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Friendly fire: Engineering a fort wall in the Iron Age

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ABSTRACT

There is widespread evidence that the walls of Iron Age forts across Europe were set on fire, causing partial melting of the stonework followed by either recrystallization or glass formation on cooling – a process termed “vitrification”. The motivation for fort wall firing has remained speculative since its first description in 1777. Since the suggestion of MacKie (1969) that fort vitrification might destabilize fort walls, the debate as to motives has focused on combative or destructive intentions. Here, a multidisciplinary analysis of experimental fort wall samples shows that in fact vitrification results in strengthening, not weakening. The strengthening involves diffusive and viscous sintering of material aggregates and size-dependent heat transfer. These new results support a long-since-dismissed idea that Iron Age fort walls were intentionally set ablaze in order to fortify the walls.

1. Introduction

Archaeological science strives to constrain the practices and motives of people in antiquity. One exquisitely preserved example of their doings is represented by the so-called “vitrified” Iron Age forts of Western Europe. Vitrified is a term is used to describe a fort wall construction that contains glass or a devitrified product thereof and usually interpreted to be the result of high temperature activity. While hundreds of examples of vitrified Iron Age forts exist across Europe, the motive for their firing and resultant vitrification remains an outstanding question in archaeology. Of late there is general consensus that fort wall vitrification was intentional (Christison, 1898; Nisbet, 1974; Youngblood et al., 1978). Four categories of intentional motive have been proposed (Wadsworth et al., 2015); (a) strengthening of the stonework (Brothwell et al., 1974; Christison, 1898; Nisbet, 1974), (b) hostile attack with destructive intent (Aylwin Cotton, 1954; Small and Cottam, 1972), (c) post-occupancy destruction by the builders of the wall (MacKie, 1969; Ralston, 1986), or (d) ritual or cultural practices with other motives (Bowden, and McOmish, 1987).

That vitrification was an intentional process for strengthening the fort walls (here: “the engineering argument”) has been considered “untenable” since Mackie (1969, 1976), citing the large-scale experimental vitrification of a stone wall by Childe and Thorneycroft (1938), proposed that burning of a wall will cause local instability and collapse. This has led to a paradigm guiding subsequent work toward a combative (Aylwin Cotton, 1954; MacKie, 1976; Nisbet, 1974) or destructional (MacKie, 1969; Ralston, 2007) intent for vitrification. That, in turn has been supported by evidence that vitrification occurred toward the end of occupation (Gifford, 1992; Kresten and Goedicke, 1996; MacKie, 1976) rather than during construction.

Ample evidence exists to demonstrate that exposure to high temperature generally decreases the bulk strength of building materials by inducing microcracks (Hajpál, 2002; Heap et al., 2012). Vitrification however, achieved by the significant sintering of blocks and interstitial particles in dry-stone fort walls in the presence of a partial melt, is another matter. Based on evidence from sintering experiments on glass fragments we have previously shown that such sintering results in a dramatic *increase* in material strength (Vasseur et al., 2013). We therefore speculate that the firing of Iron Age fort walls to temperatures where significant vitrification is achieved through sintering is likely to result in significant strengthening.

Here we provide experimental evidence that firing of Iron age forts may have led to their strengthening after all. The new evidence is based on controlled experiments on heat-treated samples of a sandstone and a powder thereof – designed to represent, respectively, the blocks and the disaggregated mortar that comprise a typical Iron Age fort wall.

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2. Materials and methods

Darley Dale sandstone (Derbyshire, England) was chosen for this study due to its widespread use and characterization in the rock deformation literature and its textural and compositional homogeneity (Brantut et al., 2014). It also derives from the same stratigraphic stage in the Carboniferous period as the Parkgate sandstone from which the Wincobank Iron Age vitrified fort was constructed (Wadsworth et al., 2015). The initial mineral assemblage of Darley Dale sandstone comprises quartz (69 wt.%), feldspar (26 wt.%), clay (2 wt.%) and mica (2 wt.%) (Heap et al., 2009; Wu et al., 2000) and the diameter of the particles (or grains) in the sandstone blocks varies between ~80 and 800 μm (Wu et al., 2000).

Differential scanning calorimetry (DSC) in combination with thermogravimetric analysis was performed using a Netzsch Pegasus 440C simultaneous thermal analyzer (STA). These techniques show the evolution of the specific heat capacity and the sample mass during high temperature treatment, which are critical for the interpretation of macroscopic property evolution such as material strength. Samples of Darley Dale sandstone were slowly crushed by hand in an agate mortar to avoid the heat produced during mechanical milling techniques and then sub-samples of 40–55 mg were placed in lidded platinum crucibles and heated at 10 or 25 °C min^{-1} to 1400 °C. Two identical cooling and heating cycles were performed for each experiment to identify any potential changes in sample state after initial heating. An empty-crucible baseline was subtracted and the specific heat capacity was obtained by the standard ratio technique by comparison with identical runs with a pure sapphire standard of near-identical mass. We note that the sample mass used is necessarily small to ensure precision and repeatability of the results and repeat runs were performed to confirm representativeness of the bulk sample behaviour.

Optical dilatometry was performed in a Hesse Instruments® heating stage in order to assess sample volume changes during heating. Samples of sieved, <63 μm, hand-crushed sandstone particles were formed into cylindrical free-standing samples (Wadsworth et al., 2014) and were heated at 10 or 25 °C min^{-1} to 1400 °C; conditions identical to the thermal analysis described above. Images of the sample were captured parallel to the cylinder's axis of rotation. Continuous measurements of pixel area, height and width (continuous data) of the sample were obtained at 1 Hz, while images were taken every ~10 °C (discrete data). The continuous data were converted to volume by using a cylindrical assumption while the discrete data were processed by the solid-of-rotation method. The solid-of-rotation involves the numerical integration of the sample radius R (detected from binary images using a Canny edge detection algorithm) around a central axis of symmetry in the y-direction over the sample height L such that the volume $V = \int_0^L \pi R^2 dy$. The volumes in voxels from both methods were converted to porosity ϕ by knowing an initial porosity ϕ_i. The initial porosity was determined by the volume, mass and powder-density where the powder-density was measured in a helium pycnometer. Then $\phi = 1 - V_i(1-\phi_i)/V$ where V_i is the initial sample volume.

Cylindrical cores of Darley Dale sandstone were drilled from a single block to 20 mm diameter and precision ground to a nominal length of 40 mm. These were heated at 10 °C min^{-1} in a box furnace to target temperatures 800–1400 °C and then held isothermally for either 10 min or 5 h before cooling to room temperature at a rate limited by the furnace. Hand-crushed powder of the same sandstone was loosely packed into alumina ceramic tubes. The alumina tubes were 60 mm height with an internal diameter of 40 mm and an external diameter of 44 mm. These tubes were carefully placed in the box furnace and heated to the same target temperatures for an isothermal hold period of 5 h, before being cooled and then drilled and ground to dimensions identical to the cylindrical cores of sandstone described above. Helium pycnometric determination of connected sample porosity was conducted on samples prior to and following heat treatment. Finally, the uniaxial compressive strength, a standard metric for material strength, of intact (i.e. untreated) Darley Dale sandstone and of all thermally treated cores was determined using a uniaxial deformation apparatus that provided continuous measurement of axial stress and axial strain leading to macroscopic sample failure at a constant axial strain rate of 10^{-5} s^{-1} (adhering to the International Society for Rock Mechanics suggested methods). Following the compression experiments, the remnant sample material was crushed so that a pore-free matrix density could be measured (using helium pycnometry) in order to convert the connected porosity data to total sample porosities. Henceforth the term porosity refers to the total porosity measured using a helium as the pore fluid. All samples were dried in a vacuum oven at 40 °C for at least 48 h prior to experimentation at ambient temperature and humidity. A lubricating wax was applied to both ends of the samples to limit any stress due to friction between the rock and the pistons during deformation.

In order to know the firing timescale required to ensure that thermal equilibrium was achieved in our samples we use the heat diffusion timescale λ as a scaling approximation. Given that $\lambda \approx R^2/D$ where R is the cylindrical sample radius – 10 mm – and D is the thermal diffusivity, we estimate that the time-to-equilibrium for our cylindrical samples is ~20 min. This is in agreement with fully numerical 2D simulations of heat transfer in our cylinders which are presented in the Supplementary Information along with the constraint of D as a function of porosity and the thermal properties of the pore and solid phases. We conclude that the experiments in which samples were heated for 5 h were in thermal equilibrium, whereas those heated for 10 min were not.

3. High temperature performance of vitrified wall materials

The temperature dependence of the heat capacity of Darley Dale sandstone reveals mineralogical changes and the onset of melting. We find that at heating rates of 10 and 25 °C min^{-1} the well-constrained α-to β-quartz transition (Glover et al., 1995; Heaney, 1994) occurs as a sharp endothermic spike at 577 and 579 °C, respectively, on both first and subsequent heating runs (Fig. 1a). However, the peak heat capacity associated with this transition is diminished on the second heating cycle, suggesting that quartz content has been reduced during heating to and cooling from 1400 °C (as confirmed for a compositionally similar sandstone from the Wincobank vitrified hillfort site; Wadsworth et al., 2015). A heat capacity exotherm occurs at 1002 °C for the sample heated at 10 °C min^{-1}. As heating continues, this exotherm is followed by a broad melting endotherm. The aforementioned exotherm occurs at a higher temperature of 1019 °C when heated at 25 °C min^{-1} due to the increased lag associated with heat transfer as a function of increasing heating rate. Very minor (~1%) sample mass loss occurs only on the first heating cycle with peak mass loss rates at ~650 and ~680 °C for 10 and 25 °C min^{-1}, respectively (Fig. 1b). Mass loss, associated with the dehydration of mica and clays, is therefore of negligible importance for the process of vitrification in these samples (Wadsworth et al., 2015). However, the dehydrated product of the mica and clay or the water liberated may play a crucial role in modifying the onset of melting (Friend et al., 2007).

The initial porosity of the Darley Dale sandstone is ~0.17 ± 0.005. When individual cores of the Darley Dale sandstone are thermally treated, the measured porosity increases to a maximum of ~0.25, which is a 47% increase. By contrast, when a powder aggregate of the same material is heated, the porosity decreases from ~0.45 (the initial porosity interstitial to the particles) to 0.05–0.07, which is an 84–89% decrease. During the optical dilatometry experiments,