Chapter 6.3

MONITORING OF THERMAL CONDITIONS IN BUILDING STONE WITH PARTICULAR REFERENCE TO FREEZE-THAW EVENTS

Kevin Hall
Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Pretoria, 0002, South Africa, Present address: Geography Program, University of Northern British Columbia, 3333 University Way, Prince George, BC, Canada V2N 4Z9, hall@unbc.ca

Abstract: Although attempting to consider the impact of freeze-thaw, the monitoring of associated thermal conditions must, effectively, be context free. This is important for several reasons. First, although freeze-thaw is being evaluated, data must be of a nature that also allows determination of the spatial and temporal role of other processes. Second, by being 'holistic' rather than (assumed) 'specific' in character the data do not pre-determine the outcomes. Third, by being able to be used for evaluation of multiple processes the data are, paradoxically, of a nature that facilitates a more detailed understanding of freeze-thaw activity itself. In considering freeze-thaw it is important to recognize that the process is not a singularity but rather comprises a range of mechanisms, each determined by an interaction between thermal and moisture conditions with the properties of any given building material. In the absence of (the required) moisture data, the thermal data need to be adequate to validate, or invalidate, specific mechanisms, as well as to offer indirect proxy information indicating whether or not some form of freeze-thaw weathering indeed took place. Significant in this regard are not just freeze-thaw amplitudes and durations but also the associated rate of change of temperature ($\Delta T/\Delta t$). In addition, the record rate must be fast enough to monitor (should they occur) 'exotherms' – the latent heat released as water turns to ice; this being a proxy identification that water was present and did indeed freeze (the finding of 'zero curtains' can also be used as a proxy for the existence of water that froze within the material). In reality, the thermal data acquisition requirements for monitoring of both $\Delta T/\Delta t$ rates and exotherms are effectively the same; namely high-frequency thermal monitoring at an interval of at least one-minute. Thermal monitoring at one-minute intervals may have produced logistical problems in the past but modern data loggers with multiple channels, long-life battery power and large storage capacities can handle such requirements with ease. The resulting data are of a temporal nature that allows for the evaluation of thermal stresses, especially those associated with $\Delta T/\Delta t$ events $\geq 2\ °C \cdot min^{-1}$. Equally, such data are able to resolve the short-interval heat transfer associated with latent heat release at phase transfer. Significantly, such data not only identify the occurrence of exo-

S.K. Kourkoulis (ed.), Fracture and Failure of Natural Building Stones, 373–394.

therms but also show the temperature at which freezing took place. Further, given sub-zero rock temperatures, the absence of exotherms shows when thermal conditions may have been suitable but no water was available to freeze or despite water being present it did not freeze. Thus, this approach provides objective data allowing for the true counting of actual events rather than the subjective counting based on the assumptions that (a) water was indeed present and (b) that it froze within a certain thermal range. This latter approach (assumed counting) has now been shown to suffer from potentially massive error, especially within a spatial context. In respect of thermal monitoring, the key prime requirements are: large data capacity loggers with multiple channels, high resolution loggers, high-frequency logging capacity, high resolution transducers, fast response time transducers, large spatial distribution of transducers (including, where possible, with depth within the material being monitored). In terms of transducers, experiments have suggested that 40 gauge thermocouples satisfy resolution (0.1°C) and response time (0.04 sec) while at the same time, due to the almost invisible nature of the wire, not impacting on the aesthetics of a site. If drilling of the building material (for the emplacement of transducers) is possible, holes are less than 0.2 mm in diameter, or, if a predrilled block is situated at the site, the visual impact is still very small. Where any form of attachment or drilling is prohibited, infra-red (IR) sensors are now of a resolution (0.1 °C), response time (0.002 sec) and monitored area (1 mm^2) that can provide excellent data; but at an aesthetic cost during monitoring. The use of infrared sensors is ideal for monitoring of surface pigments (e.g. in cave art) or fragile components unsuitable for direct contact sensors. Once collected, data have shown that many pre-conceived notions, especially in respect of freeze-thaw, are in error. Despite cold temperatures (the common "indicator" for the assumed occurrence of freeze-thaw) data have shown that either water was not present in the rock to freeze or it simply did not freeze at the available temperature; equally the temperature at which freezing occurs has been found to often be colder than the assumed value. Sometimes the freezing of water was found to be progressive with depth while at other times it was instantaneous over the outer several centimetres of the rock. Spatial and temporal variability of freeze-thaw events were both extremely large. Thermal stress events often, in magnitude, frequency and spatial distribution, exceed freeze-thaw in terms of number of occurrences. Further, moisture and thermal conditions show that, in cold environments, chemical weathering can occur for long periods – perhaps all winter. Finally, as much as these data help us to go forward in our understanding of weathering, they still need to be *directly* linked to actual breakdown – we cannot simply assume that because freeze-thaw may occur it is (in the absence of *proof*) the cause of the damage we observe. This is the next step – the connectivity of material failure with specific process.

Key words: freeze-thaw weathering; thermal conditions; processes; scale; monitoring; building stone.

1. INTRODUCTION

With respect to freeze-thaw weathering of building stone, the 'freeze-thaw' attribute is usually discussed as if it were a singularity. That is to say, the term is used in a manner that suggests the weathering ('freeze-thaw') comprises but a single mechanism as indicated by the descriptor used. Further, in many studies the action of 'freeze-thaw' appears to be assumed rather than proven – the considered role being based on a climate that experiences "cold" coupled with observed physical weathering of the stone. Equally, in many studies where the building material resides in a zone of cold winter conditions so the monitoring protocols, assuming the activity of freeze-thaw, are set up in such a manner as to monitor just this and, in so doing, are inadequate for determination of other processes. Thus, the "proof" of freeze-thaw becomes one of a self-fulfilling prophecy rather than scientific evaluation. In truth, the proof (as opposed to assumption) of actual freeze-thaw events occurring *within* the stone are almost non-existent and such proof connected to actual weathering outcomes within a field situation even less so (Hall et al., 2002). While some laboratory undertakings have linked weathering with the freeze-thaw events, their veracity is questioned based on the unrealistic (to the real world situation) simulation conditions (Thorn, 1992). Paradoxically, the ability to show freeze-thaw events *did* occur while, at the same time, being able to evaluate other weathering mechanisms comes from attempts to monitor processes *other* than freeze-thaw – and in so doing also indicates the data-bound weakness of most freeze-thaw directed studies.

Perusal of many building stone weathering studies suggests unqualified assumption of both the freeze-thaw mechanism and the nature of the ensuing damage. The examples in which process, especially freeze-thaw is assumed, are too numerous to cite, and it would really be inappropriate as the goal is not criticism of studies but rather to consider the way forward based upon sound principles. To give an example, *without prejudice*, one could note the discussion of Lawrence (2001, p. 26) regarding the deterioration of Canada's Federal Parliament Building, where it is stated that among the many causes of breakdown some "Damage was attributed to …..penetration of water into open joints and subsequent freeze-thaw activity…". The key word in this otherwise excellent review by Lawrence (2001), and this pertains to subsequent discussion, is "attributed"; this attribution, I would argue, is largely a function of the cold climate and thus assumed role of freeze-thaw. Equally, Mitchell, et al. (2000) calculate the number of freeze-thaw cycles affecting Lichfield Cathedral (England) based on recorded temperatures and humidity, but without actual evidence that the water did indeed freeze and, in so doing, effect damage. Apropos later discussions, the study of Mitchell, et al. (2000) recorded temperatures at 15-minute intervals and these were used for evaluation of thermal stresses; it will later be shown that such a record interval is inadequate for any such evaluation except in the broadest terms.

Indeed, from the perspective of the "bigger picture" a major stumbling block to a realistic dealing with practical problems of building stone weathering, is that of our application of discipline-specific knowledge and/or approaches. Sad to say but, despite our accessibility to literature, there is little cross-fertilization between disciplines: engineers continue with their standard techniques (whether or not those have any relationship whatsoever to actual processes), geomorphologists work in the landscape but frequently without recourse to non-landscape studies, building conservation and asphalt road studies stay within their topic-specific literature, and specialists such as rock fracture mechanics scientists stay within their, often theoretical, sphere. Reading of the literature within any discipline is often as if none of the others even exist; sometimes with amazing conceptual outcomes or decisions. Obviously there are exceptions across the board to this: the paper by Whalley and McGreevy (1984) berating geomorphologists for not using the wealth of information from engineering studies being a classic example (however, nearly 20 years on the paper might not have existed!). Pragmatically, this is a serious issue and one that hinders studies and, if I were allowed a personal note, it would be a cry for researchers to look outside of their discipline for techniques, theory, equipment, approaches etc. Failing that, the answer would be to create multi-disciplinary teams to deal with the issues. Here, from my own perspective, I hope to suggest some issues to consider within the context of freeze-thaw affecting building stone. Obviously the discussion cannot be all inclusive, but the ideas and approaches for the findings and data presented were, in the first instance, derived from a wide range of literature. Here, rather than a plethora of data and graphs, many of which may suffer from the very ills noted above, the aim is to consider the underpinning issues, some of the practical problems, and the complexities in dealing with freeze-thaw within building materials – and only to use data to exemplify those issues.

2. FREEZE-THAW PROCESSES

As noted above, it is not a single process that comprises ‘freeze-thaw’ but rather there are a range of possible mechanisms (Table 1). McGreevy (1981) provides an excellent review of the multiplicity of mechanisms available within the catch-all term of “freeze-thaw” (or any of its many synonyms) and, despite its early date, subsequent to that paper the only significant addition to the mechanical aspect of rock breakdown due to the freezing of water is that of the (theoretical) model by Hallet (1983). Combined, the mechanisms require a range of different moisture conditions, freezing rates, freezing temperatures and rock properties (Table 1). Further, dependent upon mechanism, the spatial location within the material where the process may operate can differ. Thus, it is indeed critical, to both obtain adequate data on the controlling attributes and to determine the actual mechanism(s) operating; noting that there can be temporal and spatial variability in mechanism for any given site (Figure 1). The data shown in Figure 1 are simply surface temperatures recorded on each of the cardinal aspects (on a vertical brick) for one winter’s day (March, 2004). Consideration of this one day shows the large spatial variability in respect of temperature and hence possible weathering processes, including freeze-thaw. South experiences very high surface temperatures coupled with large short-term fluctuations while North barely gets above freezing and has many crossings of 0°C during the day (probably *not* effective in terms of freeze-thaw but may influence water availability and/or thermal stresses). This spatial complexity is further exemplified by Figure 2 which shows the surface temperatures of two South-facing bricks but with one vertical and one at 45°. The vertical brick, being almost normal to the low angle winter sun, experiences temperatures up to +20 °C while the 45° brick, although facing the same direction, never gets much warmer than -10 °C (Figure 2); the low air temperatures (-16 °C) during that day clearly influencing the angled brick more. Thus, not only can the vertical brick, given available water, experience chemical weathering during that day but also it would be the only one able to experience freeze-thaw action; any water within the 45° brick remained frozen. While these two figures clearly illustrate the spatial variability of temperatures, there is also a temporal influence insofar as, with the changing angle of the sun through the seasons, the impact of slope angle changes – and hence the weathering potential.

Consideration of Table 1 shows that the two key elements in freeze-thaw are the moisture and temperature conditions (and their spatial and temporal variability); material properties, especially with building stone, may be well known or even able to be controlled. Regarding the two attributes of temperature and rock moisture, thermal conditions have dominated data in most studies while that for moisture are highly limited. However, with regard to the thermal conditions, data of the critical ΔT/Δt (rate of change of temperature) have been inadequate as a result of low-frequency data collection (Hall, 2003). This low-frequency data acquisition, partly as a result of process presumption, has meant that other possible processes could not be evaluated. Available data are actually inadequate to "prove" freeze-thaw, but with the assumption of freeze-thaw activity the data become a self-fulfilling prophecy as to its existence and role (see Hall, 2004 for a discussion).

Table 1. Freeze-thaw mechanisms and their controls

Person(s)	**Date**	**"Process"**	**Moisture**	**Temperature**	**ΔT/Δt**
Bridgeman	1912	Water freezing	>90% sat		none
Powers	1945	Hydrofracture	Low % sat		none
Taber	1950	Capillary action	>90% sat		Slow
Battle	1960	Volumetric	>90% sat	-5 to -10 °C	Fast
Dunn & Hudec	1966	Ordered Water	Any[1]	>-40°C	none
Mellor	1970	Freezing rate	>50% sat		V. fast
Connell & Tombs	1971	Crystal Growth	Low % sat		V. slow
Hallet	1981	Ice lenses	>90% sat	-10 to -15 °C	V. slow
Grawe[2]	1936	Questions	How much?	How cold?	

[1] Rock properties play a larger role as the available water must be in pores <5 microns in size.

[2] Grawe (1936) is included here, but put last, as he questioned the components of the freeze-thaw system from the perspectives of physics and reality rather than introduced a new mechanism (see text).

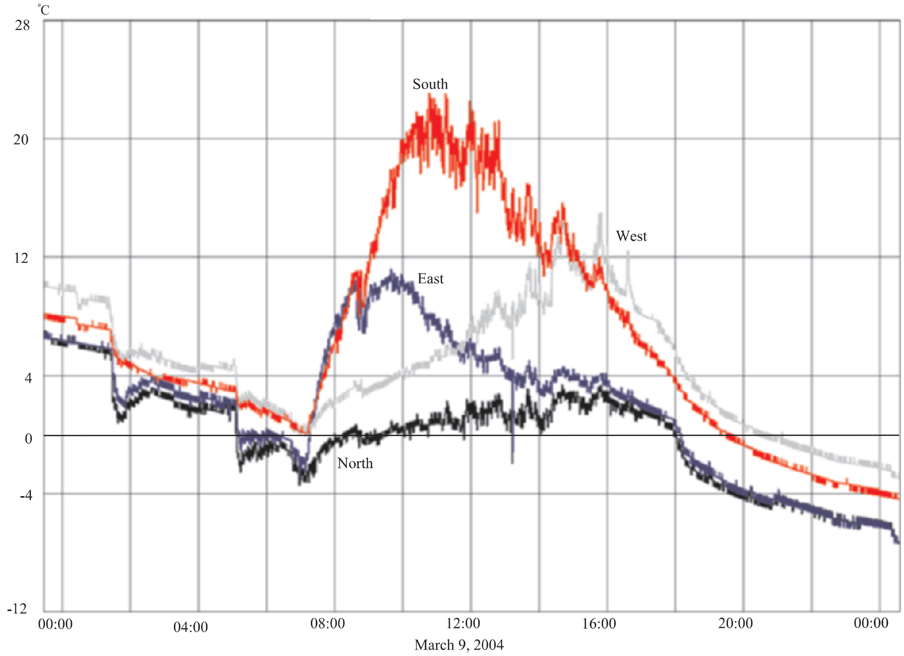

Figure 1. Temperature data for the surface of bricks facing the four cardinal directions to show the large spatial and temporal variability in temperatures, especially for the day-time.

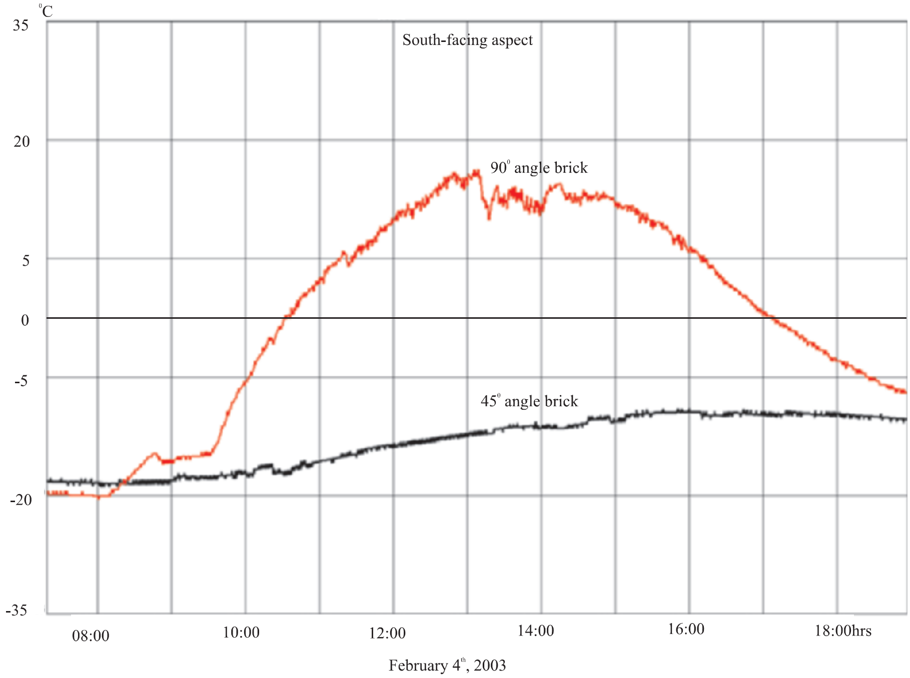

Figure 2. To show the impact of slope angle on building brick temperature in northern Canada.

The paper by Grawe (1936) is cited within Table 1 insofar as it questioned the many held beliefs with regard to freeze-thaw weathering, notably the possible stresses that can be exerted by freezing water, and despite being published over 80 years ago the questions raised are no less valid today. Indeed, the veracity of freeze-thaw might be less strong had greater recognition been given to this paper in many studies. Grawe (1936) raised the questions surrounding the greater-than-any-rock-can-withstand pressures that freezing water can generate, and thus, in principle, the overall possible effectiveness of the process. To generate the high potential pressures, the rock body needs to be totally saturated, have a temperature of -22 °C, and to comprise a completely closed system; of course, to attain the maximum possible pressure the body would also have to be able to withstand that pressure. Thus, as effective as freezing water can be in generating destructive pressures, there are significant constraints and limitations. The pressures are temperature dependent and thus values less than -22°C have commensurately lower possible maximum pressures, and this is lowered more still by less-than-saturated conditions, and, if extrusion can occur because it is not a closed system, so the pressures may then be negligible. Thus, even though the water may indeed freeze, there need not be any weathering taking place. Hence Table 1 shows variations on a theme to try and overcome some of these issues to exploit the destructive potential of freezing water.

Thus we see a range of possible freeze-thaw mechanisms requiring varying degrees of moisture, different rates of change of temperature, and each finding its own way to overcome the necessity for a closed system. Hidden within this are also the attributes of the material itself and, in respect of freeze temperatures, the period to which the material is subject to sub-zero temperatures. In respect to the latter, Battle (1960) showed that, for effective freezes, temperatures had to be between -5 °C and -10 °C, figures not greatly dissimilar to those suggested by Hallet (1983). Along the same lines, studies from France (Lautridou, 1971) have shown that to be effective, freezing temperatures had to be maintained for periods of at least 10 hours. Later studies (Lautridou and Ozouf, 1978) also showed that the rate of change of temperature was important, with rapid freezes negating water loss from the rock; conversely, Hallet (1983) suggested that, for his model, very slow rates of freeze were required to allow continued water migration to the freezing location. At the same time, the properties of the material are also important in influencing thermal changes; for example, permeability as well as the pore sizes and shapes can influence freezing (note Dunn and Hudec, 1966 re pore size and shape). Clearly, rocks with very low porosities and permeability are going to respond to available water, and hence the effects of freezing, in quite a different manner to the more porous and permeable rocks; note Trenhaile and Mercan (1984) and Hall (1986) have shown that even under conditions seemingly conducive to high moisture contents some rocks remain with very low degrees of saturation.

Thus, despite the almost casual application of the freeze-thaw concept, it is actually a very complex mechanism dependent upon an association of critical levels of moisture with specific temperature conditions, all mediated (in part) by the rock properties themselves. Thus, for any evaluation, particularly of damage actually ensuing from a freeze-thaw mechanism knowingly taking place, it is essential to obtain data in respect of thermal and moisture conditions in the material under study. At the same time, to assess the actual role, if any, of freeze-thaw it is imperative to monitor any *other* processes occurring at the same site through the annual cycle. Fortunately, many of the other processes, including chemical weathering, are (at least in part) able to be evaluated by the same combinations of temperature, moisture and rock property data as are required for an effective study of freeze-thaw. Thus, in monitoring adequately for freeze-thaw it is possible to gather a better picture of the weathering synergies and the place of freeze-thaw within this bigger picture; a more scientific approach than the ill-founded attempt to monitor just freeze-thaw.

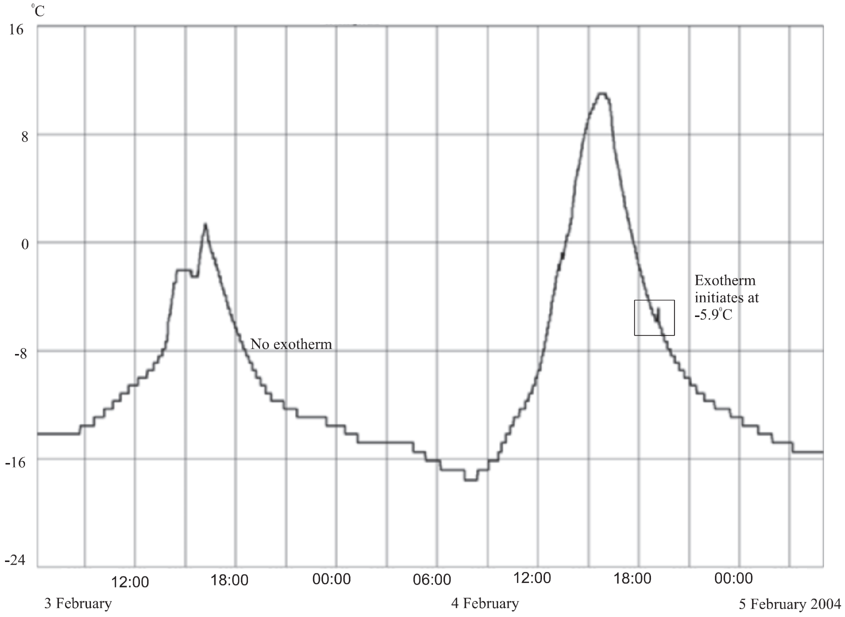

Figure 3. Example of two consecutive days with comparable freeze temperatures but only one shows evidence of water freezing (an exotherm).

3. MONITORING

In most field situations where freeze-thaw has been assumed to be active the weathering protocols were of a nature that, ironically, were unable to validate this process except by recourse to gross assumptions. Paradoxically, it has been the attempt to prove processes *other* than freeze-thaw that have generated data sufficient to validate the freezing and thawing of water within building stone (Hall, 2003, 2004). Freeze-thaw has usually been assumed operative based on geographic location – a site where cold conditions occur

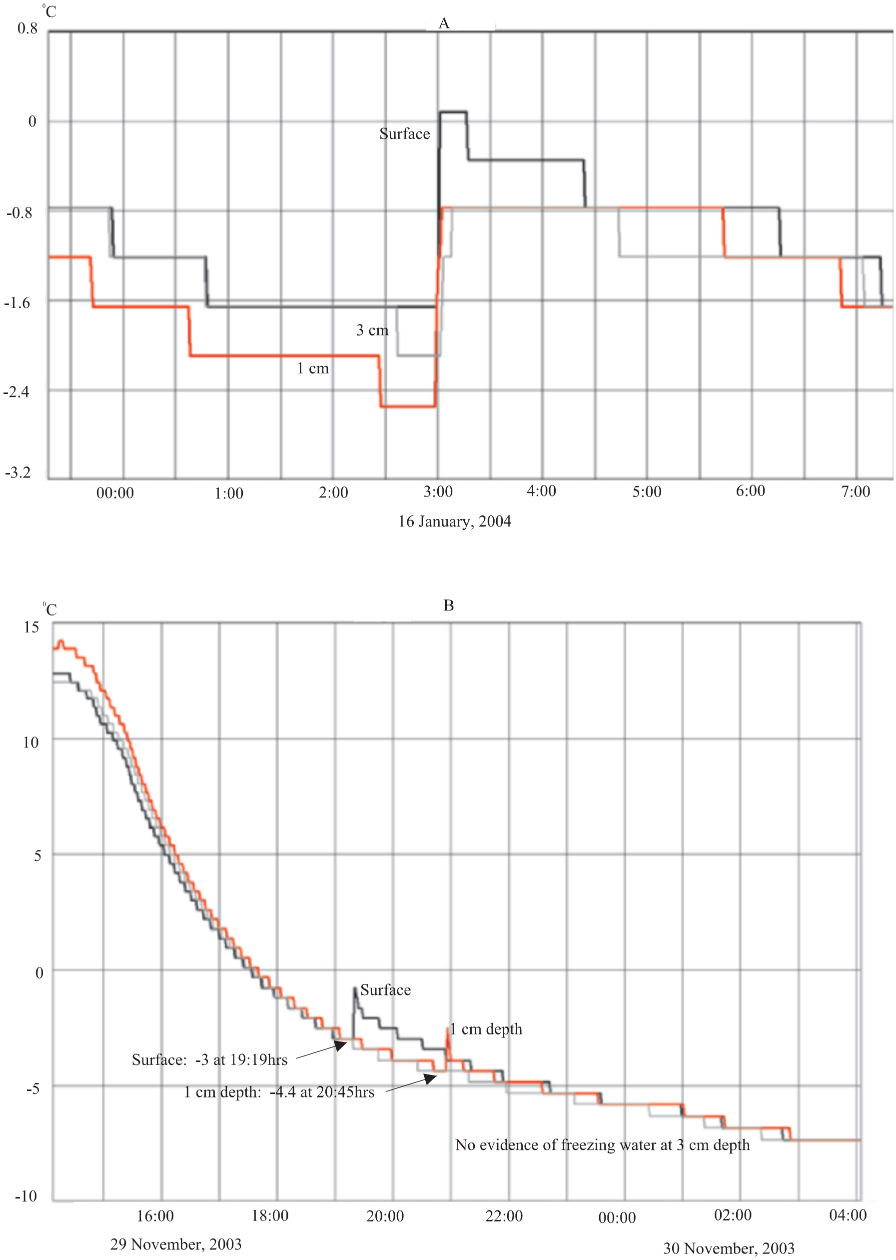

Figure 4. A. Example of all levels (surface, 1cm depth and 3cm depth) freezing simultaneously. B. Example of a progressive freeze down to 1 cm depth in the brick.

during the winter. In such studies, the general approach has been to assume the presence of water within the building material and thus when sub-zero temperature conditions (usually below a threshold of such as -3 °C: Matsuoka, 2001) could be monitored so each such event was thought to generate a freeze cycle. However, as will be discussed below (see Figure 3), where data are available, it has been shown that despite the sub-zero thermal conditions no transformation of water to ice took place; presumably (simply) because no water was present to freeze. Thus, it becomes critical that, in the case of freeze-thaw, monitoring procedures are such that it can be clearly shown that water did indeed freeze.

Thus, in 'monitoring' for freeze-thaw there are a number of attributes that need to be considered. With respect to solely thermal conditions there needs to be recognition of the large spatial and temporal variability (Figures 1-2). For the evaluation of freeze-thaw weathering impact on buildings, so the spatial variability in freeze-thaw operation, including as a function of slope, must be taken into account. To further help evaluate the spatial effectiveness of freeze-thaw so there needs to be monitoring of temperature at different depths within the material (see Figure 4 below). The rate of change of temperature is critical for evaluating the freeze-thaw mechanism itself as well as for studies of thermal stress. In the absence of moisture data, so it is important to have thermal data at a sufficient frequency that exotherms can be resolved (Figures 4-5), thereby providing proxy information of both the presence of water and that it actually froze. As building material albedo can influence thermal conditions (see below and Figure 7) so monitoring should also take this into account where there is variability in the brick and/or stone used. Lastly, as with any study, recognition must be given to processes operating at a range of scales and, where possible, an attempt made to monitor accordingly.

3.1 Monitoring suggestions - The 'holistic' approach

To monitor freeze-thaw weathering is to monitor weathering – not, in reality, to monitor just 'freeze-thaw'. There is no singular attribute that needs to be monitored that is not a requirement of some other process – even the freezing of water indicates when, for example, chemical weathering is *not* taking place. It is quite a different thing to monitor the pressure exerted by the freezing water, but no less so than the pressure exerted, at the same location but during the summer, by hydration of salt. The pressure exerted by the freezing water is an attribute *within* the freeze-thaw mechanism and is not a factor *controlling* whether freeze-thaw takes place or not; it may only control the effectiveness of freeze-thaw as a weathering mechanism, not its occurrence. Thus, to set up an effective monitoring system, the attributes of rock properties, rock moisture and rock temperatures need to be ascertained - and how these change in both space and time. The monitoring protocols need to be able to evaluate all of the weathering mechanisms and thus data acquisition times need to take this into account. In other words, if the data acquisition for monitoring thermal conditions in respect of thermal stress are adequate to evaluate freeze-thaw then they can be used; the corollary (hypothetically) that the basic data for freeze-thaw are inadequate for evaluating thermal stress thus prohibits their use. This becomes quite a complex issue, but then weathering *is* complex!

Problems, practical, aesthetic and technical, can arise in determining quite what to monitor, where and at what rate. This becomes a much bigger issue when scale attributes are taken into account. However, outside of data management, consideration of most attributes at the micro-scale will provide much data also suitable for macro-scale determinations of weathering. Pragmatically, many building stone studies will not be able to monitor at all scales, or with regard to all attributes, or with spatial or temporal variability in an adequate fashion. This is just a reality. However, it becomes less of an issue *if* the inadequacy is recognised and thus weathering evaluations take this into account. That said, most building construction, considering the thickness of the brick or stone, may well be impacted mainly by micro- or meso-scale weathering. Indeed, that very recognition may suggest specific types of measurement that can be requested for future studies or might be able to be simulated in a laboratory situation. The key is to monitor as extensively as possible the moisture and thermal attributes affecting the various building materials and, where possible, to have as much data as possible on those building materials – both the initial nature of the material and its present condition. Then, with an understanding of process and hence what information is needed to truly determine specific process operation (or not), it is possible to evaluate the available data in an objective manner.

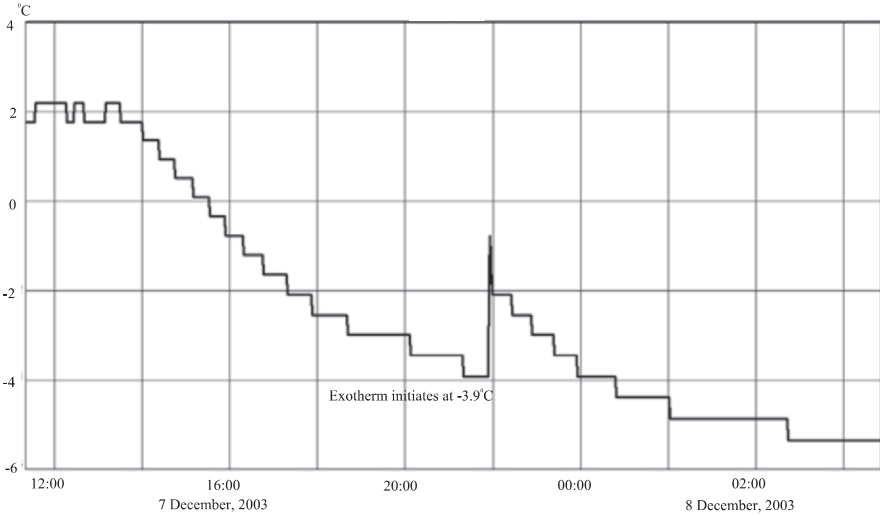

Figure 5. To show an example of an exotherm from the south-facing, vertical brick.

3.2 Monitoring techniques and technology

Recognizing the importance of both scale and aesthetics, a number of recent studies (Hall, 2003, 2004) have used ultra-small, ultra-responsive 40 gauge Type-T thermocouples with a precision of 0.1 °C. With a diameter of less than 0.15 mm the units are almost invisible to the naked eye and so can be used in aesthetically sensitive situations. The small size also allows for implanting of the sensors within materials without any significant damage; this facilitates the opportunity to monitor thermal conditions at different depths. The fast response time (>0.02 secs) also allows for high-frequency data logging sufficient for monitoring of both exotherms and rates of change of temperature that will facilitate meaningful evaluation of thermal stress. High-frequency data from such sensors (Figure 6) are ideal for evaluating processes at the micro-scale (granular disintegration) while the long-term data can still provide information suitable for macro-scale determinations (e.g. seasonal thermal variability). There is no reason why freeze-thaw cannot be happening at the micro-scale ("microgelifraction") so such data may be imperative for an understanding of rates and timings at this level; indeed, much building damage due to frost action may be at this surficial scale.

Where it is not possible to affix transducers to the building material it is still possible to obtain the same high-quality data by use of infrared thermometers. Measuring over an area of ≤0.5 mm with a resolution of 0.1 °C and a response time of 0.05 seconds the resulting data are almost comparable to those from the thermocouples. The distinct advantage is that the infrared systems can be used to monitor such as frescoes or components of a mosaic without any contact with the materials being studied. Such monitoring may be critical for evaluation of thermal differences between components with different albedos. Technological advances are now beginning to bring ever better degrees of resolution to thermal imaging systems that will soon be adequate for thermal monitoring of extensive areas (e.g. a whole wall with multi-point display of chosen areas within that) through time. The trade-off is that infrared monitoring is not so aesthetically acceptable and is, currently, more expensive.

In essence, logger and transducer technology are now such that long-term, high-frequency monitoring with adequate resolution (0.1 to 0.4 °C) and large storage capacity is now readily available at relatively low cost. Some units, such at the ACR TrendReader from Canada, can monitor eight channels at intervals down to 0.01 seconds with 12-bit precision, an internal battery providing 10 years of continuous operation and storage for one million data points – and the unit will fit in a shirt pocket! There are also practical attributes in that the units have a small aesthetic impact and, in many situations, the small size can make for easier security. Thus, outside of the overall costs ramifications, there are few technological reasons to inhibit thermal data collection of a quality commensurate with that required for process evaluation.

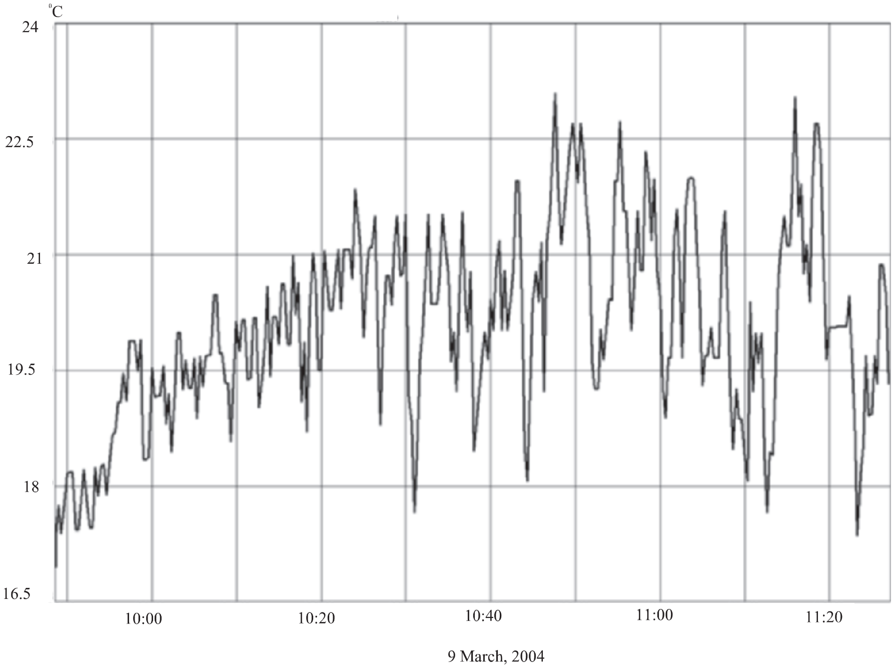

Figure 6. Surface temperatures collected at 20 second intervals on a south facing, vertical brick to show the short term thermal variations.

Data collection regarding rock moisture is substantially behind that of the thermal conditions and almost negligible with respect to such as rock moisture distribution and chemistry. The reality is that monitoring of moisture has been technologically far harder than thermal conditions. That said, this too has benefited from technological changes, and the work of such as Sass (2004, 2005) shows what can be done, particularly within the context of freeze-thaw evaluations. Moisture really is a critical factor and one so often, and in a variety of ways, ‘taken for granted’ within freeze-thaw studies. Not only is it necessary to understand the temporal and spatial variability of moisture, but it is also required that some understanding of the chemistry be known. The chemistry not only affects the freeze temperature (Hall et al., 1986) but can also be important in respect of other weathering processes occurring when the water is not frozen. Data on rock water chemistry are, however, all but non-existent (Hall et al., 1986; Thorn, 1988). In terms of moisture distribution within the building stone, this is critical for a number of reasons. In respect of freeze-thaw, if the mechanism is controlled (at least in part) by the degree of saturation then this is key to understanding process. While, for instance, a brick may have only 20% saturation when viewed as a whole, it is possible that the outer zone of that brick is 100% saturated while the inner part is dry. Equally, in such a scenario, this would imply the location of weathering by wetting and drying is at the inner boundary of the outer wetted zone – inside the brick. As wetting and drying can change pore properties (Hall and Hall, 1996) so this may be the precursor to freeze-thaw or it may be working synergistically with freeze-thaw.

Thus, for any meaningful evaluation of freeze-thaw it is imperative that data regarding moisture be available. Failing that, then the proxy information provided by such as exotherms (Hall, 2004) becomes all the more critical for without it there can be no way of discerning whether there was any water available to freeze and, if water were present, whether it did indeed freeze (Figure 3). This, in turn, leads to the last attribute – to monitor whether any weathering (i.e. the actual breakdown, *in situ*, of the material) took place as a result of the process occurring. Again, it is often assumed that because freezing of water did occur then weathering resulted. This need not be so. Perhaps the ice simply extruded or there was space available for the volumetric expansion to be accommodated and so no stress was exerted on the rock; even if there was a stress exerted, it may have been far less than the strength of the material. Thus there needs to be connectivity between the weathering process and the effect – an attribute missing in almost every study. Even where blocks are shown to be moved by ice wedges during the freeze event (e.g. Matsuoka, 2001) this need not, as noted above, imply weathering *per se* but rather may simply be movement of the already freed block by the ice (i.e. transport). That said, quite how to monitor, especially at an aesthetically sensitive site, is another question. Strain gauges may help and can be kept small, and non-destructive ultrasonic monitoring may be viable in some situations. As difficult as it may be to undertake monitoring of the linkage between weathering process and their effect, it is crucial for building studies if a realistic appraisal of process spatial and temporal variability is to be obtained.

3.3 Use and Interpretation of the Data

In broad terms, if the protocols outlined above have been implemented, the resulting data are essentially unconstrained by process, but can be used to *deduce* process. The data are holistic and can be used to evaluate thermal stress as well as to discern exotherms; they are also adequate for evaluation of chemical weathering processes. In other words, the data should be viewed from the perspective of “what processes are occurring” rather than “this proves what I thought” – although the latter can clearly be an outcome of the former. Essentially the call is for obtaining data that are not simply a self-fulfilling prophecy because they are inadequate to do otherwise, but rather the data show freeze-thaw occurred because they are able to prove other processes could not have occurred. The reality is that, the most likely outcome is a variety of weathering processes that, in both series and parallel, change through time and as a function of aspect. Thus, when evaluating the data, give due consideration to *all* processes and anticipate some degree of spatial and temporal variability in these. In other words, while freeze-thaw may certainly occur, the questions might be as to its timing, extent, location, and its relationship to the other processes taking place through the year. Where freeze-thaw is clearly an operative process, so the data might be able to suggest the mechanism(s) and this, in turn, may lead to effective remedial or preventative measures.

A brief example of the importance of considering data regarding freeze-thaw in respect of other processes illustrates the points above. In essence, freeze-thaw is a function of thermal cycling that, because the thermal changes cross a threshold that causes available water to freeze, may produce stresses in excess of the strength of the material. Thus, in terms of recognizing the action of freeze-thaw and determining the specific mechanism it is critical to obtain high-frequency thermal data. Thermal stress and thermal shock (Yatsu, 1988) are also the product of thermal cycling, but here the threshold is a function of the rate of change of temperature ($\Delta T/\Delta t$); the rate needing to be $\geq 2° \text{ min}^{-1}$. Thus, both mechanisms require thermal cycling, it is primarily the 'thresholds' that differ. However, and extremely important in the context of building materials in cold environments, it is a rapid *fall* in temperature that is more stressful than a rapid rise in temperature (Mavorelli et al., 1966). Thus, in cold climates where solar radiation warms a wall, possibly transforming water into an unfrozen state and readying it for another freeze-thaw cycle (and providing a short-term opportunity for chemical weathering), so as the heat source is removed the resulting values of $\Delta T/\Delta t$ can be very high due to the cold air; thermal stress/shock can result and be particularly effective as it is a falling temperature $\Delta T/\Delta t$ event. The thermal stress precedes the freezing of water and any subsequent freeze-thaw effect; the scale (depth) of effectiveness depends on the specific thermal conditions and the nature of the building material(s). In essence, the two weathering mechanisms are operating in series and, depending on the situation, the overall weathering impact may be misinterpreted as solely freeze-thaw; equally the thermal stresses may help enhance the freeze-thaw impact and so exacerbate its effectiveness. Thus, the data need to be considered from several perspectives, including in a temporal context, to fully comprehend the weathering environment and process relationships.

4. SCALE

Scale is a significant issue and one often ignored – both in terms of monitoring protocols and with respect to the actual process (Hall, Subm). The considerations with respect to monitoring have been dealt with above – sensors and monitoring frequencies appropriate to the scale under investigation. In respect of the process(es) themselves, the level at which they operate and the temporal variability within this, less empirical recognition has been given; the best has been qualitative recognition that scale differences may exist. This is a very important consideration as, by the time damage (ostensibly due to freeze-thaw) has been identified there may already have been a process - scale change. Equally, if identification of freeze-thaw can be made at the micro- or nano- scale, then damage may be able to be inhibited before if becomes an aesthetic or remedial issue. As recently discussed by Inkpen (2005 p. 129-130), scale need not be an absolute quantity but rather relativistic – varying as a function of the entities being studied. Here, the scale attribute would be that of processes causing breakdown of the building material at the nano- and micro- scales, and the relative and temporal role of freeze-thaw within that.

In terms of mechanical weathering processes, it has been argued (Hall and Andre, 2003; Hall, Subm.) that little or no recognition has been given to either the processes or the measuring of attributes influencing the weathering processes, at the micro-scale, let alone the nano-scale. Although the qualitative judgement regarding the occurrence of "granular disintegration" or "flaking/scaling" may be made, and sometimes attributed to frost action (Matsuoka, 2001; Ballantyne, 2002; Curry and Morris, 2004), data on this are rare (Hall and André, 2003). Thus with the increasing recognition of chemical processes at the nano-level (Butenuth, 2001; Hochella, 2002), coupled with developments in technology that facilitate measurement at smaller and smaller scales (spatial and temporal), so it is really incumbent upon us to start considering the role of mechanical weathering (including freeze-thaw) at the micro-scale; as Van der Giessen and Needleman (2002, p. 141) state, "…fracture spans several length scales from the atomistic to the macroscopic scale". This is important at two levels other than that of simply process recognition. First, because of the ever-progressive damage to buildings that can occur from flaking and granular breakdown itself, and second, because the activity of micro-scale weathering may change material properties in a manner that allows macro-scale weathering processes to occur. The first of these two attributes (flaking/granular disintegration) is a practical (and aesthetic) issue and one that can impact some sites/lithologies in a detrimental manner such that knowledge of the process is imperative in order to effect inhibiting or remedial action. The second may be more significant. By identifying the macro-scale breakdown as due, for instance, to freeze-thaw activity, this may misinterpret the initial causative processes and possibly suggest remedial or inhibiting procedures that could actually exacerbate the true initial weathering process(es). In some low porosity/low permeability materials, initial weathering processes causing changes to those properties may be other than freeze-thaw; the observable breakdown from freeze-thaw is a later stage in the weathering continuum and was only able to occur because those changes had taken place.

In respect of changes to material properties through time, and the resulting process transitions, this may be a key factor not adequately considered in building stone weathering. For example, studies (Hall and Hall, 1996) have shown that wetting and drying can cause changes to the pore size distribution within sandstone as well as granular disintegration itself. In many environments, the number of wet-dry cycles may significantly exceed effective freeze-thaw events. Further, under some conditions the wet-dry weathering effects may be sub-surface in location (Hall and Hall, 1996) such that later freeze-thaw events may be misinterpreted as the actual causative mechanism. These are important considerations. If a better understanding of the processes initiating weathering can be obtained then it may be possible to inhibit the latter, perhaps more detrimental, processes. Equally, because a block of building material, of whatever size, is seen to be "moved" (released) by freeze-thaw this does in no way imply that the freeze-thaw caused any actual weathering *sensu stricto.* The block may already have been weathered 'free' (i.e. all boundaries had been disassociated) by other processes and the block was only *moved* by the effect of ice growth within the building material – thus it was transport not weathering. Further, while the block may have been viewed as the product of macro-scale action by freeze-thaw (macro-gelivation), the actual weathering and disassociation along the boundaries may have been the product of micro-scale processes (micro-gelivation) - the product of which was a block (Hall, Subm). Again, misinterpretation may lead to the wrong remedial methods.

5. A FEW LAST THOUGHTS

In recognizing the bigger picture and the need to consider freeze-thaw within a spectrum of processes that operate within a spatial and temporal framework, a framework that is itself to be considered as a function of scale, so a number of practical problems may arise to confound. Based on recent studies it is germane to indicate a few things for consideration. First, studies (Hall, 2004) have shown that even in 'cold' climates, the rock surfaces on the equator-facing aspect may achieve high (+30 °C) temperatures during the day, despite air temperatures of -20 °C. A significant implication of this is that, given the presence of water, so, within the heated zone, chemical weathering can continue throughout the winter in high latitudes that still receive winter sun. Obviously there is a spatial aspect as well as a scale one (the depth of thaw), but these too will vary through the seasons and as a function of latitude. Nevertheless, the significance is that, processes *other* than mechanical may have to be considered.

In terms of freeze-thaw, studies have shown that the temperature at which freezing begins (Hall, Submitted) can vary significantly (between -1.8 °C and -9°C for the same point in this study) such that any approach that uses counting of thermal events across a given threshold may be in error. Further, by identifying freeze events within building stone by means of exotherms

(Figure 5) it was possible to show the number of times when thermal conditions were suitable but *no* freeze occurred as there simply was no water present to freeze. Thus, the situation is clearly not 'simple'. The available data (Hall, 2004) have shown that sometimes there is a progressive freeze from the rock surface downwards and sometimes freeze occurs simultaneously from the surface to a specific depth (Figure 6); in some cases freeze begins sub-surface first. All of this has significant spatial and temporal variability, not the least as also a function of slope (Hall, 2004). Again, this sort of information may have ramifications for protective/remedial approaches, particularly to large buildings that have variation in building materials and extensive exposures, at varying slopes, on each aspect (e.g. Lawrence, 2001).

Dependent upon the scale under consideration, there can be a significant difference in process perception. For example, at the micro-scale the thermal regime is significantly different to that at the macro-scale and, despite the macro-level operation of freeze-thaw, there may be micro-level granular disintegration resulting from thermal stresses. Data (Hall, 2003; Hall and Andre, 2003) have shown that that the grain scale there can be thermal fluctuations >10 °C in intervals down to 20-seconds. These create thermal stresses at the grain boundaries and/or within the outer shell of the rock to cause fatigue leading to flaking or grain release. Even here, this can be further complicated by albedo effects (Hall et al., 2005) with dark-coloured stones being hotter than the light-coloured; however, under some circumstances the lighter-coloured minerals or building stones that can be hotter than the dark (Figure 7). Thus, again, the simple assumptions we all often apply, without testing, may be false and so generate erroneous data. Finally, while preoccu-

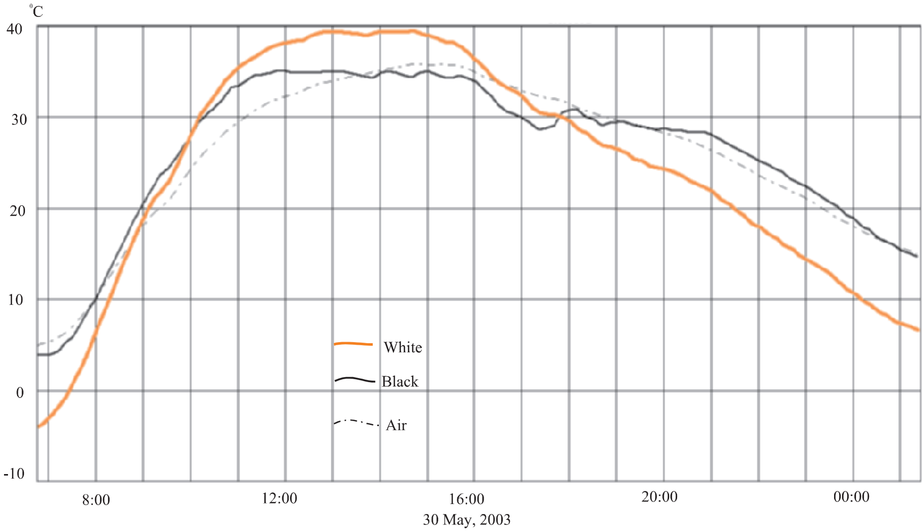

Figure 7. Example of the white brick being hotter than the black brick on a day when solar radiation heated the bricks to temperatures higher than the air.

pation has been with the thermal conditions, the reality is that much more data are required regarding moisture conditions – amount, spatial and temporal distribution, and chemistry. Very few studies have attempted to consider any of these attributes but the recent work of Sass (2004, 2005) suggests that techniques are available and that we should be applying these with the same spatial and temporal variability, and considering data across the same range of scales, as have been applied to the thermal conditions.

6. CONCLUSIONS

It seems, in some ways, that the study of the role of freeze-thaw on building stone is at a 'crossroads', or perhaps a 'roundabout' is a better metaphor. We have theory upon which the mechanisms of freeze-thaw are founded but that theory is, in part, the outcome (or, at least, affirmed by) the available data. At the same time, data acquisition technology is improving and becoming cheaper such that there should now be data better able to test the theory. However, the notion of 'freeze-thaw' is so entrenched that rarely is it felt necessary to obtain truly adequate data. As a corollary, the idea of thermal shock has been so discounted (at least in geomorphological literature) that data to test whether it does actually occur or not are rarely seen as necessary. Thus the ideas regarding what weathering 'is taking place' remain entrenched, affirmed by data that can do no other, and rarely is the weathering of the building stone ever truly researched without prejudice – i.e. in an objective manner. And so the roundabout continues to go round, stopping only to let on those who have bought in to the concept, and thus it never actually gets anywhere (scientifically). To quote the recent discussion by Inkpen (2005, p. 25): "*An important point, however, is how do you select which theories are the most coherent? What criteria do you use and who has the final say? The scientific community seems to develop and agree theories, but this is not necessarily a guide to how true those theories are".* This then extends in to the applied aspects associated with the preservation of building stone where he states (Inkpen, 2005, p. 26): "*The success of a theory is judged on how successful it is in its practical implementation. Success…lies in its successful implementation. Functionalist pragmatism is not concerned with the truth of reality, but with how truths about reality are thought to be identified, with the processes of scientific endorsement. Success is defined by how well those practices provide answers to our particular goals".* Thus, if it is assumed freeze-thaw is the causative mechanism for breakdown and the only available data support this, then it must be so. If, at least in the short-term, remedial or restorative practices work, then this only but affirms that the theory must have been correct. Sadly, however, this means neither do we ever get a proper appraisal of the weathering processes and their effects at a given site – we just think we have. As Inkpen concludes (2005, p. 26): "*...goals and pur-*

poses are important and can be matters of taste, evaluation is not. Evaluation requires a rationale, it requires rules and procedures that permit comparison of 'truths' between individual". We need to 'get off of the roundabout', having enjoyed the ride, with the goal of looking at things anew, of asking ourselves quite what are we measuring and what does it really tell us?

Following the metaphor of the 'crossroads' – we are now in a position to change direction, to truly evaluate processes, their connections and interactions, and their individual and combined effects. Whether we see fit to do this remains the question. Nevertheless, the technology is now available. True, to carry out a comprehensive study is daunting and requires a substantial undertaking of time and effort, but why should we do less? Pragmatically we are not always able to do all that which we may wish as resources are often an issue. However, recognition of the limitations regarding the data we are able to collect are imperative if our deductions are to be meaningful; consider what the data can really tell us, not necessarily what we would like it to say. It may also be beneficial to a better understanding for us all to look outside of our narrow disciplines and consider comparable theory and studies in other fields. And so, with thermal evaluation of weathering and freeze-thaw in particular, as McCarroll (1997, p.1) states: "*We do not improve our theories or models by admiring them, or by proclaiming how well they seem to fit our observations. The only way to improve them, and therefore to make progress, is actively to seek conflict between our models and the real world.*"

ACKNOWLEDGEMENTS

While there are many who have helped influence and develop my interest in weathering, especially freeze-thaw, I would like to recognize the following: Jim McGreevy, Brian Whalley, Colin Thorn, Jean-Pierre Lautridou, David Walton, Marie-Françoise André, Ian Meiklejohn and Jan Boelhouwers. That is not to say that any of them would necessarily endorse my thoughts outlined above!

REFERENCES

Ballantyne, C.K. (2002). Paraglacial geomorphology. *Quaternary Science Reviews*, 21, 1935-2017.

Battle, W.R.B. 1960. Temperature observations in bergschrunds and their relationship to frost shattering, in: *Norwegian Cirque Glaciers*, Lewis, W.V. ed; Royal geographical Society Research Series 4, 83-95.

Bridgeman, P.W. 1912. Water in the liquid and five solid forms, under pressure. *American Academy of Arts and Sciences*, 47, 439-558.

Butenuth, C. 2001. *Strength and Weathering of Rock as Boundary Layer Problems.* Imperial College Press, London, 270pp.

Connell, D. and Tombs, J. 1971. The crystallization pressure of ice - a simple experiment. *Journal of Glaciology*, 10, 312-315.

Curry, A.M. and Morris, C.J. (2004). Lateglacial and Holocene talus slope development and rockwall retreat on Mynydd Du, UK. *Geomorphology*, 58, 85-106.

Dunn, J.R. and Hudec, P.P. 1966. Clay, water and rock soundness. *Ohio Journal of Science*, 66, 153-168.

Grawe, O. R. 1936. Ice as an agent in rock weathering: a discussion. *Journal of Geology*, 44, 173-182.

Hall, K.J. 1986. Rock moisture content in the field and the laboratory and its relationship to mechanical weathering studies. *Earth Surface Processes and Landforms*, 11, 131-142.

Hall, K. (2003). Micro-transducers and high-frequency rock temperature data: changing our perspectives on rock weathering in cold regions, in: *Permafrost*, M. Phillips, S.M. Springer and L.U Arenson eds; Balkema, Lisse, Vol. 1, 349-354.

Hall, K. (2004). Evidence for freeze-thaw events and their implications for rock weathering in northern Canada. *Earth Surface Processes and Landforms*, 29, 43-57.

Hall, K. Subm. Perceptions of rock weathering: a discussion on attributes of scale. *Geomorphology*.

Hall, K. and André, M-F. (2003). Rock thermal data at the grain scale: Applicability to granular disintegration in cold environments. *Earth Surface Processes and Landforms,* 28, 823-836.

Hall, K. and Hall, A. 1996. Weathering by wetting and drying: Some experimental results. *Earth Surface Processes and Landforms*, 21, 365-376.

Hall,K., Verbeek, A., & Meiklejohn, K. 1986. The extraction and analysis of solutes from rock samples and their implication for weathering studies: an example from the maritime Antarctic. *British Antarctic Survey Bulletin*, 70, 79-84.

Hall, K., Thorn, C., Matsuoka, N. and Prick, A. (2002). Weathering in cold regions: Some thoughts and perspectives. *Progress in Physical Geography*, 4, 576-602.

Hall, K., Lindgren, B.Staffan, and Jackson, P. 2005. Rock albedo and monitoring of thermal conditions in respect of weathering: Some expected and some unexpected results. *Earth Surface Processes and Landforms,* 30, 801-811.

Hallet, B. 1983. The breakdown of rock due to freezing: a theoretical model. *Proceedings of the 4th International Conference on Permafrost*. National Academy Press, Washington D.C., 433-438.

Hochella, M.F. 2002. There's plenty of room at the bottom: Nanoscience in geochemistry. *Geochimica et Cosmochimica Acta*, 66, 735-743.

Inkpen, R. 2005. *Science, Philosophy and Physical Geography.* Routledge, Oxford, 164pp.

Lautridou, J-P. 1071. Conclusions generales des experiences de gelifraction experimentale. Recherches de gelifraction experimentale du Centre de Geomorphologie, V. *CNRS, Centre de Geomorphologie de Caen Bulletin*, 10, 84pp.

Lautridou, J-P. and Ozouf, J-C. 1982. Experimental frost shattering: 15 years of research at the Centre de Geomorphologie du CNRS. *Progress in Physical Geography*, 6, 215-232.

Lawrence, D.E. 2001. Building stones of Canada's Federal Parliament Buildings. *Geoscience Canada*, 28, 13-30.

Marovelli, R.L., Chen, T.S., and Veith, K.F. (1966). Thermal fragmentation of rock. *American Institute of Mining, Metallurgical and Petroleum Engineers*, 235, 1-15.

Matsuoka, N. (2001). Microgelivation versus macrogelivation: Towards bridging the gap between laboratory and field frost weathering. *Permafrost and Periglacial Processes*, 12, 299-313.

McCarroll, D. (1997). 'Really critical' geomorphology. *Earth Surface Processes and Landforms*, 22, 1-2.

McGreevy, J.P. 1981. Some perspectives on frost shattering. *Progress in Physical Geography*, 5, 56-75.

McGreevy, J.P. and Whalley, W.B. 1984. Weathering. *Progress in Physical Geography,* 8, 543-569.

Mellor, M. 1970. Phase composition of pore water in cold rocks. *US Army Core of Engineers, Cold Regions Research and Engineering Laboratory, Research Report,* 292, 61pp.

Mitchell, D.J., Halsey, D.P., Macnaughton, K. and Searle, D.E. 2000. The influence of building orientation on climate weathering cycles in Staffordshire, UK, in: *9th International Congress on Deterioration and Conservation of Stone, Proceedings Volume 1,* Fassina, V. ed; Elsevier, Amsterdam, 357-365.

Powers, T. C. 1945. A working hypothesis for further studies of frost resistance of concrete. *Journal of the American Concrete Institute*, 16, 245-272.

Sass, O. (2004). Rock moisture fluctuations during freeze-thaw cycles: preliminary results from electrical resistivity measurements. *Polar Geography*, 28, 13-31.

Sass, O. (2005). Rock moisture measurements: techniques, results, and implications for weathering. *Earth Surface Processes and Landforms*, 30, 359-374.

Taber, S. 1950. Intensive frost action along lake shores. *American Journal of Science*, 248, 784-793.

Thorn, C.E. (1988). Nivation: a geomorphic chimera, in: *Advances in Periglacial Geomorphology*, M. J. Clark ed; Wiley, Chichester, 3-31.

Thorn, C.E. (1992). Periglacial geomorphology: What, Where, When? in: *Periglacial Geomorphology,* J. C. Dixon and A. D. Abrahams eds;Wiley, Chichester, 1-30.

Trenhaile, A. S. and Mercan, D. W. 1984. Frost weathering and saturation of coastal rocks. *Earth Surface Processes and Landforms*, 9, 321-331.

Van der Giessen, E. and Needleman, A. 2002. Micromechanics simulations of fracture. *Annual Review of Material Research*, 32, 141-162.

Yatsu, E. (1988). *The Nature of Weathering: An Introduction*. Tokyo, Sozosha, 624pp.