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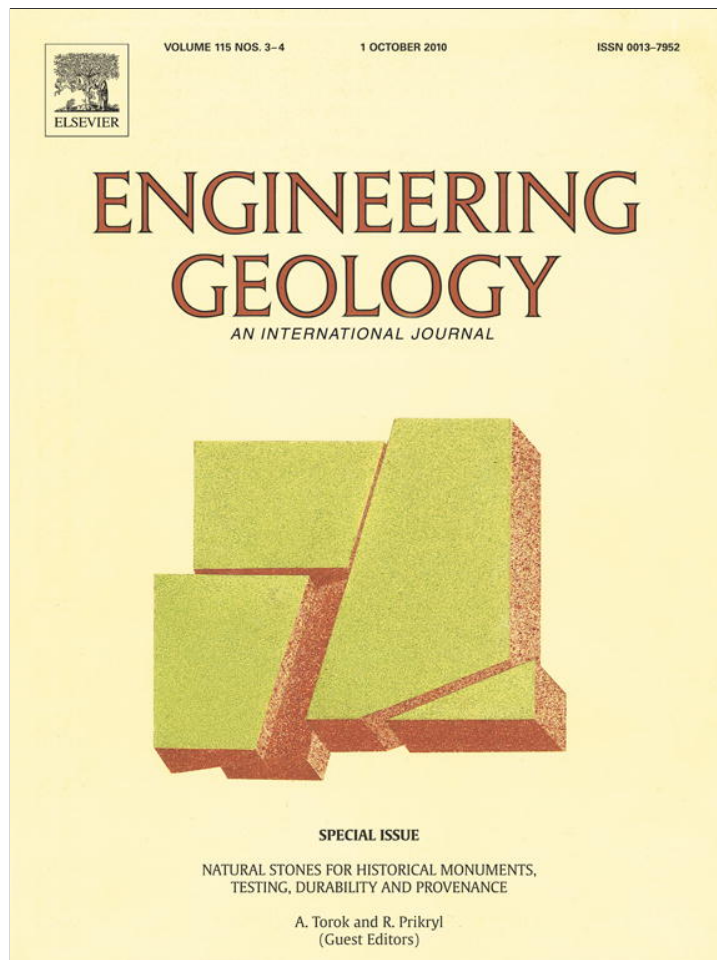Link to publication record in Queen's University Belfast Research Portal

Exploitation of inherited weakness in fire-damaged building sandstone: the 'fatiguing' of 'shocked' stone

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ABSTRACT

The problem of the long-term impact of historical fire on masonry is not clearly understood. Much research focuses on the damage that is caused by fire in isolation, and omits to investigate the subsequent exploitation of weaknesses inherited from fire events. Fire can, for example, cause significant physical, chemical and mineralogical change to sandstone, which may then be exploited by background environmental factors such as salt and freeze–thaw weathering. To explore this experimentally, blocks of Peakmoor Sandstone were subjected to a real fire (as well as lime rendering/removal and frost cycle pre-treatments), and their subsequent response to salt weathering cycles was monitored by weight loss and visual assessment of the pattern of surface damage.

Results illustrate that the post-fire deterioration of sandstone is strongly conditioned by fracture networks and soot cover inherited from the fire. The exploitation of fractures can lead to spalling during salt weathering cycles — this takes place as granular disaggregation steadily widens cracks and salts concentrate and crystallise in areas of inherited weakness. Soot cover can have a profound effect on subsequent performance. It reduces surface permeability and can be hydrophobic in character, limiting salt ingress and suppressing decay in the short term. However, as salt crystals concentrate under the soot crust, detachment of this layer can occur, exposing fire-damaged stone beneath. Understanding the subsequent exploitation of stone exposed to fire damage by background environmental factors (for example, salt weathering/temperature cycling) is key to the post-fire management of stone decay.

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1. Introduction

Fire is an important agent of change in rock weathering (Blackwelder, 1926; Emery, 1944; Dorn, 2003; Scotter, 1970). It has also been identified as an important factor in the cultural context of conserving monumental heritage, raising the crucial (but little explored) issue of the potential long-term impact of historical fire on the performance of masonry (McCabe et al., 2007, 2010). Fire is clearly a major threat to cultural heritage, with estimations of one historic structure being lost every day in the EU (Gómez-Heras et al., 2006a; COST C17, 2001). Over their long lifespan, it is likely that a historic structure will experience fire, perhaps on more than one occasion (Obojes et al., 2006). Fire damage is also a concern in the preservation of rock art (Tratebas et al., 2004), where irreplaceable works of ancient art are destroyed by fire each year. With this threat to cultural heritage ever present, practical research is needed to better understand the complex problem of fire damage to stone, and, in the important context of complex stress histories (McCabe, 2007; Smith and Prikryl, 2007), how the stress legacy inherited from fire can be exploited by subsequent background environmental weathering processes. This paper explores the supposition that stone response to stress is invariable cumulative, and the immediate impact of a fire event will depend upon previous stress history, and will in turn determine response to any subsequent stresses. If this is the case, then historic fires could have important consequences for subsequent stone performance. However, research often focuses on damage produced in the fire itself and omits to investigate the subsequent exploitation of inherited weaknesses (an area important for the post-fire management of stone) — the impact of historical fire has not been rigorously investigated with regard to its role in determining the long-term weathering response of sandstone.

One of the complicating factors in this inheritance is the probability that the impact of historical fire on masonry is not likely to be uniform — each block in a façade may experience different temperatures for different durations, leaving the structure with a wide range of inherited effects. For example, some stone may have been escaped the impact of fire altogether and have no 'memory' of the event. Other blocks may have been affected in the near-surface zone, and may now have lost the 'memory' of historical fire through the detachment of 'failed' material. Perhaps most importantly for the subsequent management of decay, many blocks, although showing no obvious evidence of physical damage, may now conceal a complex 'memory' of both fire and other previous stresses and so contain weaknesses that are yet to be exploited (McCabe et al., 2007, 2010).

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This non-uniform response of masonry to fire is a reflection of the nature of fire itself — temperature changes are not consistent spatially or temporally. Thus, they can rise extremely rapidly at the surface (creating steep stress gradients), but are not stable, fluctuating continually through time. Added to these physical attributes of a fire, the gases produced in a wood fire are complex, and the surfaces of stone blocks are likely to accumulate deposits of combustion particles and residues (for example, soot and oils) (McCabe et al., 2007, 2010).

This paper takes an experimental approach to exploring these issues as there is no standard test for fire-damage to building sandstones or their response to salt weathering after fire. As pointed out by Warke & Smith (2007), standard durability tests with regard to salt weathering (see Leary, 1986) are limited in giving an real understanding of the decay pathways of sandstones. One of the experimental elements of this paper is to use a salt solution closer to reality (in terms of concentration) than those often used in standard tests, thus helping to reveal subtle nuances in the decay pathway of a building sandstone after exposure to fire.

1.1. Physico-chemical impacts of fire

Fire has both physical and chemical implications for stone decay. Physical strain can be brought about because of the sudden extreme temperature changes caused by fire. Surface to sub-surface stress gradients are rapidly established, and can cause spalling or splitting of rock. The thermal diffusivity properties of a sandstone are key to its response to fire or extreme heat. The thermal diffusivity characteristics control the difference in temperature between rock exterior and interior, and hence the rate of differential expansion (Goudie et al., 1992) — which, if it exceeds the ability of the stone to adjust enough to accommodate the required deformation, can cause spalling (the result of compressive surface stress and the shear stress induced by it (Yatsu, 1988)). This is a common response to thermal shock, which describes change/stress that is beyond the ability of the stone to absorb. Thermal shock can occur when temperatures rise or fall very suddenly, generating steep surface/substrate temperature gradients. It is the mechanical failure of stone brought about in response to a single event. This is in contrast to fatigue, which describes the mechanical failure of stone in response to the slow accumulation of repeated thermal stresses over time (Gomez-Heras, 2006; Yatsu, 1988). In granular rocks such as sandstone, physical disruption by fire can occur at the scale of single grains, for example, it is common for quartz grains to fracture when temperatures exceed 573 °C (Chakrabati et al., 1996). For this reason, past studies have suggested that quartz sandstones can be particularly susceptible to extreme heat (Goudie et al., 1992).

Chemically, the extreme heat caused by fire can induce changes in the mineral matrix or cement of a sandstone. As is often the case in

Fig. 1. Localised fire at the base of a wall at Dungiven Priory, Co. Londonderry, Northern Ireland.

Table 1
Summary of characteristics of Peakmoor and Dungiven sandstones (Dungiven Sandstone permeability measurements taken from weathered field sample).

	Peakmoor Sandstone	Dungiven Sandstone
Age	Carboniferous	Carboniferous
Mineralogy	Quartz, kaolinite	Quartz, kaolinite, montmorillonite
Colour	Buff	Buff
Av. permeability	31.67 mD (range 9.42–88.2 mD)	210 mD (range 156–301 mD)
Water absorption capacity	5.07% (by wt)	4.4% (by wt)

stone decay, chemical processes can weaken the integrity of the stone, leaving it susceptible to physical decay processes and mechanisms. It has been suggested that, while mechanical decay by fire plays an important role in the breakdown of more dense stone types (for example, granite and basalt), chemical weathering in the form of matrix alteration is more important in the decay of sandstones (Gómez-Heras et al., 2004). A common form of chemical action caused by fire is the oxidation of iron — even with minor amounts of iron (ferrous minerals) in the cement of a sandstone, significant colour change can occur with oxidation (Gómez-Heras et al., 2004). Compositionally, most sandstones have minerals that contain iron (for example, goethite, glauconite, talc, haematite), usually forming a cement, or comprising clay minerals in pore spaces. The ultimate product of heating iron oxides is haematite (Hajpal and Török, 2004), the most stable phase of iron. When iron is present in less stable forms, for example, goethite, it can transform to haematite when temperatures exceed 300 °C (Hajpal and Török, 2004), bringing with it a change in colour (often to reddish/pink). At 900 °C the typical pattern of well-crystallised haematite develops. The first stages of this transformation are spoken of as the disordered embryo haematite structure (Brindley and Brown, 1980).

Further to physical stress gradients and mineralogical alteration, fire damage can include the by-products of fuel burning. Fig. 1 shows a photograph of a localised fire at Dungiven Priory, Co. Londonderry, Northern Ireland. Reddening of the stone has occurred due to the oxidation of iron (discussed above), but more obvious than that is the blackening from soot. The impact that soot can have on subsequent decay is the subject of ongoing research, but initial reports by McCabe et al. (2007, 2010) suggest that the presence of soot can lower surface permeability as well as potentially lending the stone surface a hydrophobic character.

2. Methods

To explore the impact of fire on sandstone, and the subsequent exploitation of inherited weaknesses, blocks of Peakmoor Sandstone (characteristics for this sandstone, and Dungiven Sandstone from Dungiven Priory shown in Table 1) were subjected to various stress histories. A summary of the different stress histories experienced is shown in Table 2 — these are based on the event timeline of a real historic sandstone structure in NE Ireland, Bonamargy Friary (described by McCabe et al., 2007, 2010). This includes founding and lime rendering (1500), fire (1584), exposure to LIA conditions
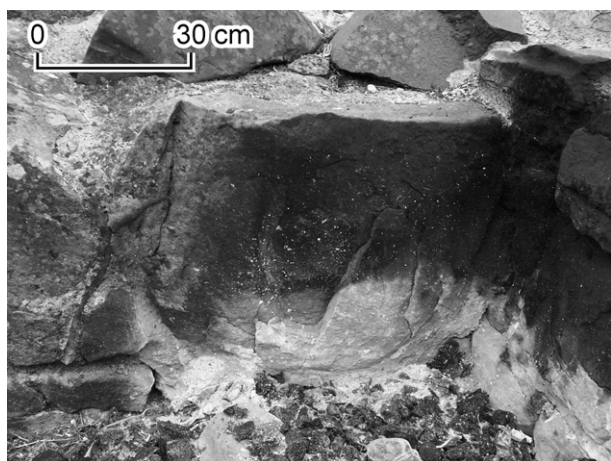
Table 2
Summary of stress history groups 1–5.

	Lime	Fire	Frost	Salt
Group 1				★
Group 2			★	★
Group 3		★		★
Group 4		★	★	★
Group 5	★	★	★	★

(c. 1590–1850) and the present-day temperate maritime environment — each of which is likely to have an important impact on the decay pathway of the stone. An outline of the pre-treatments carried out to investigate these events follows.

2.1. Lime render pre-treatment

Lime rendering of building sandstones has been shown to have significant implications on subsequent decay (particularly for non-calcareous stones), carrying both chemical (in terms of potential sulphation due to calcium loading) and physical (in terms of surface roughness and pore blocking) consequences (Smith et al., 2001; McCabe et al., 2006; Young, 2006). It has been hypothesised that, while lime render may initially increase the integrity of a stone surface, after the render has been removed or has deteriorated over time, the exposed stone may experience accelerated decay through the action of calcium salts (for example, gypsum). Furthermore, salts have been shown to concentrate more at depth (up to 3 cm) in blocks that have previously been rendered than in unrendered blocks. This may be due to the blocking of surface pores by the surface rendering which effectively prevents salts being drawn back to the surface upon drying (McCabe et al., 2006).

For this experiment, walls of Peakmoor Sandstone (comprising blocks from group 4) were constructed in the laboratory and rendered with lime putty in an attempt to simulate a simple medieval lime mortar. The walls were sprayed regularly for the first week with a fine mist of water to stop the render drying out too quickly and cracking. After 1 month, the walls were demolished and the render was chipped and scraped off blocks, before proceeding to the next pre-treatment appropriate to each stress history group (Table 2). This rendering was short term, but aimed to achieve both the initial calcium loading of the stone (by lime water) that can occur as render dries, and the physical surface sealing effect of the render.

2.2. Fire pre-treatment

Three stress history groups (3, 4 and 5) of Peakmoor Sandstone were burned in a real wood fire (described in detail in McCabe et al., 2007, 2010). One of these groups had been previously lime rendered (Group 5). Blocks were placed in an empty oil drum and surrounded by wood. The fire was lit and was not interfered with — it was allowed to take its natural course, rather than be extinguished (it is unlikely that historic fires were extinguished with the same efficiency as in the present day). The duration of the fire was approximately 220 min (from the lighting of the wood until blocks re-achieved a temperature reflecting ambient air), wit flames reaching 590 °C at their peak, and stone surface temperatures reaching 330 °C. Temperatures in the centre of the fire exceeded 700 °C. The fire experiment was characterised by the non-uniform response of sandstone blocks — some faces were scorched black with soot, some were reddened by oxidised iron, some were unaltered in appearance. The soot lowered the average permeability of the surface (from 31.67 mD from a range of 9–88 mD on fresh Peakmoor Sandstone, to 28.20 mD from a range of 8–60 mD). These variations in response highlight the spatial and temporal complexity of temperature fluctuations during a fire event. This pre-treatment was carried out to give the blocks a thermal shock inheritance — the exploitation of which was explored by salt weathering cycles (described below).

2.3. Freeze–thaw pre-treatment

To simulate the exaggerated effects of freeze–thaw that are likely to have been experienced during the Little Ice Age (increased frequency and intensity are proposed, with data reported by Swindles (2006) suggesting that conditions were both colder and wetter) blocks of Peakmoor Sandstone (from stress history groups 2, 4 and 5) —

including blocks that had previously undergone lime rendering and fire pre-treatments in isolation and combination, and one group of fresh blocks — were subjected to 50 freeze–thaw cycles. At the beginning of each alternate cycle, blocks were immersed in de-ionized water for approximately 10 s to provide moisture. Temperatures cycled between 10 °C and − 10 °C (Fig. 2). The decrease in average ultrasonic pulse velocity in Peakmoor blocks over the 50 freeze–thaw cycles (2984 m/s to 2583 m/s) implies increased discontinuities in blocks as a result of this pre-treatment (with consequences for subsequent salt weathering).

2.4. Analysis of mineralogical change

Clay minerals, common in the matrix of sandstones, are very susceptible to the effects of heat. Studies using Fourier Transform Infrared spectroscopy (FTIR) analysis have monitored clay mineral alteration with changes in temperature (Berna et al., 2007, Kolarikova et al., 2005, Bruno et al., 1992). When clay minerals are heated above room temperature, they can begin to lose pore and adsorbed water. Shrinkage is caused as the water is lost, and plasticity is reduced. From 100 °C–300 °C, smectites begin to lose the ability to swell again — this is related to the complete loss of interlayer water. Between 200 °C and 300 °C, the oxidation of organic matter in the clays takes place (followed by the oxidation of sulfides from 400 °C to 500 °C). Between 400 °C and 700 °C the hydroxyl structural water is lost. Within this temperature range, the structure of the clay minerals themselves is often altered (Grim 1962). Kaolinite, a common clay mineral in sandstone (and present in Peakmoor Sandstone) is said to structurally collapse at approximately 500 °C (Hajpal & Török, 2004). Following the loss of coherent structure, clay minerals often develop new crystalline phases (that are not as stable as the original form). Alteration of clay mineral structure can mean a deterioration in the properties of the material — i.e. more susceptibility to exploitative decay processes and a reduced ability to absorb change (Kolarikova et al., 2005).

Mineralogical analysis of clays held in samples after the furnace/fire pre-treatment (from both surface and substrate) was carried out
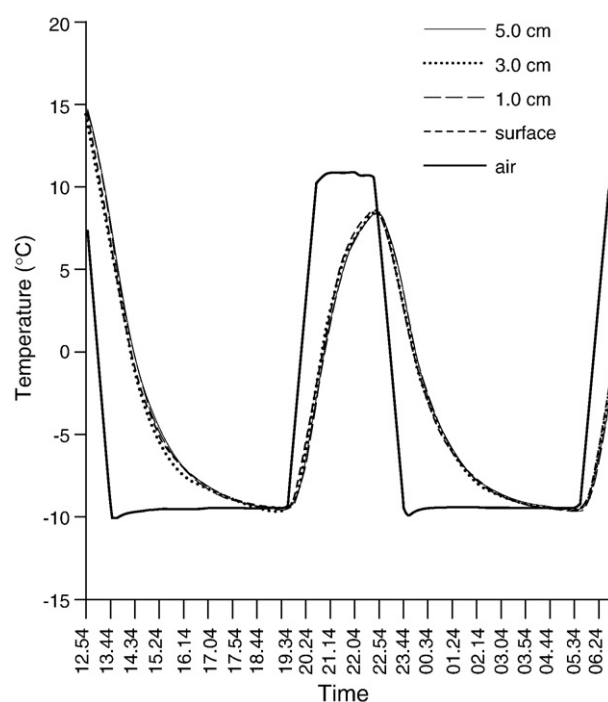
Fig. 2. Temperature regime during freeze–thaw pre-treatment (from McCabe, 2007, reproduced with permission from Springer).
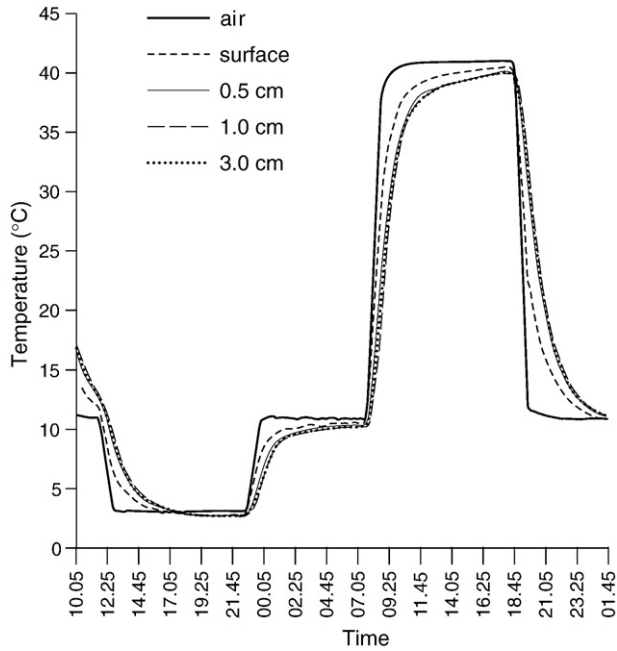
Fig. 3. Temperature regime during salt weathering cycles (from McCabe, 2007, reproduced with permission from Springer).

compressed under vacuum into a tablet, through which infrared light is transmitted, over a range of frequencies.

2.5. Salt weathering cycles

When appropriate lime, fire and frost pre-treatments were completed, blocks from each stress history group (groups 1–5, Table 2) were subjected to repeated wetting and drying with a 10% salt solution (equal parts NaCl and $MgSO_4$), simulating a present day temperate maritime environment. These salts were chosen for the study because they are often associated with maritime environments, and have commonly been used in previous salt weathering simulation studies (Goudie, 1974; Goudie, 1986; Smith and McGreevy, 1988; Goudie, 1993; Smith et al., 2005). A two-day temperature cycle was used because it allowed the complete drying out of blocks, attempting to replicate natural conditions of regular temperature cycling combined with periodic wetting. The temperature regime for the two-day cycle is shown in Fig. 3, and is based on observations of stone surface and subsurface temperatures from the north Antrim Coast of Northern Ireland during the month of May. Temperatures in the field were recorded by embedding bead thermistors within blocks at different distances from the block surface (surface, 0.5 cm, 1 cm, 3 cm). The top temperature of 40 °C is commensurate with stone surface temperatures achieved on clear, sunny days. It is also in the range of temperature cycles previously used in salt weathering simulation experiments (for example, Warke et al., 2006). At the start of each cycle blocks were immersed in a 10% salt solution. Debris released during this immersion was collected, dried and weighed. It should be stressed that the aim of the study was not simply to achieve the rapid breakdown of Peakmoor Sandstone blocks (which could be achieved with more a aggressive salt solution and temperature

by Infrared Spectroscopy (FTIR). Samples from fresh and fire-damaged sandstones were ground to a powder of <63 μm. 2 mg of sample was mixed with 200 mg of potassium bromide. The mixture was
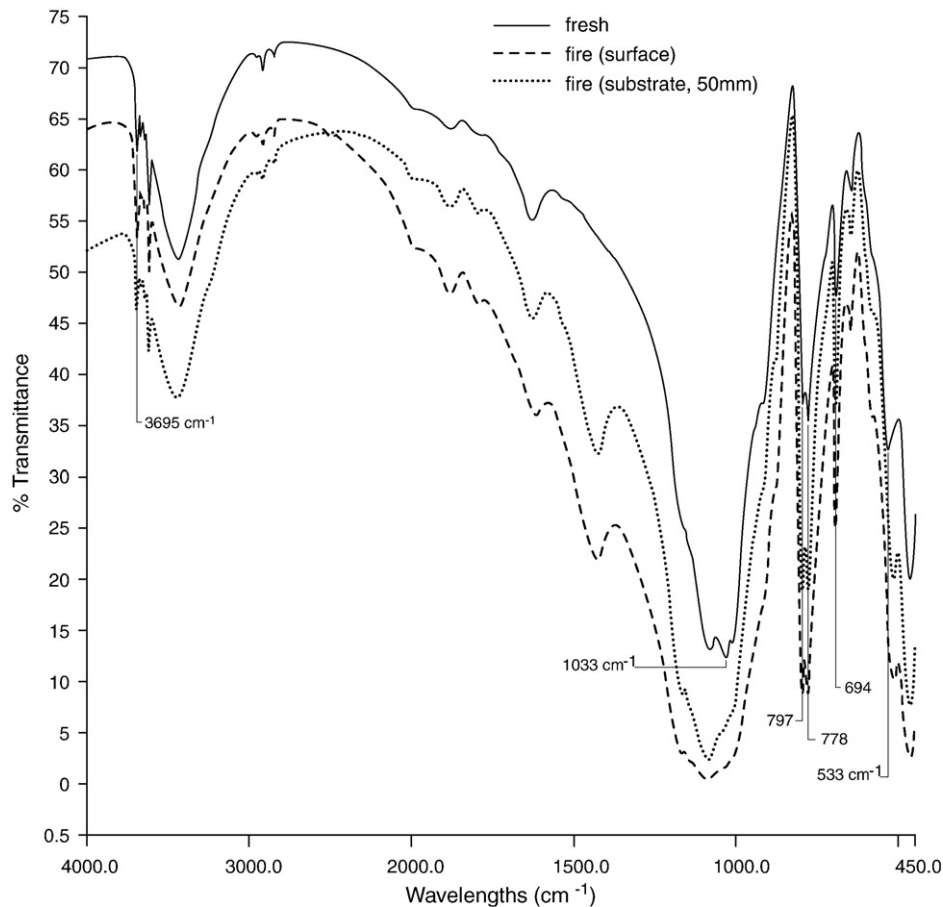

Fig. 4. FTIR trace for Peakmoor Sandstone (fresh, fire-damaged surface, fire-damaged substrate at 50 mm).
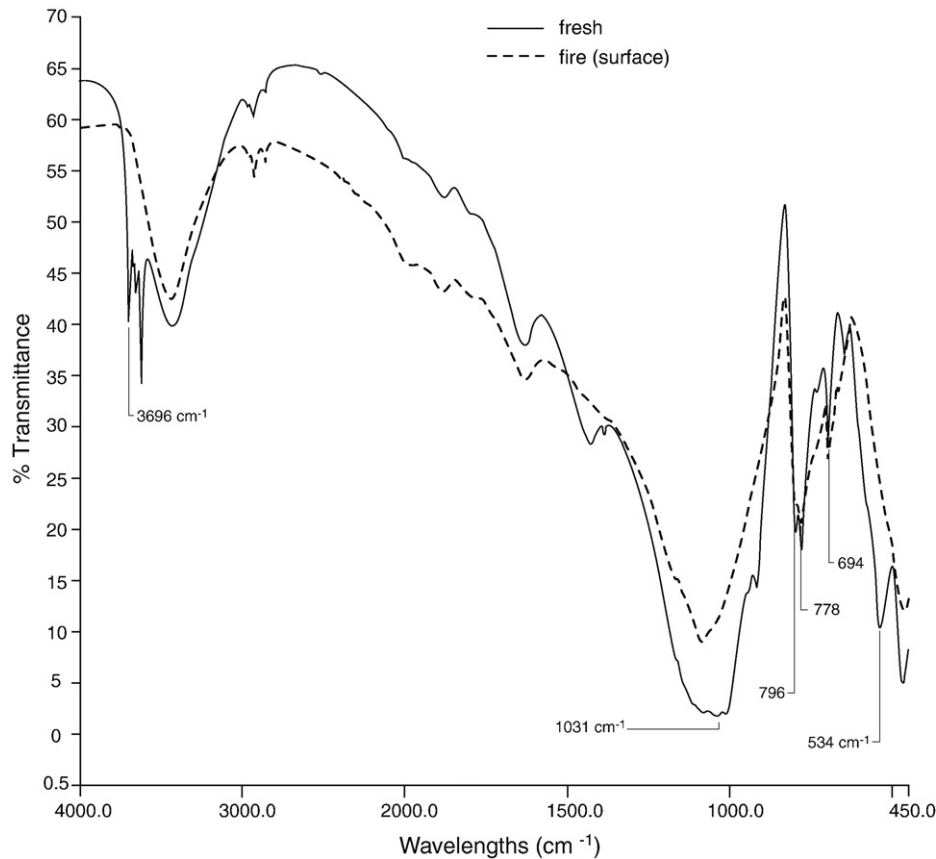
Fig. 5. FTIR trace for Dungiven Sandstone (fresh, fire-damaged surface).

regime), but rather, to monitor the slow and realistic deterioration of blocks. Thus, decay monitoring of blocks was achieved both qualitatively, by photographing the surface decay on blocks at regular intervals, and quantitatively, by monitoring weight loss.

3. Results

3.1. Mineralogical change

After carrying out the furnace-heating and fire experiments, blocks were sampled (surface and substrate at 50 mm) and analysed by FTIR to assess how mineralogy had been affected by the extreme heat of the furnace and the wood fire.

It can clearly be seen from FTIR traces that clay minerals have experienced alteration (Fig. 4). The small kaolinite peaks seen at 3695 cm^{-1} show a very slight shift after the fire, indicating possible shrinkage of this clay. However, more substantial evidence is seen in the clay absorption peak at approximately 1033 cm^{-1}, which is missing from surface and substrate samples of 'fired' blocks. Furthermore, the fresh Peakmoor Sandstone trace shows a smectite absorption peak at 533 cm^{-1}, which has also disappeared in heated samples. This suggests the structural collapse of smectites in the sampled blocks and the inability of these clays to swell again.

To confirm the impact that fire can have on clay mineralogy, an FTIR trace for Dungiven sandstone, both fresh and after the small fire event at Dungiven Priory in 2006 (photograph shown in Fig. 1) is shown in Fig. 5. This FTIR trace suggests that temperatures experienced were in excess of 500 °C, with the disappearance of the kaolinite peaks c. 3695 cm^{-1}, 3651 cm^{-1} and 3619 cm^{-1}, the clay peak at 1031 cm^{-1} and the smectite peak at 534 cm^{-1}.

Quartz peaks (c. 797 cm^{-1}, 778 cm^{-1} and 698 cm^{-1}) remain largely unchanged in both sandstones, as might be expected, however, there is

perhaps a slight shifting/reduction in intensity of the 797 cm^{-1} peak (especially in the Dungiven Sandstone field sample), suggesting that quartz was not entirely unaffected.
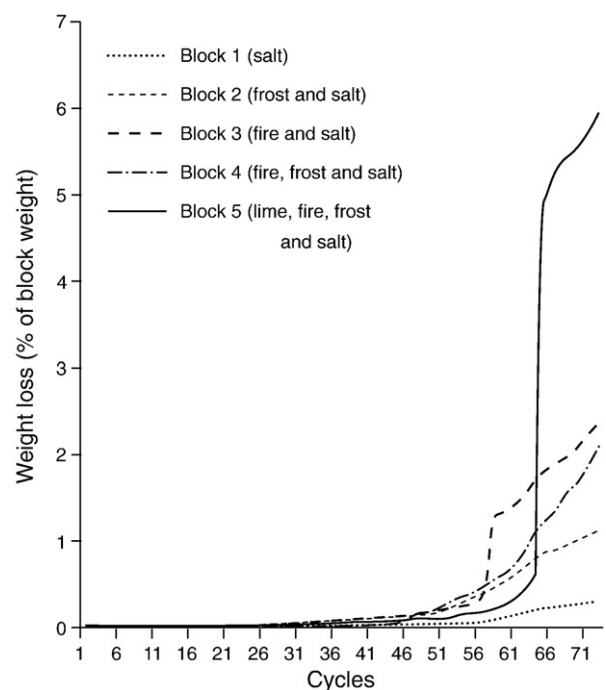

Fig. 6. Weight loss response of Peakmoor Sandstone to salt weathering cycles after experiencing stress histories 1–5 (Table 2).

As previously stated, this alteration of clay minerals (including shrinkage and collapse of clay structures) can mean a deterioration in the properties of the material, and is likely to play a part in paving the way for mechanical breakdown of the stone by exploitative processes.

3.2. Response to subsequent salt weathering

Fig. 6 shows cumulative weight loss from representative blocks from stress history groups 1–5 (Table 2), referred to as blocks 1–5.

- Group 1 (salt) — Over 75 salt weathering cycles, the least weight loss occurred in group 1, as may be expected. Debris release in block 1 remains suppressed and fairly constant throughout the experimental run. This slow and steady breakdown reflects the durable and predictable nature of 'fresh' Peakmoor Sandstone. However, the impact of different stress histories on this stone type, in altering porosity and surface characteristics, can change behaviour markedly.
- Group 2 (frost and salt) — Weight loss follows a similar path to block 1 until approximately 20 cycles elapsed. At this stage, accelerated weight loss occurred in block 2 as discontinuities inherited from freeze–thaw pre-treatments (and detected by ultrasonic pulse velocity measurements) were exposed by accumulating salts. The smooth nature of the weight loss plot reflects the slow fatiguing of blocks subjected to freeze–thaw cycles by salt weathering, in contrast to the exploitation of shock (groups 3 and 5).
- Group 3 (fire and salt) — Debris release in block 3 begins slowly and steadily, accelerated from cycle 40 to approximately cycle 57. At cycle 57, there is a dramatic jump in weight loss, related to a spalling event — the exploitation of a fracture created in the fire, lowering stone strength until it was breached by the accumulation of stresses from repeated salt weathering cycles. After this event, weight loss slows again (reflected in the concave shape of the weight loss plot), showing brief period of quiescence before debris release (by granular disaggregation) accelerated one more.
- Group 4 (fire, frost and salt) — Debris release is again relatively suppressed until cycle 40, when block breakdown begins to accelerate. This acceleration of debris release continues until the end of the experimental run (cycle 75). There is no jump in weight loss related to a spalling event (as seen in blocks 3 and 5), but the accelerated decay is still related to characteristics inherited from the

fire, namely, soot cover. The hydrophobic effect of soot cover on fire-damaged sandstones is highlighted by McCabe et al. (2007, 2010). Accelerated weight loss occurred when this surface layer covered by soot eventually began to detach from the block (Fig. 7), presumably because soluble salts that did manage to penetrate the surface were concentrating and crystallising behind it. The exposed stone underneath the crust showed discolouration from iron oxidation, and was much more permeable than unweathered Peakmoor Sandstone (an average of 133 mD from a range of 78–169 mD).

- Group 5 (lime, fire, frost, salt) — Block 5 exhibits the greatest amount of weight loss over the experimental run. Debris release is again slow to begin with (the 'baked' lime layer suppresses breakdown, lending artificial integrity to the block surface). At approximately 64 cycles, however, a jump in weight loss is seen, again related to a spalling event (the result of the exploitation of fractures inherited from the fire). This spalling event is followed by accelerated granular disaggregation (reflected in the convex shape of the weight loss plot). A photographic record of the breakdown of block 5 (at 0 cycles, 25 cycles, 50 cycles and 70 cycles) is seen in Fig. 8. This shows that the fracture on the top right hand corner of the block (created by shock response to the differential stressing in the fire) was exploited and widened by salt weathering, until spalling occurred. Ultimately, the greatest factor contributing to the high weigh loss percentage of this block was major stress legacy inherited from the fire.

All groups subjected to fire ultimately experienced accelerated weight loss in response to salt weathering, either by spalling (blocks 3 and 5), or by the detachment of the soot crust deposited on the surface during burning (block 4).

4. Discussion

Fire damage to sandstone produced appreciable change in Peakmoor Sandstone (experimentally) and Dungiven Sandstone (in the field). Change in both sandstones occurred with respect to colour (surface blackening and subsurface reddening), the probable development of fracture networks, and the alteration of clay minerals. These changes imply a decrease in the stone strength and in the ability of the stone to absorb future change.
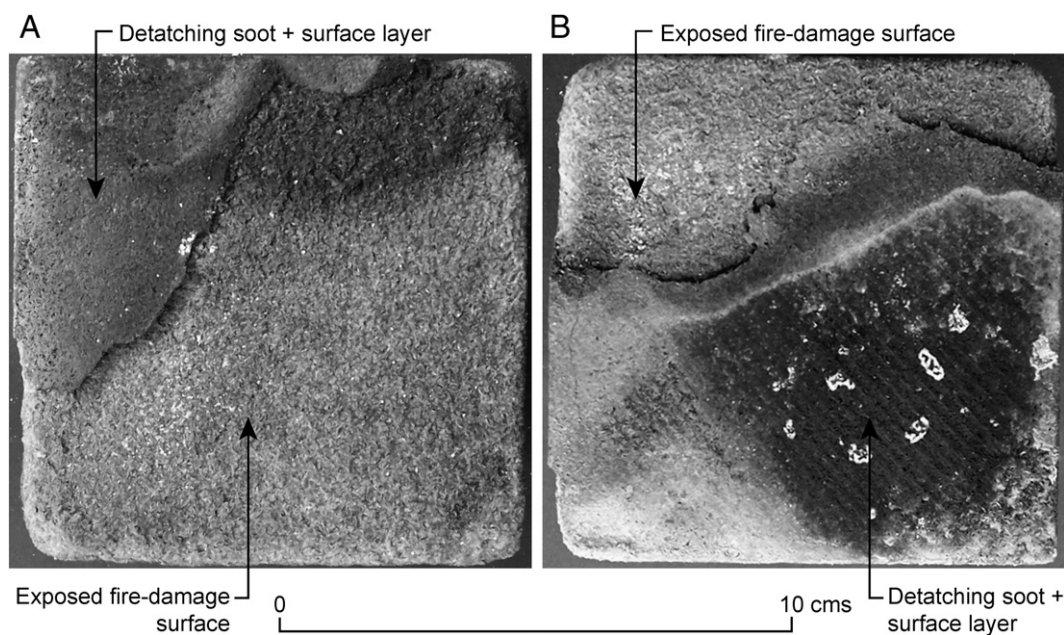

Fig. 7. The detachment of the soot and surface layer on two faces of a block in response to salt weathering.

It is important to note that, with one exception, the fire pre-treatment did not bring about the complete 'failure', or splitting, of Peakmoor Sandstone blocks. Blocks, although showing evidence of being subjected to stress (described above), were still intact — a fire event in isolation was not sufficient to cause complete failure (depending on where a block was situated in the fire). This suggests that it is in the context of long and complex stress histories (the combination of fire with other stress events or with background environmental factors) that the importance of historic fire in the decay of historic sandstone should be seen. Thus, fire can bring about the shrinkage and alteration of the mineral matrix, can lead to a weakening of intergranular bonds, and ultimately, through exploitation by processes like salt weathering and freeze–thaw weathering, granular disaggregation of the surface. In terms of individual stone building blocks, the increase in surface fractures and discontinuities within blocks due to fire can lead to greater susceptibility to decay by the same exploitative processes. An increase in discontinuities within blocks is likely to lead to further ingress of moisture, increasing potential damage from salt and frost cycles.

It may be expected that blocks that have been subjected to the fire pre-treatment will reflect their stress history by accelerated weight loss in response to salt weathering cycles. The potential for soot to play a role in subsequent decay should also be stressed, with lowering of surface permeability and potential hydrophobic behaviour influencing the degree of moisture ingress during frost and salt weathering cycles.

The 'intangible' fatigue effect following the freeze–thaw pre-treatment (also noted by Warke 2007) manifests itself in weight loss during salt weathering cycles by steady granular disaggregation. This may be conceptualised as block response to $fatigue_1 + fatigue_2$, and is seen in the smoother cumulative weight loss plots of Fig. 6. In contrast, block response to salt weathering after the stone has been shocked can produce major episodic/catastrophic weight loss events, with the potential for major strength thresholds to be breached as the accumulation of salt in the system exploits weaknesses (in the form of fracture networks) created by the pre-shocking. The reduced ability of these 'shocked' blocks to absorb stress produced by accumulating salts can result in spalling events. This may be conceptualised as block response to shock + fatigue. The reality of this model has been illustrated in Fig. 8, showing a block of Peakmoor Sandstone, subjected to fire pre-treatment, before, during and after 75 salt weathering cycles. In Fig. 8, the fracture created by the multiple thermal stresses set up within the block during the fire can be seen, and this corner eventually spalled off (at approximately cycle 65, seen in the cumulative weight loss graph, Fig 6) after exploitation by salt
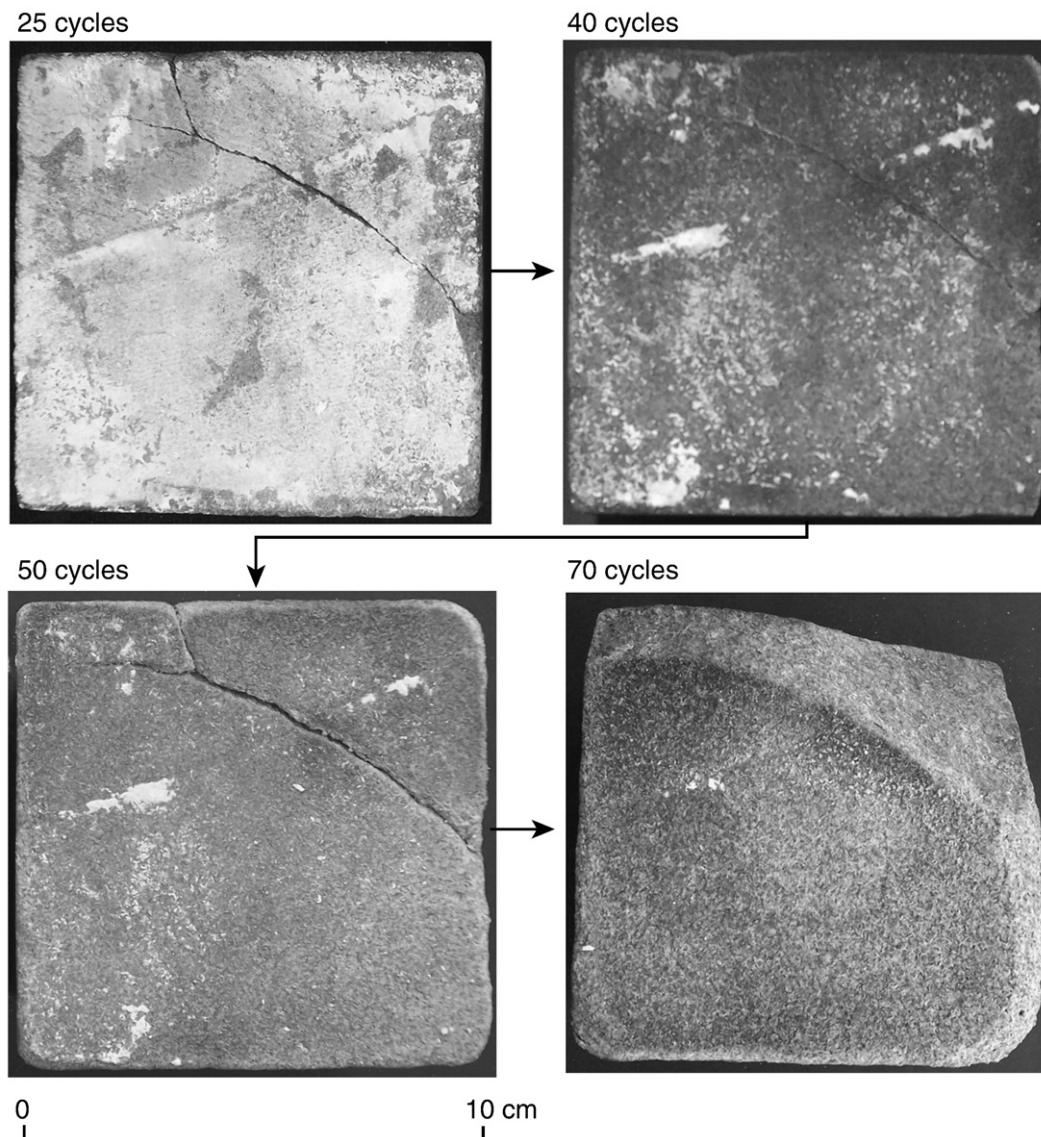

Fig. 8. Progression of decay illustrating the 'fatiguing' of 'shocked' stone — a block from stress history Group 5, after 0, 25, 50 and 70 salt weathering cycles.

weathering. This spalling of corners occurred in several cases (see weight loss graph for blocks that had experienced fire, Fig 6), and other blocks that had been subjected to fire were on a decay pathway that is likely to have included spalling as a future response to accumulating background environmental stresses — fractures created by the complex stressing in the fire were being exploited and widened by salt weathering.

Another important issue for discussion is the impact that fire may have on blocks in a real-world façade, surrounded by mortar and other blocks. In the simulation of fire described by this paper, blocks were not restrained. At a micro-scale, quartz grains are restrained by surrounding grains and, as differential thermal expansion occurred (Kingery, 1955; Gómez-Heras et al., 2006b) due to the fire, stresses were produced, causing microfracturing in blocks. However, at the larger scale of single blocks, expansion was allowed to occur. If these blocks had been placed in a façade, surrounded by mortar and other building blocks, a similar restraining effect may have occurred as that which is proposed at a granular scale. It is likely that restrained blocks, when experiencing differential thermal expansion during a fire event, may experience more damage than those unrestrained blocks in this study (for example, spalling may occur as a direct result of the fire, as seen in the localised 2006 fire event at Dungiven Priory (Fig 1)). It would be beneficial to carry out similar fire simulations on restrained blocks to explore sandstone response in a façade context.

4.1. 'Reading' historic fire on a façade

The notion of 'reading' a façade (Woodcock, 1997) is perhaps helpful in understanding the pathology of a historic structure (Watt, 1999) and in the post-fire management of stone decay. As proposed at the beginning of this paper, the response of stone to stress is conditioned by inherited weakness from previous stresses, and helps to determine response to subsequent stresses. "Landscapes are not 'clean' pure products of contemporary processes but have in them a background of residual effects of earlier periods" (Thornes and Brunsden, 1977, p. 19). This key geomorphological idea is equally applicably to historic façades. Whether one may be able to 'read' a fire event on a façade may depend on whether the fire was experienced by the stonework recently or in the distant past. If a fire has occurred recently then blackening of stone is the most obvious 'memory' effect. The blackening of stone from soot is an important by-product of fire, and the most obvious immediate surface effect. This soot cover brings with it the possibility of reduced permeability and hydrophobic tendencies, influencing subsequent exploitative decay processes. The soot-cover promotes surface/subsurface heterogeneity and can result in detachment of the deposited surface crust in the form of flaking, when salt concentrates and crystallises beneath the surface. After the soot layer has detached in this way (or perhaps been removed by cleaning), the exposed surface can exhibit rapid granular disaggregation caused by the alteration of the sandstone matrix by the extreme heat of the fire. The newly exposed surface can be expected to have a higher permeability caused a combination of the fire event itself and the mechanisms of salt weathering. Other 'memory' effects caused by fire are the reddening/pinking of blocks due to the oxidation of iron (if present) in the cement. This chemical alteration can weaken the stone and may facilitate the ingress of moisture. Three-dimensional networks of fracturing may also be evidenced as a result of fire caused by thermal shock and differential expansion of adjoining materials (for example, soft sandstone/rigid mortar). This highlights the possibility that fire damage in the context of a real-world façade, where a block is restrained by mortar and surrounded by blocks, may be greater than that demonstrated using unrestrained blocks. With the subsequent exploitation of weaknesses inherited from a fire event by background environmental cycling, it may be expected that detachment/spalling of block corners would be exhibited on façades.

5. Conclusions

- Much previous research has focused on the damage that is caused by fire in isolation, omitting to investigate the subsequent exploitation of weaknesses inherited from fire events — an area that needs to be more fully understood if the post-fire management of natural building stone is to be improved.
- Clay minerals, common in the matrix of Peakmoor and Dungiven sandstones, experience alteration in extreme temperatures, with deformation, shrinking and disappearance of kaolinite and smectites identifiable by FTIR traces. The alteration of clay minerals can compromise the integrity of a sandstone matrix, weakening intergranular bonds and ultimately increasing susceptibility to exploitative weathering processes that can cause material loss.
- The un-predictable/rapid weight loss in response to salt weathering cycles ultimately evidenced in blocks that had experienced the real fire, reflects the complex, fluctuating, stresses produced in the fire. The rapid jumps in weight loss are the exploitation of the shock response produced in the fire (shock + fatigue), in contrast to the smoother weight loss curves, which reflect exploitation by fatigue alone (for example, blocks 1 and 2, Fig. 6).
- Block response to salt weathering following a shock event can produce major episodic/catastrophic weight loss events, with the potential for major strength thresholds to be breached as the accumulation of salt in the system exploits weaknesses (in the form of fracture networks) created by the shock pre-treatment. The reduced ability of these 'shocked' blocks to absorb stress produced by accumulating salts can result in spalling events.

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