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Review

Thermal fatigue and thermal shock in bedrock: An attempt to unravel the geomorphic processes and products

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ABSTRACT

Widespread acceptance in science at-large notwithstanding, the ability of thermal stresses to produce thermal fatigue (TF) and/or thermal shock (TS) in bedrock and coarse debris in the field is often doubted. Commonly called *insolation weathering* in geomorphology, the results of questionable laboratory experiments have led many geomorphologists to consider terrestrial temperatures to be inadequate to generate thermally induced stresses leading to rock failure; the exceptions are the action of fire or lightning. We comprehensively survey the general scientific literature on TF and TS while rigorously scrutinizing that relating to geomorphology. Findings indicate theoretical and experimental information is adequate to establish the feasibility of TF and TS in rock stemming from rock temperatures monitored in the field. While TS may exhibit fracture patterns that are uniquely diagnostic, those of TF lack any such attributes. It would appear unlikely that TF can prepare or weaken rock to increase the likelihood of TS. The question of whether widespread polygonal versus rectilinear cracking is diagnostic of TS is presently an open one as possible explanations invoke process(es) and/or host material(s) and, consequently, to assign palaeoenvironmental significance to such fracture patterns is premature at this time. Further geomorphological laboratory research into TF and TS is merited as sufficient theoretical underpinning already exists. However, laboratory experimentation needs to be much more rigorously defined and executed and is faced with significant hurdles if it is to be effectively linked to field observations.

1. Introduction

> *Everything is vague to a degree you do not realize till you have tried to make it precise.*
>
> [Bertrand Russell (1918)]

Few things are more ubiquitous on bedrock outcrops and the associated coarse debris than cracks or fractures. The importance of these phenomena is that they are one of the primary pathways by which water – the driver of most weathering processes – penetrates previously coherent rock masses. Clearly, many individual mechanisms and combinations thereof initiate and/or expand fractures. In such a context a reasonable approach is to posit that mechanisms initiating crack formation merit the serious attention of geomorphologists. While research is usually directed at topics deemed central to a discipline, the nature of that research is often also shaped by prevailing disciplinary fashions (Sherman, 1996), some characteristics of which inevitably stem from research in other disciplines. Among the most pervasive trends in present-day weathering studies are a reduction in the scale of investigation and alignment of geomorphic research with that occurring in other scientific disciplines. By combining these issues, this paper attempts to survey the present-day evidence surrounding the potential role of thermal stresses in cracking bedrock and coarse debris. Within weathering studies, few mechanisms have a more interesting or checkered history than thermal stress. While the history of the topic is interesting and informative, here we place emphasis on the present-day situation, in particular what we see as the present broader scientific context and the research questions we believe geomorphologists should now be addressing.

If we consider weathering by thermal stresses in broad scientific terms it is an expression of thermo-mechanical fracture — that is the nature of fracturing or cracking stemming from thermal loading (Giannopoulos and Anifantis, 2005). This is found most commonly in the form of thermal fatigue. Thermal fatigue (TF hereafter) is produced by temperatures that lead to repeated stresses (often far) below the normally determined strength of the material involved. However, thermal shock (TS hereafter) is a single stress event whereby sudden (large) changes in temperature produce fracture because of the resulting stresses exceeding the capacity of the rock to adjust other than through instantaneous failure. Both processes are defined formally and discussed at length below. However, it should be emphasized that today TF and TS are viewed as distinct mechanisms.

Definitive research into the chemical and physical processes commonly invoked in weathering studies is rarely conducted within

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geomorphology: rather, concepts from other disciplines are imported and applied as closely as possible to geomorphic situations. If viewed historically this statement rings even truer because geomorphology was dominated by field studies that inherently meant coarser scales of research, and concomitantly, most geomorphologists had neither the inkling nor the facilities to pursue laboratory research. With the benefit of hindsight, clearly early laboratory experimentation conducted by geomorphologists had limitations or their results were interpreted rather naively. Initially, thermal stress was viewed as a viable weathering mechanism. It was seen as a process that produced fracturing 'due to rapid changes in temperatures associated with frost, sun-heat, and the like…by such means strain is set up within the mass…through unequal expansion or contraction' (Warren, 1914, p. 418). Hall (1999) provided a historical review of the literature on thermal stress and noted (p. 49) that mainline thinking within geomorphology divided in the 1930s. Much of the original work on the topic (e.g., Holman, 1927) had focused on temperatures exceeding those to be found at the Earth's surface, save in fires (and lightning). Geomorphological laboratory experiments by Blackwelder (1933) and Griggs (1936) tended to discount the feasibility of weathering by thermally induced processes. Their rejection of the process became the prevailing viewpoint in geomorphology, for example Selby (1985, p. 191), although some continued to cling to the idea (e.g., Ollier, 1969; Rice, 1976; Winkler, 1977). The nuance that seems to have eluded most geomorphologists is that the experiments by Blackwelder and Griggs addressed only TS, but nevertheless TF fell by the wayside as well. Presumably, this is simply by association in the absence of a firm grasp of the difference between the two mechanisms, although such an assertion can be not better than a best guess. In other disciplines, the findings of Blackwelder (1933) and Griggs (1936) had little impact and research into TS, and TF continued apace (Hall, 1999). A logical explanation would appear to be that temperatures exceeding those believed to occur at the Earth's surface (excluding fires and lightning) may be readily invoked as relevant in other disciplines. Belatedly, the arguments of Ollier (1969), Rice (1976), and Winkler (1977) – combined with the creation of more thermal data (notably the work of Smith (1977) – encouraged geomorphologists to once again consider the role of thermal shock and thermal fatigue in rock breakdown. However, before addressing the present-day research scene directly, a number of important ancillary issues are considered, not least of which is terminological confusion.

Distinguishing between TS and TF is critical: this is a topic that we take up in detail below. The only time that we use the expression *thermal stress* is when it was used by the original authors of a paper and we are unable to interpret whether their statements refer to TS or TF. The term *insolation weathering* has long been used in geomorphology, although clearly insolation itself does not weather rocks, i.e., cause them to breakdown; rather, insolation creates the thermal stresses that may break rock down. As Turkington and Paradise (2005, p. 231) pointed out, insolation weathering as a concept had some degree of acceptance prior to the experiments of Blackwelder (1933) and Griggs (1936). Discussion of TS and TF is also frequently muddied by use of the term *spalling* or synonyms. Spalling is not a process (cause), rather it is a physical manifestation (response) to any one of a number of physical and chemical processes (acting independently or synergistically) and is a form of *buckle* (Wang and Evans, 1999) that is related to fatigue along a boundary layer (see Hall and Thorn, 2011, p. 85, for a discussion). Thus, generally, spalling is deemed a product of fatigue (whatever the driver) and so is not considered as a separate issue here. A single exception to this statement where a spall *can* be produced by TS is noted below.

The resurgence in interest in TF and TS is reflected in a variety of studies (e.g., Goncharov et al., 1968; Levi, 1973; Kranz, 1983; Harmuth et al., 1996; Chen et al., 1999; Lion et al., 2005; Gómez-Heras et al., 2006; Moores et al., 2008; Wanne and Young, 2008; Levy et al., 2010) now argue for the fracturing of rock by thermal stresses as a mechanism for rock breakdown and especially as a mechanism applicable to cold regions (e.g., Hall, 1999, 2003; Hall and André, 2001, 2003; Hall et al., 2008a,b; Levy et al., 2011) where it is still often called insolation weathering (e.g., Williams and Robinson, 1989; French, 2007). However, some researchers continue to have serious reservations about its efficacy (e.g., Ryan, 1962; Matsuoka, 1995). Naysayer's notwithstanding, visually discernible fractures assumed to be induced by thermal stresses (e.g., see Fig. 1A and B of Bertouille et al., 1979; or Figs. 1–3 of Hall, 1999) and not explicable by other known weathering mechanisms are spatially widespread (e.g., Williams and Robinson, 1989, Fig. 4). Furthermore, a thermal origin for cracking is supported by thermal fracturing studies from a host of other disciplines, e.g., ceramics (Kingery, 1955); road engineering (Vinson et al., 1996); asphalt pavements (Shalaby, 1997); mining (Williams, 1986); construction (Logan, 2004); archeology (Tite et al., 2001); extraterrestrial studies (Levy et al., 2010). Attention is drawn to the paper by Weaire and Rivier (1984) who identified the strong similarity (and origin relationship) as well as the common misconceptions (e.g., the *hexagonal* nature of cooled basalts) for a variety of rectilinear fracture forms (as is noted in more detail below).

Failure resulting from TF will, by all current definitions, exploit *pre-existing* weaknesses in the rock (bedding planes, crystal boundaries, etc.) whereas TS cuts across, rather than follows, any such boundaries or other lines of weakness. Thus, while TF may lead to granular disintegration, that is reduction to individual grains (e.g., Gómez-Heras et al., 2006; Hall et al., 2008a,b) or fractures parallel to the rock surface (exfoliation/flaking/spalling: Holzhausen, 1989; Walsh and Lomov, 2013), the latter are quite different from the rectilinear or polygonal fracture effects of TS. Although TF could be thought to prepare (i.e., weaken) a rock for TS, in reality the two mechanisms are independent of each other. Thermal shock (TS) is not the same as TF but rather is a mechanism wherein rapid temperature change induces a cooling or heating rate for an object that exceeds its ability to deform, and it fails (releases strain energy) by fracturing. Thus, TF requires replications of stress that result in disassociation along preexisting boundaries, while TS is a singular event that produces failure which exhibits fracture patterns commonly cutting across preexisting lines of weakness. Further, the notion that TF can prepare a rock for TS is also in error. That a rock has become weaker as a result of multiple low magnitude TF events is not preparation for TS at a threshold lower than the normal rate (see discussions below) but rather it is preparation for a higher magnitude TF event that causes failure (along those preexisting lines of weakness) due to the previous (TF) weakening of the rock. This is *not* a version of TS but simply a higher magnitude TF event that, given the lowered strength of the rock, now causes failure along the same lines of weakening that the lower TF events were affecting. Further, the multiple cracks that researchers instinctively interpret as a pattern may result from a single TS event. Thermal shock appears to produce two primary patterns of fracture, namely rectilinear (or *orthogonal*) and polygonal (Fig. 1).

The literature suggests that TS can cause a range of effects on rocks spanning scales from nanometers to meters. Although when quoting individual authors we retain their terminology, in this text we use the prefixes micro-, meso-, and macro- to indicate, respectively, intragranular or individual grains, agglomerations of grains (intergranular), and boulder and/or bedrock scales. This clearly embraces a degree of imprecision, but more precise specification suggests a degree of knowledge that is simply unfounded. Illustrations (Fig. 1) include the microcracking of rock (e.g., Kranz, 1983), as well as large-scale fracturing creating *polygonal cracking* (e.g., Levy et al., 2010, 2011) or *hierarchical rectilinear fractures* (e.g., Bahr et al., 1986). Commonly, but not universally (Williams and Robinson, 1989), all such patterns have been considered to result from TS. Comparable but smaller forms have also been found in (consolidated) mudstones within permafrost areas (Hall, personal observation: Fig. 2) and in sandstones within a