.

The consequences of this research not only impact upon our current knowledge of weathering studies but indeed have further reaching consequences for disciplines such as heritage conservation. Without some knowledge of the development of fragile areas in heritage sites during armed warfare it will be near impossible to develop adequate conservation strategies. Considering the rich body of heritage currently under threat in areas such as the Middle East, and areas which are earmarked to experience higher incidents of conflict in light of political unrest and climate change, it is becoming increasingly important and urgent to understand how these impacts drive deterioration and how we can prevent catastrophic loss over the course of decades.

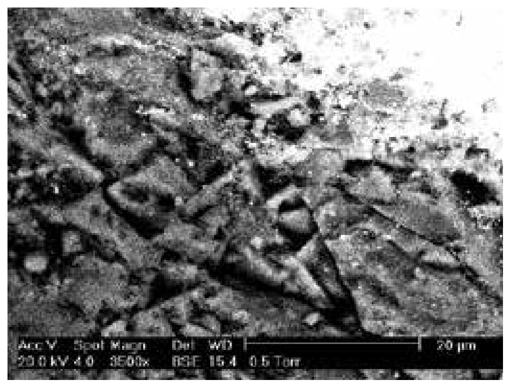

Figure 20: Lead deposit on the impact surface of sample 7, the white areas indicate where lead has covered the quartz grains

In conclusion, this article reports on the initial findings of a laboratory investigation into the microscale effects of bullet impacts upon stone surfaces. It is shown that while the overall shape of the impact area is dependent on pre-conditioning of the surface through case hardening or other cementation of the surface, the damage to grains in the impact zone is near-identical. These correspond to grain damage observed in impact areas of meteorites, though damage is restricted to the direct impact zone.

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