“A MULTIPLE METHODS APPROACH TO ASSESSING BALLISTIC DAMAGE TO HERITAGE STONE”

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The Threat to Heritage Stone

Recent conflicts have illustrated how deliberate targeting of cultural assets by combatants or indiscriminate targeting practices can result in the loss or damage of crucial cultural assets.

This has led to destruction or irreparable damage of a number of famous sites, including Palmyra, the Al-Nouri Mosque of Mosul, and historic districts of Timbuktu and Sana’a amongst others [1,2].

Small arms are the most ubiquitous weapons in these conflicts, and thus it is imperative that we gain an understanding of ballistic damage in order to inform conservation strategies.

Portable, non-destructive and rapid methods will also be necessary in order to assess ballistic damage to stone in inaccessible conflict regions.

Bullet impacts into 3000 year old rock art, Wadi Rum, Jordan[7]

The site of the colossal Bamiyan Buddha in Afghanistan, destroyed by the Taliban in 2001[8]

Previous Work

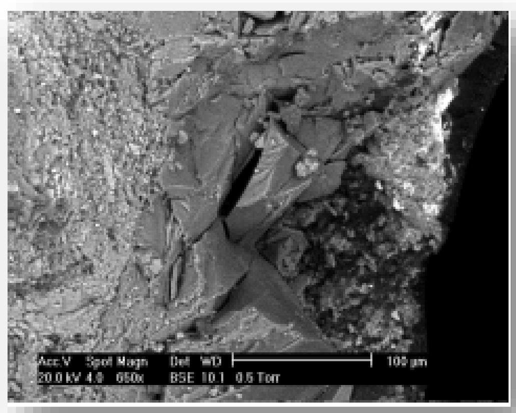
Relatively little work has been undertaken to understand the effects of ballistic impact into stone, although some parallels can be found in research into meteorite impacts [3].

Studies which have studied the effects of bullet impacts have focussed on lower velocity, deformable projectiles, such as .22 lead bullets and musket balls.

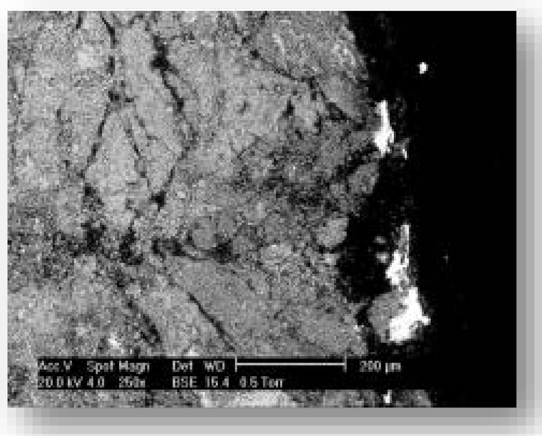
These studies have identified some important trends:

- There is compaction of the stone matrix at the point of impact, which can elevate the hardness of the impact point [4].
- That there is fracturing of quartz grains on a microscopic scale at the point of impact [5].
- X-ray micro-computed tomography (µCT) shows that fractures arising from ballistic impact may exploit pre-existing bedding planes within the stone, [6].

Fracturing of sandstone quartz grains after Ballistic Impact[9]



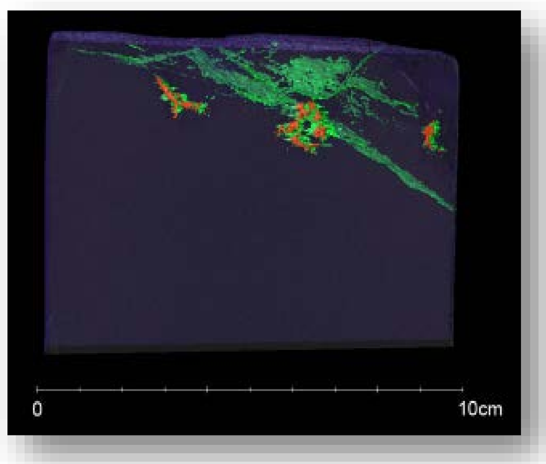
Compaction of Sandstone matrix after Ballistic Impact[9]



Research Objectives

- To explore the potential for surface studies of stone impacted by military grade ammunition (7.62 x 39mm) to reveal surface fractures and other damage patterns, which weaken the stone, and could feasibly contribute to accelerated weathering of the stone [6].
- To establish whether findings established for lower velocity projectiles hold true for modern military ammunition.

Fracture networks along bedding planes in impacted sanstone[10]



Materials & Methods

The sample was a well consolidated block of mesoporous Huesca sandstone measuring 14.7cm x 14.7cm x 14.7cm. The stone was freshly quarried, so as to avoid any pre-existing defects caused by exposure to weathering. The sample was then shot with a 7.6x39mm cartridge fired from an AK-103 assault rifle at a range of 200m. To ascertain the surface hardness and permeability of non-impacted stone a control sample of non-impacted Huesca sandstone was used.

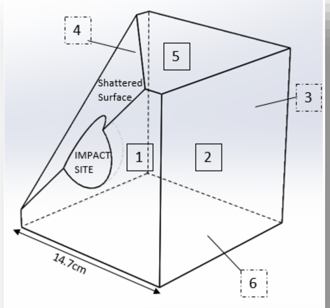
On each of the sides of the sample, an alpha-numeric grid was created to facilitate sampling using permeametry and Equotip rock surface hardness readings. All measurements were conducted 3 times for each cell and averaged.

The rock surface hardness survey of the sample surface was conducted using a Proceq Equotip portable Rockwell probe. The Equotip measures surface hardness by firing a 3mm tungsten ball at the target surface at a known velocity. The rebound velocity is measured, and the ratio between the initial and rebound velocities is multiplied by 1000 to give a hardness in Leebs (L)

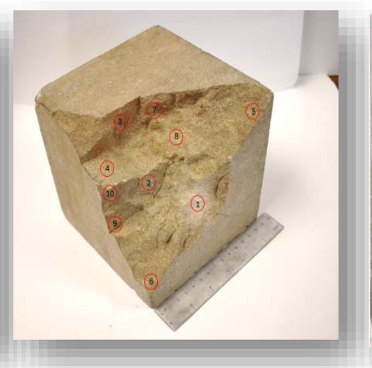
The permeability of the samples’ surface was investigated using a New England Research TinyPerm3 air Permeameter. This instrument assesses permeability to air of the stone by creating a vacuum through a piston stroke, drawing air from the sample. The instrument monitors the volume of air withdrawn, and the transient vacuum pulse created at the surface. This data is computed by the instrument and converted into a permeability value in Darcys (D).

The sample was scanned using a Nikon XTEK320/225 Custom Bay CT scanner CT data was reconstructed in Nikon CT-Pro software and exported as 32-bit .vol data for further processing. Data was subsequently imported in Avizo 9.6.

Schematic diagram of the sample side code system



The sampling regime used on the sheared surface



The alpha-numeric cell used for surface surveys

Surface Survey Results

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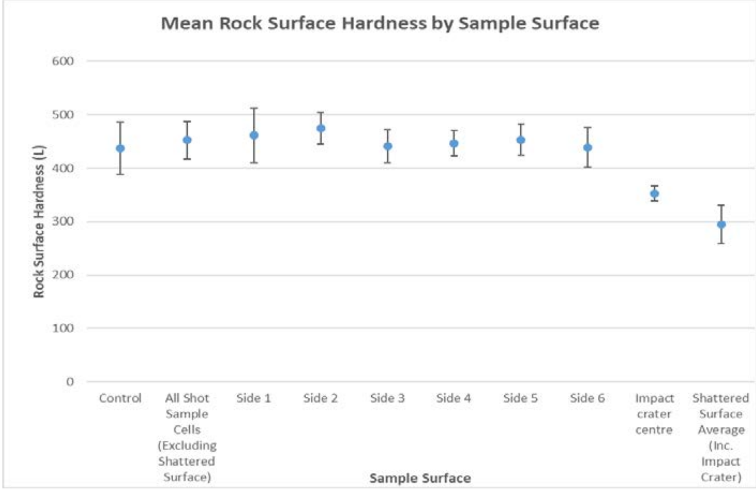
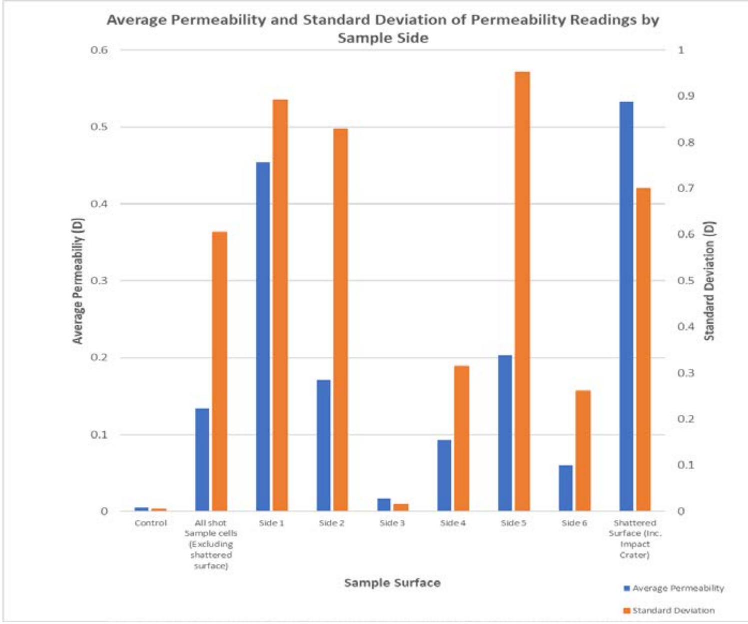
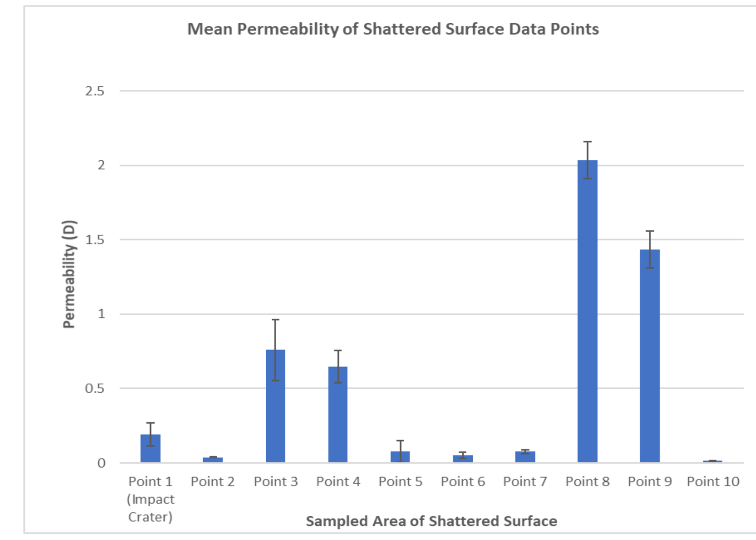
- The Equotip hardness data shows that the shattered surface and impact crater have a much lower hardness than the impacted side.
- The Impact crater appears to undergo a lesser loss of hardness than the wider shattered surface. This is likely due to the compaction of the stone matrix in the impact crater highlighted in other studies.
- Permeability data shows that the impact face and shattered surface have the highest permeability and standard deviation, whilst sides furthest from the impact have the lowest. Fracturing of quartz grains in the impact crater may lead to slightly higher permeability compared to other areas of the shattered surface.





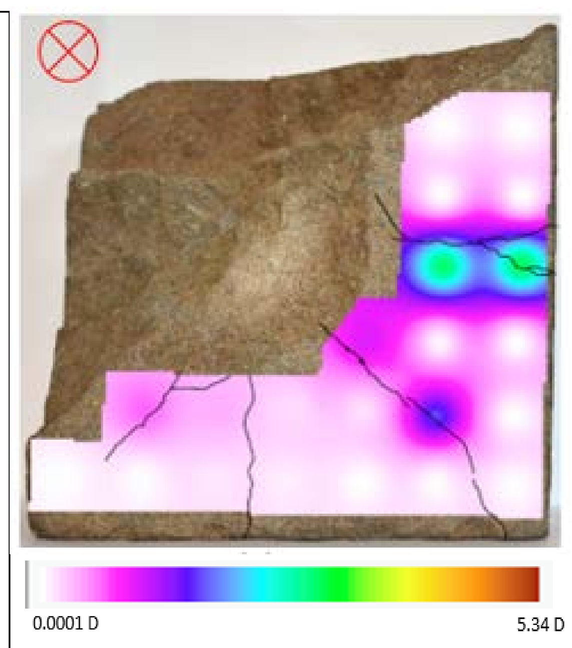


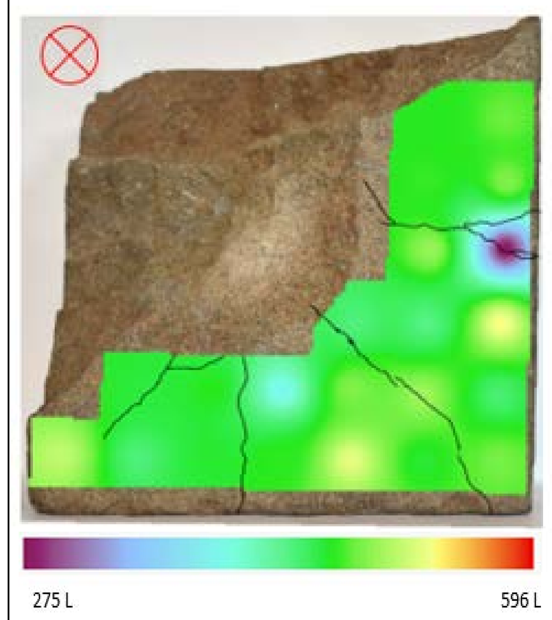
Spatial distribution analysis (“Heat Mapping”)

The data for permeability and surface hardness for each cell was converted into a series of heat maps covering each of the 6 sides of the sample using the ArcGIS Pro software package.

The permeability heat maps appear to strongly correlate to the fracture patterns evident on the sample surface, illustrating the ability of permeability surveys to find likely points of ingress of weathering agents, such as moisture and salt.

Although there is some agreement between areas of lower hardness and the presence of surface fractures, there surface hardness data seems to be less indicative in this area. This may be due to a larger network of micro-fractures associated with those surface fractures which do exhibit reduced surface hardness.

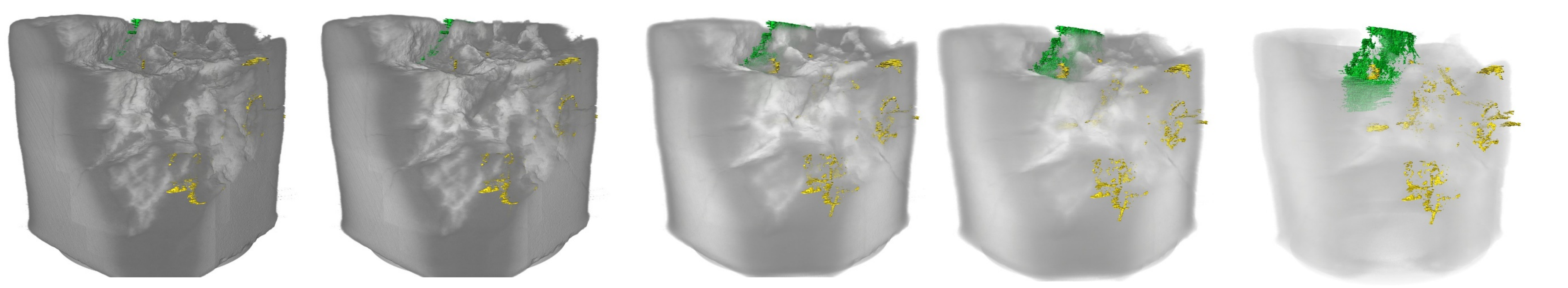




µCT Results

The CT scanning data was analysed by segmenting each of the individual TIFF file frames which made up the three-dimensional volume file. On each frame, any identifiable fractures were highlighted. It should however be noted that due to constraints of the masking function used in Avizo 9.6, not all of the internal fractures were highlighted.

The most notable trend from the CT data is that the fracture networks occur along three distinct planes, and these planes are visible on the exterior of the impacted sample as step-like fractures. The fact that this portion of the sample appears to have failed along these step-like fracture networks supports the conclusions of previous work, which suggested that the ballistic impacts cause fractures which exploit pre-existing bedding planes in sedimentary rock.



Conclusions

The results presented here serve to illustrate that surface surveys of surface hardness and permeability can be used as a portable, non-destructive means to rapidly assess damage to stone impacted by ballistic projectiles. Specifically, surface hardness surveys are effective at identifying the point of impact of the projectile, and any surface which experienced shearing or shattering at the time of impact. Permeability is also effective at discerning those sides which experienced most or least damage at the time of impact, as well as proving useful in identifying the spatial distribution of surface fracture networks.

This work has also provided evidence that suggests that conclusions reached in previous works using lower velocity projectiles have some validity when investigating modern military ammunition. The higher surface hardness at the point of impact relative to the shattered surface suggests that there is compaction of the stone matrix in this area. Furthermore, the slightly increased permeability of the impact crater when compared with other areas of the shattered site may be indicative of fracturing of quartz grains on a microscopic scale. Finally, the µCT scanning results suggest that failure of the stone may following bedding planes inside the sample.

Further work

Further work will be required to assess whether permeability and surface hardness values are related to fracture length and density. This could be done through a combination of destructive thin-sectioning for optical microscopy and further µCT scanning to fully understand the extent and morphology of the fracture network arising from high velocity projectiles impacting stone.

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