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Quantifying erosion of 'at risk' archaeological sites using repeat terrestrial laser scanning

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ABSTRACT

Effective heritage management is reliant on an understanding of the range of current and potential future threats facing archaeological sites. Despite this, the processes leading to the loss of in situ archaeological remains are still poorly understood, including the rates, timing and drivers of surface erosion. This issue is particularly significant for abandoned historical metal mines in upland landscapes, where erosion rates are typically higher due to a combination of the unstable character of the archaeological deposits and the increased effectiveness of surface erosion processes. This study utilises repeat terrestrial laser scanning (TLS) to monitor the changing condition of two adjacent lead mines in the North Pennines, UK, over an 18 month period. The high spatial and temporal resolution of the TLS data, in conjunction with land cover characteristics derived from an unmanned aerial vehicle (UAV) survey, allows the detailed quantification of the causes and impacts of surface change. The results demonstrate that stream bank erosion is the process responsible for the most widespread and archaeologically significant damage, although localised gullying of mine waste heaps resulted in the largest volumetric loss of material (>160 m^3). Temporal variation in the erosion of upland archaeological sites is highly episodic, being dominated (>70%) by high magnitude but low frequency storm events. These results provide invaluable information regarding the causes and impacts of erosion of upland archaeological remains, as well as establishing a proven methodology which can now be applied to archaeological sites in other landscape contexts.

1. Introduction

Understanding the rates, timing and drivers of erosion on archaeological sites has long been recognised to be of fundamental importance when developing effective heritage management strategies to ensure the long-term survival of threatened remains (Bell and Boardman, 1992). For these reasons, experimental earthworks at sites such as Overton Down (Wiltshire) and Wareham (Dorset) have been crucial for our understanding of past and present soil processes (e.g. Bell et al., 1996) and geoarchaeology is routinely incorporated into the analysis of archaeological landscapes (for examples see Goldberg and Macphail (2006)). Potential damage to archaeological sites comes from a wide range of both natural (Pederson et al., 2006; Robinson et al., 2010) and anthropogenic (Wilkinson et al., 2006; Rossi and Webb, 2007) sources, each of which may operate through different physical mechanisms and over variable timescales. Schemes designed to assess and manage archaeological resources are therefore entirely dependent on the accuracy of baseline information in defining what specific threats are likely to be encountered and their relative significance under different scenarios. Although this need for informed approaches to the management of archaeological remains has been widely recognised at both international (Wijesuriya et al., 2013) and national (Darvill and Fulton, 1998) levels, defining the degree of risk still remains a challenge.

1.1. Current approaches to monitoring archaeological sites of national importance

The monitoring of vulnerable archaeological sites of national importance typically depends upon schemes such as Historic England's 'Heritage at Risk' register; an annual listing of those scheduled or protected sites deemed most at risk of damage (Historic England, 2015a). This programme involves the annual field walkover inspection of threatened archaeological sites and the use of qualitative category definitions to rank its condition (Historic England, 2014). While many scheduled sites have their own individual management plans, the key limitations of such approaches are that they are typically only carried out by archaeologists, with little involvement from geomorphologists, and that they are largely reliant on qualitative assessments with no quantitative survey measurements. Although the archaeological significance of damage may be accurately identified, the drivers and rates of change are

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often overlooked or misunderstood, which in turn restricts the ability to design and implement appropriate conservation schemes, particularly at a time when budgets and personnel are stretched.

Recent research has been directed towards alternative approaches to monitoring the changing condition of archaeological sites, using a range of quantitative techniques involving satellite-borne (Barlindhaug et al., 2007; Kincey et al., 2014), airborne (Kincey and Challis, 2010; Hesse, 2015) and terrestrial sensors (Barton, 2009). Importantly, some of these studies have analysed multi-temporal digital elevation data to extract quantified change between the surface topography of archaeological sites over time periods ranging from years to several decades (Risbøl et al., 2015; Papworth et al., 2016). Although these approaches are extremely valuable for assessing longer-term patterns of change on archaeological sites, not least currently when sites are threatened by looting and destruction inside war zones (Casana and Panahipour, 2014), coarse temporal resolution surveys of this kind inevitably overlook or misinterpret important process-related topographical information from intervening periods (Lindsay and Ashmore, 2002). In contrast, terrestrial laser scanning (TLS) indirectly measures the surface topography across relatively large areas at a much higher spatial and temporal resolution; generating detailed 3-dimensional data that can be used as a point-in-time survey record or as the basis for quantitative comparisons. TLS is fast becoming a standard technique for quantifying high resolution morphological change in a range of geomorphological settings (Schürch et al., 2011; Brasington et al., 2012; Grayson et al., 2012), as well as being increasingly used for monitoring the condition of upstanding structural remains (Hinzen et al., 2013). However, prior to this paper, the use of repeat TLS for monitoring archaeological sites is very limited and has been restricted to coarse (bi-annual/annual) temporal intervals (Romanescu et al., 2012; Romanescu and Nicu, 2014). The potential of terrestrial laser scanning to inform understanding of high temporal resolution changes on archaeological sites still therefore remains to be demonstrated.

1.2. Research aims and archaeological context

This study uses repeat terrestrial laser scanning to monitor the changing condition of surface archaeological remains at Whitesike and Bentyfield mines; two post-medieval (17th to early 20th century) lead mining complexes in the North Pennine uplands of Cumbria, UK. Surveys were conducted on an approximately monthly basis over an 18 month period between September 2012 and March 2014 and were supplemented by an unmanned aerial vehicle (UAV) flight to characterise broader land cover characteristics. The results of change detection analyses between monthly digital elevation models (DEMs) are used to provide invaluable insights into the causes, timing and significance of erosion on these nationally important archaeological sites. These results are then considered against the longer-term pattern of change as revealed by a time series of cartographic and aerial photographic sources.

Historical metal mines present a particular challenge for the heritage community because of the scale and richness of the archaeological remains and their good state of preservation, coupled with their relative inaccessibility and the combination of interests represented in their management. The significance of surviving industrial remains and the corresponding need to preserve them has been widely acknowledged for several decades (Palmer and Neaverson, 1995). However, due to the phytotoxic nature of heavily contaminated metal mine sediments, the vegetation cover on abandoned mines is often limited and their surface deposits may be highly unstable (Toy and Hadley, 1987; Ostrander and Clark, 1991). The typical location of mining remains within dynamic upland environments where geomorphic processes tend to be most active further exacerbates this erosion potential (Jones et al., 2004). The combined consequence of these factors means that industrial remains have often experienced much higher rates of decay and destruction when compared against other categories of archaeological monument and this introduces particular challenges around their effective preservation (White, 1989; Barnatt and Penny, 2004).

2. Study site

Fieldwork focused on Whitesike and Bentyfield mines, two adjacent historical lead mine complexes located approximately 1 km northeast of Garrigill, Cumbria (54°46′36.48" N, 2°23′07.84" W) (Fig. 1). These mines straddle the middle reaches of Garrigill Burn, an east-west flowing tributary of the South Tyne; one of the major rivers draining the Alston Moor area of the North Pennine uplands. The documented history of extraction at the two mines covers the period from the late 17th century until their abandonment in the early 1900s (Strickland and Wooler, 2012), although recent archaeological surveys suggest that active mining extends back considerably earlier (Oakey et al., 2012; Railton and Wooler, 2012). Recorded mineral statistics indicate that lead production from these mines was relatively small-scale, especially in relation to the nearby workings around Nenthead (Burt et al., 1982).

Despite this, the archaeological significance of the mines is considerable, due primarily to the survival of abundant surface remains relating to different stages in the mining process and the presence of deeply stratified and potentially waterlogged deposits (Fig. 2). Based on these criteria, the two mines are jointly designated by Historic England as a single Scheduled Monument (No. 1015832), with the extent of the protected area including all of the mine levels, processing areas, structures and spoil heaps (Historic England, 2015b). Importantly, the majority of Whitesike Mine is also designated a Site of Special Scientific Interest (SSSI) due to the calaminarian (metallophyte) grassland species found on the metal rich soils resulting from the historical mining operations (Natural England, 2000).

Walkover assessments as part of Historic England's ‘Heritage at Risk’ (HAR) register identified the archaeological remains at Whitesike and Bentyfield mines as being at risk of immediate rapid deterioration as early as 2000. By 2010, the mines were described as being in ‘very bad’ condition and became a HAR priority site for North West England in 2011 and 2012 (Historic England, 2012). Archaeological and hydrological qualitative assessments undertaken in 2012 (Newson, 2012; Strickland and Wooler, 2012) were subsequently used to inform a repair scheme aimed at stabilising the archaeological remains and preventing further erosion. These consolidation works were primarily focused on managing the potential for damage caused by the flow of Garrigill Burn through the mined area and included the repair of 19th century retaining walls and the revetment of selected stream banks. Additional structural repairs were also undertaken, with level entrances being cleared at both mines and the wheel pit and mine lodging shop at Bentyfield being stabilised. Following completion of the repair scheme in mid-2012 the mines were removed from the HAR register, effectively indicating that they are no longer considered to be ‘at risk’ of further significant degradation. Fieldwork for this present study commenced in September 2012 and therefore after the completion of the repair scheme. It therefore provides a useful test of the efficacy of these particular stabilisation works, as well as a broader assessment of current approaches to characterising heritage at risk.

3. Material and methods

3.1. Terrestrial laser scanning (TLS)

High spatial and temporal resolution topographic change was measured using repeat terrestrial laser scanning (TLS) surveys conducted over an 18 month period between September 2012 and March 2014. A total of 14 TLS data sets were captured during this monitoring period,