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

Mark Kincey[a*], Chris Gerrard[b] and Jeff Warburton[a]

[a] Department of Geography, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE UK

[b] Department of Archaeology, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE UK

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.

Keywords

Laser scanning; Change detection; Metal mining; Geoarchaeology; Erosion; Industrial archaeology

[*]Correspondence to: Mark Kincey, Department of Geography, Durham University, Durham, DH1 3LE

Email: m.e.kincey@durham.ac.uk

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 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 (17^{th} to early 20^{th} 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 (NY 753 425) (Figure 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 (Figure 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.

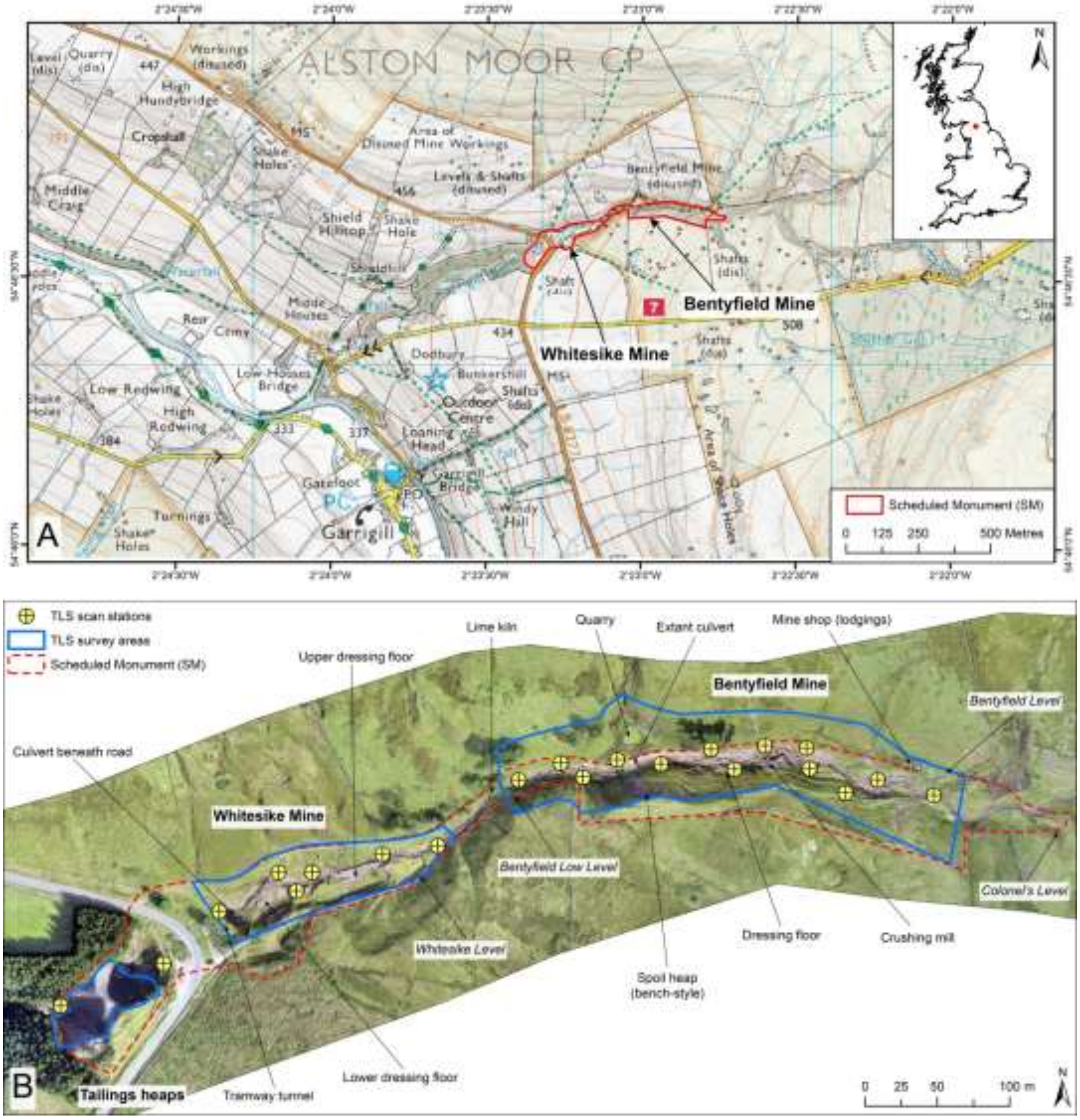

Figure 1 – Location of Whitesike and Bentyfield mines (A) and UAV orthophoto mosaic showing TLS survey setup and key archaeological features (B) (Map data © Crown Copyright and Database Right 2016. Ordnance Survey (Digimap Licence).

Figure 2 – Photograph of Whitesike dressing floors taken in c.1895 (A), with key mining features highlighted (Image © Nenthead Mines Conservation Society / Peter Jackson). A photograph of the dressing floors taken from a similar viewpoint in 2012 is provided below for comparison (B).

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, with adverse weather conditions meaning that surveys could not be completed in December 2012, February, April and July 2013 and February 2014. Data were collected using a Riegl VZ-1000 terrestrial laser scanner, a time-of-flight based instrument with integrated digital camera and GPS receiver.

Monthly scans were collected from 21 individual scan stations distributed throughout the overall survey area, in order to minimise the effect of occlusion on final point cloud coverage (Figure 1b), with the same scan positions being used for each survey. For ease of data collection and processing the survey was subdivided into three sections, with the easternmost area covering Bentyfield Mine (18905 m^2), the central area focusing on Whitesike Mine (6539 m^2) and the westernmost area on the tailings heaps to the west of the site (2144 m^2). Scan positions and reflective target locations (n=20) were positioned using a Leica 1200 differential GPS, providing a mean 3D positional accuracy of 20 mm.

Processing of the TLS data was undertaken in RiScan Pro v1.7.9, involving the co-registration of individual point clouds (standard deviation error <10 mm), the filtering of unwanted non-ground points (e.g. vegetation) and the georeferencing of the overall data set using the reflective target dGPS coordinates. In areas of particularly steep terrain, such as stream banks, extracts from the point clouds were transformed so that the Z-axis was perpendicular to the slope face. Transformation of point cloud data in this way is necessary in areas of complex topography or where the aim is to quantify lateral change, such as with coastal cliff evolution (Rosser *et al.*, 2005) or riverbank erosion (O'Neal and Pizzuto, 2011). For this study, the transformed data allowed both lateral and surface change to be quantified and compared. Final processed monthly point clouds were exported as XYZ coordinates before being interpolated to form 0.05 m resolution digital elevation models in ENVI v5.1 (Figure 3).

3.2 Change detection analysis

Analysis of morphological surface change between each of the multi-temporal topographic surveys focused on the construction and interpretation of DEMs of Difference (DoDs). A DoD involves the subtraction of an earlier DEM from a later DEM to calculate a change in elevation for each individual raster cell, with negative values typically representing erosion and positive values deposition. DEMs often include a wide range of potential errors associated with the various stages of survey data capture, processing and surface interpolation, meaning that DoD results characteristically also include a component of vertical error (Heritage *et al.*, 2009).

Geomorphic change between successive TLS surveys was quantified through the construction of multiple DEMs of Difference (DoDs), based on the method developed by Wheaton *et al*. (2010) and using the Geomorphic Change Detection (GCD) v6.1.8 add-in for ArcGIS v10.2. This method of change detection utilises fuzzy logic to consider spatial variability in elevation uncertainty resulting from a number of survey and terrain characteristics and has been successfully employed by a number of recent geomorphological studies utilising multi-temporal DEMs for change detection analysis (e.g. Blasone *et al.*, 2014; Kuo *et al.*, 2015).

Spatially variable error surfaces were constructed for each DEM using a three input fuzzy inference system which included TLS point density, slope angle and local surface roughness as model input parameters (Wheaton, 2008). A series of FIS rules are then defined in order to relate different combinations of input categories to corresponding levels of output elevation uncertainty. The fuzzy inference system applies these rules on a cell-by-cell basis before calculating a 'defuzzified' centroid elevation uncertainty value to each cell. The resulting elevation uncertainty rasters for the two DEMs are then combined into a single propagated error raster and a *t* score used to calculate the probability that the change is real, based on the method outlined by Brasington *et al.* (2003).

The second stage of the GCD analysis involves the consideration of spatial coherence in elevation change values and is based on the concept that areas of erosion and deposition tend to occur in discrete units (Wheaton *et al.*, 2013). For example, an elevation change value representing erosion is more likely to represent real change rather than DEM error if it is also surrounded by other cells representing erosional change. A spatial coherence convolution filter (5 x 5 cells) was therefore used to count the number of cells in each analysis window that are erosional and depositional. A linear transform function was then applied to relate the output of the convolution filter to a cell-by-cell probability that elevation change is real. These conditional probability values are combined with the FIS probability values to create an updated final probability surface. Output DoD cell values are then either retained as real change or rejected as relating to error based on the specified probabilistic uncertainty threshold (95%).

Change detection analyses included pairwise comparison of each of the individual monthly TLS surveys, as well as calculation of total changes resulting from the entire 18 month monitoring period (September 2012 – March 2014). The primary outputs of these analyses were thresholded DoD surfaces displaying elevation differences and tabular information corresponding to the total volume of change and associated errors. In environments dominated by low, dense vegetation, such as the North Pennines, elevation change values within such DoDs typically represent a combination of both real geomorphic change and seasonal patterns of vegetation growth (Guarnieri *et al.*, 2009; Coveney and

Fotheringham, 2011; Fan *et al.*, 2014). The final stage of analysis was therefore to digitise areas which were interpreted as real geomorphic change within ArcGIS as vector polygons and to assign corresponding tabular information describing specific causal processes where possible. Elevation change values extracted to each of these categories of polygon (e.g. bank erosion) allowed the magnitude impact of each individual process to be quantified and compared. This approach is similar to the budget segregation method utilised by Wheaton *et al.* (2013), in which the various mechanisms of change are identified and individually quantified in order to generate a detailed volumetric sediment budget.

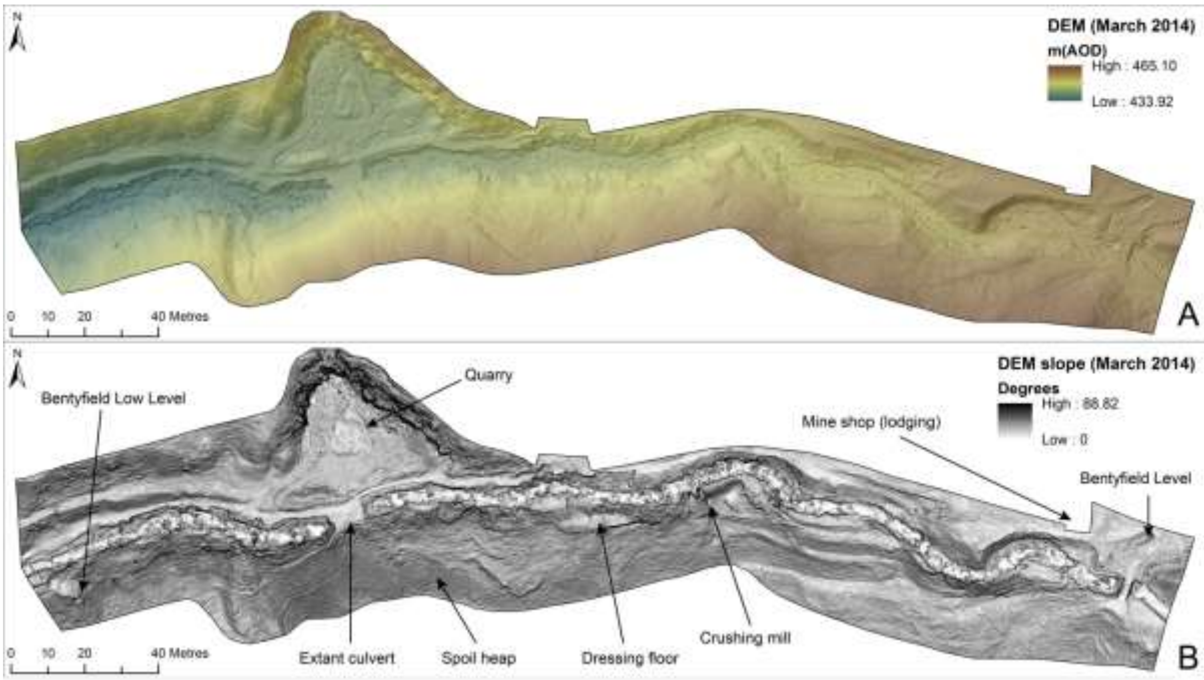

Figure 3 – Example results from the terrestrial laser scanning surveys, showing colour-shaded DEM (A) and slope raster (B) of Bentyfield Mine from March 2014.

3.3 Unmanned Aerial Vehicle (UAV) survey

Aerial imagery was obtained on 5th September 2012 using a Personal Aerial Mapping System (PAMS) SmartOne fixed-wing Unmanned Aerial Vehicle (UAV). A total of 209 images were acquired during four overlapping flight blocks from an average altitude of ~135 m above ground level. Ground control points (n=29) were recorded from locations across the survey area using a combination of differential GPS and terrestrial laser scanner survey. Image processing was conducted within Agisoft PhotoScan (v0.9.0.1586), a computer vision software that uses the structure from motion (SfM) principle to construct 3D content from input photographs. The processing workflow involved the alignment of the pre-selected images to create an initial sparse point cloud, the construction of a subsequent detailed geometry mesh and the texturing of the mesh to form a photo-realistic 3D terrain model. Following georeferencing the model was exported as a 0.04 m resolution orthophoto and a 0.15 m digital elevation model (Figure 1b).

3.4 Cartographic and aerial photographic data

Longer-term surface change occurring at Whitesike and Bentyfield mines since their abandonment was assessed through a time series of maps and aerial photographs (Table 1); an approach which can be of value for identifying the key processes affecting archaeological sites over long time periods (Nicu, 2016). However, deriving small-scale quantitative information from historic map sources is often problematic due to variations in accuracy and recording techniques (Hooke and Kain, 1982). Similarly, the poor image quality of the earlier aerial photographs precluded detailed quantitative analyses. Therefore morphological changes were primarily identified through visual inspection of the different epochs of archival data, with the key aim being to develop a qualitative understanding of longer-term trends which could be tested against higher resolution short-term quantitative analyses.

Table 1: Cartographic and aerial photographic sources

Description	Date	Scale	Source	Format
Maps				
OS First Edition County Series Map	1868	1:2500	Edina Digimap	-
OS First Revision County Series Map	1899 - 1900	1:2500	Edina Digimap	-
OS National Grid Series Map (Imperial)	1953 - 1957	1:10560	Edina Digimap	-
OS National Grid Series Map (Metric)	1978 - 1982	1:10000	Edina Digimap	-
OS modern map	2010	1:10000	Edina Digimap	-
Aerial Photographs				
RAF vertical AP (RAF/58/2655/F22/13)	1958	1:9900	Historic England	Monochrome
OS vertical AP (OS/76215/183)	1976	1:8200	Historic England	Monochrome
NMR oblique AP (NMR/17212/31)	1999	N/A	Historic England	Monochrome
Infoterra vertical AP (Miner-Farmer)	2009	1:22813	Historic England	Colour

4. Results

4.1 Short-term morphological change using repeat TLS (September 2012 – March 2014)

During fieldwork and data processing the terrestrial laser scanning surveys were divided into three broad areas representing Whitesike Mine, Bentyfield Mine and the western tailings heaps. The results of the repeat TLS surveys are considered below in relation to each of these areas, before the overall trends are considered together as part of a wider discussion of results.

4.1.1 Whitesike Mine

Total change from all geomorphic processes identified within the Whitesike Mine survey area resulted in 62.3 m^3 of net erosion over the entire 18 month TLS monitoring period. The dominant process leading to morphological change was bank erosion, which accounted for 53.5 m^3 (86%) of all documented erosion (Figure 4). Bank erosion was distributed throughout the entire length of the mined area, but with notable concentrations along both banks immediately adjacent to the two Whitesike dressing floors; the areas where the extracted ore would have been processed prior to transport to the smelt mill. A total of 5 m^3 of bank erosion occurred along the lower dressing floor during the 18 month monitoring period, equivalent to a mean bank recession rate of over 0.4 m. The significance of this erosion is not simply related to a reduction in the overall dressing floor area, with field inspection of the eroding bank section also identifying clear evidence for damage to earlier stratified dressing floor deposits and flagstone working floors (Figure 5).

Although the overall magnitude of change at the upper dressing floor was slightly less (4.4 m^3), this primarily involved the collapse of two sections of 19th century drystone retaining wall immediately adjacent to Garrigill Burn. These collapses occurred opposite a major area of bank erosion and were likely exacerbated by a combination of factors, including a step in the long profile of the stream and internal structural weaknesses (Figure 6). From a heritage management perspective this is of particular importance because the collapses occurred within only c.14 months of this section of wall having been reconstructed as part of the 2012 consolidation works, which themselves were a repair of earlier structural works carried out in 2011. The collapse of these wall sections demonstrates the continuation of streambank erosion also identified in the longer-term analyses (Section 4.2).

The impact of other geomorphic processes identified across Whitesike Mine was less than for bank erosion. However, a concentration of small-scale erosional change (2.4 m^3) was recorded on the unvegetated slope above the main western culvert transporting Garrigill Burn under the main Alston road. This erosion is likely to be due to a combination of subaerial slope processes, including soil creep, slope wash and small patch failures. Importantly, this slope face also incorporates a drystone revetment wall, a tramway tunnel leading to the western tailings heaps and earlier drystone structural features; all of which are becoming more exposed by the recorded erosion. Elsewhere, the majority of the periphery of Whitesike Mine is heavily vegetated and appears largely stable on the DoDs from the repeat TLS surveys.

Analysis of temporal variation in erosion rates based on the monthly time series of TLS data sets indicates that morphological changes at Whitesike Mine were highly episodic. For example, the large bank collapse adjacent to the upper dressing floor during the first survey interval (September – October 2012) recorded 13.8 m^3 of erosion, representing 22% of the total net change for the entire monitoring period. The interval between May and June 2013 then recorded an even greater amount of change, totalling 35.4 m^3 of erosion or 57% of the total recorded net volumetric change. This period of change primarily centred on areas adjacent to the main stream channel, including significant areas of bank erosion and the major collapses of retaining walls of the aforementioned upper dressing floor (Figure 7). The potential reasons for the episodic nature of this erosion are discussed further in Section 5.

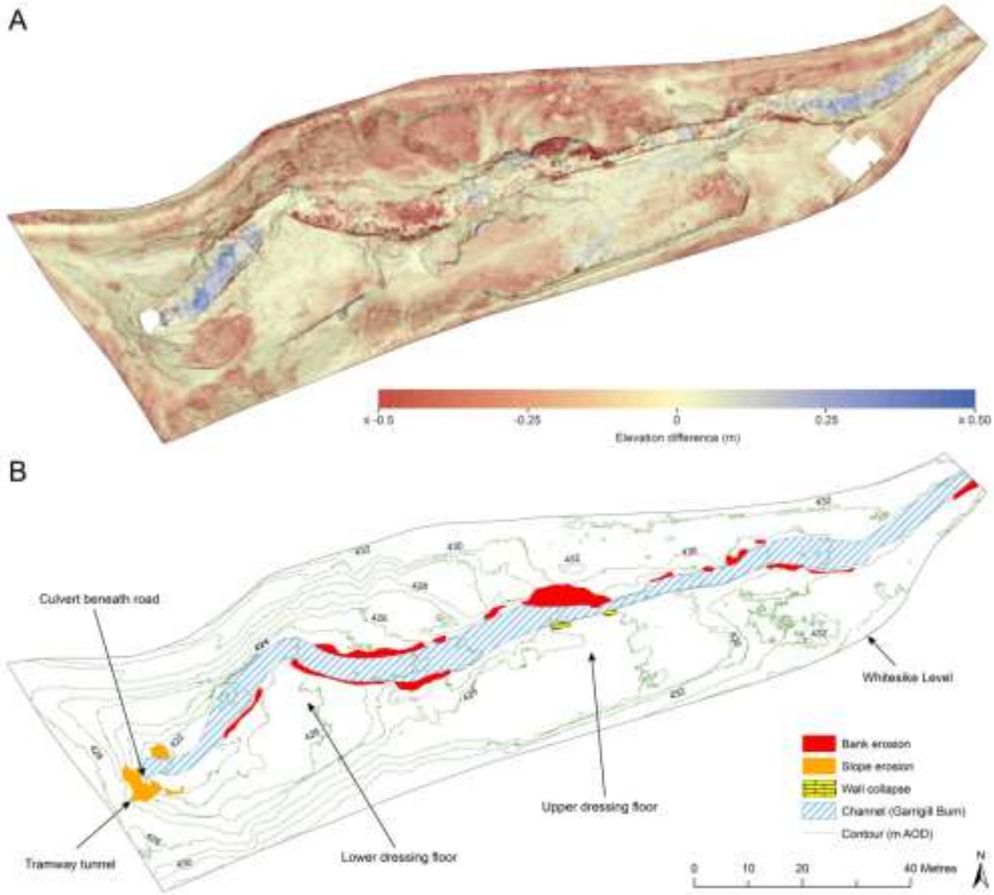

Figure 4 – DEM of difference representing total elevation changes during the period September 2012 to March 2014 for Whitesike Mine (A) and accompanying interpretative map (B). The influence of background vegetation growth on elevation change values and the corresponding need to digitise areas of real topographic change can be clearly seen in (A).

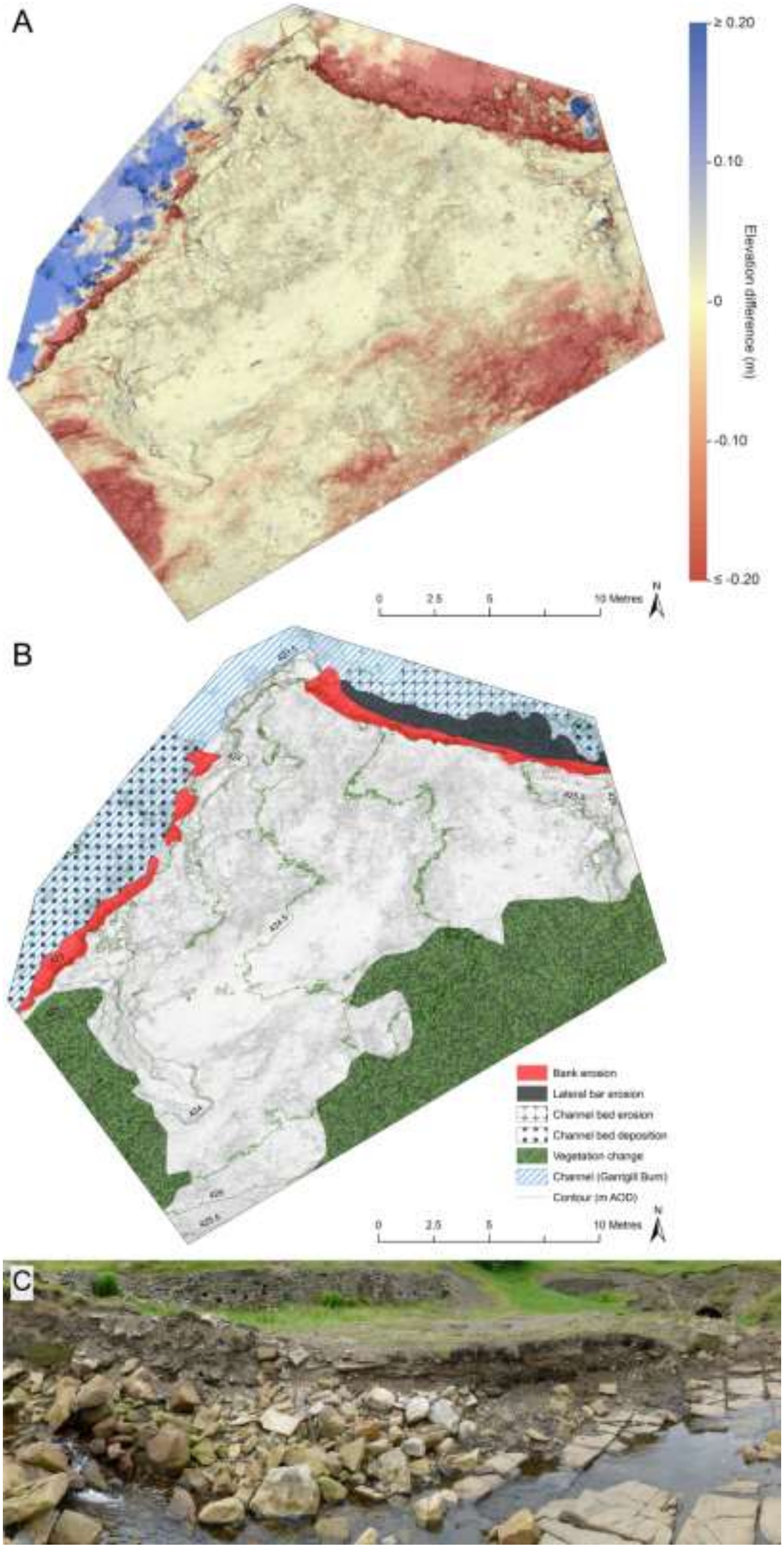

Figure 5 - DEM of difference representing total elevation changes during the period September 2012 to March 2014 for the lower dressing floor at Whitesike Mine (A), accompanying interpretative map (B), and field photograph of the eroding north bank (C). Earlier stratified dressing floor deposits are clearly visible in the bank section, including at least one phase of flagstone flooring.

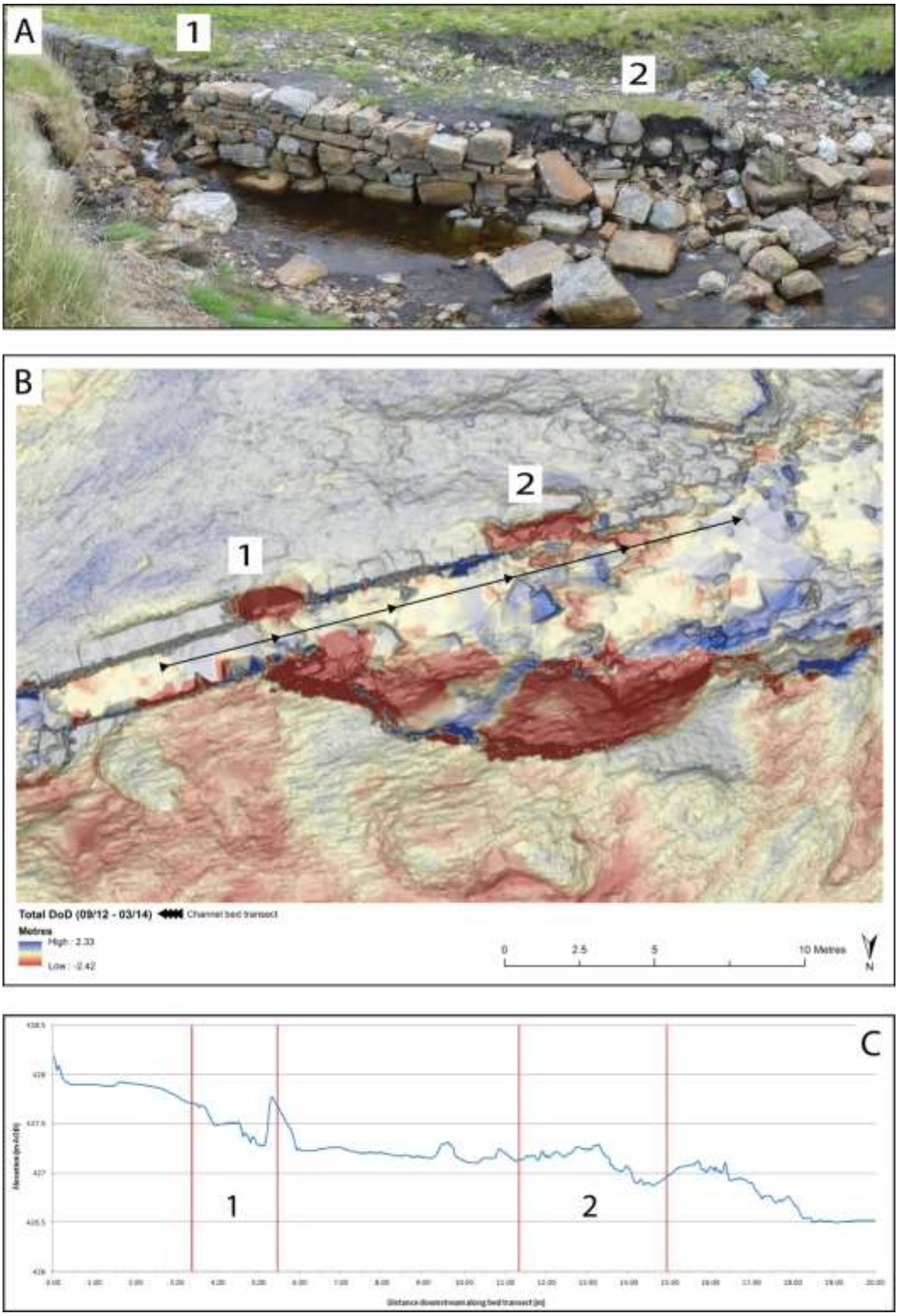

Figure 6 – Collapsed sections of the drystone retaining wall adjacent to the upper dressing floor at Whitesike Mine as seen in a field photograph from September 2013 (A) and the overall 18 month DEM of Difference (B). The relationship between the collapsed sections and the dGPS measured bed elevation profile of Garrigill Burn is shown in the associated line graph (C). Numbers 1 and 2 represent the locations of corresponding collapsed sections on each of the figure panels.

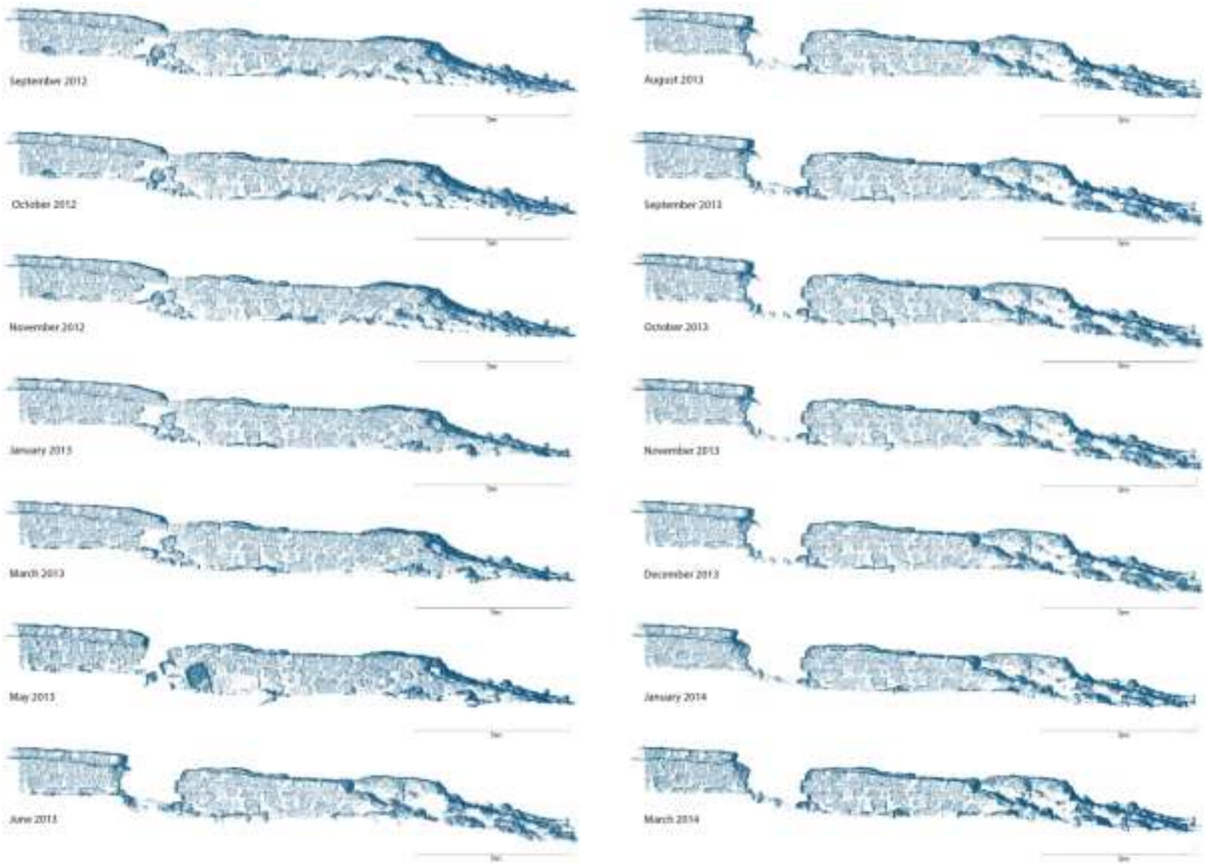

Figure 7 – TLS point clouds showing the progressive collapse of sections of the north facing elevation of the upper dressing floor retaining wall at Whitesike Mine. Sequence is read from top to bottom, column by column.

4.1.2 Bentyfield Mine

Overall erosion at Bentyfield Mine during the 18 months of TLS monitoring was 31.5 m^3, representing approximately half the net erosion from Whitesike Mine but from an area almost three times the size. Although this clearly suggests that, in general terms, the surface remains at Bentyfield Mine are more stable, the TLS surveys did highlight particular areas of ongoing concern (Figure 8). As with Whitesike Mine, the dominant geomorphic process leading to morphological change was bank erosion, resulting in a net change of 21.2 m^3 or 67% of the overall net volumetric change. Bank erosion was particularly prominent further upstream to the east of the mined area, with the TLS results indicating that it was actually due to a combination of different sub-processes operating at varying scales of magnitude and frequency. This primarily involved high magnitude change caused by gullying and direct fluvial entrainment, as well as lower magnitude change resulting from spatially extensive subaerial processes, such as soil creep and ice needle formation. These findings were in agreement with previous studies which have suggested that bank erosion is typically the result of a combination of mass failures, diffuse subaerial processes and direct fluvial entrainment (Hooke, 1979; Couper and Maddock, 2001).

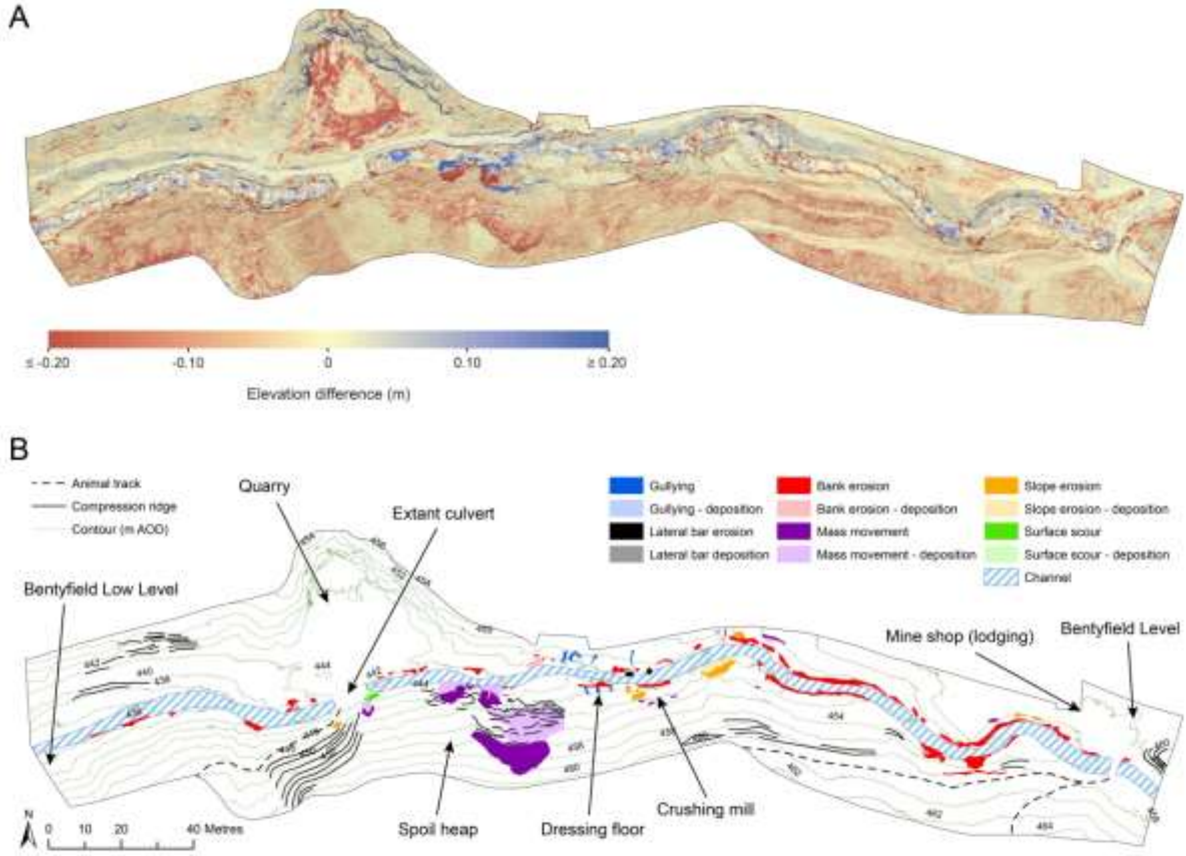

Figure 8 – DEM of difference representing total elevation changes during the period September 2012 to March 2014 for Bentyfield Mine (A) and accompanying interpretative map (B).

Although fairly limited in spatial extent and magnitude, the archaeological implications of the bank erosion at Bentyfield Mine are significant. Erosion of the north-facing bank of the Bentyfield dressing floor is disturbing important stratified deposits and exposing wooden planks and structural features from an earlier ore-processing phase. Further upstream, the erosion of the south-facing bank immediately adjacent to the two-storey Bentyfield mine shop is progressively exposing and undermining a previously unrecorded stone structure (Figure 9). The date and function of this structure are currently unknown but it is clear from the TLS surveys that continued bank erosion in this location will result in the loss of important structural elements associated with the earlier mining landscape.

The other major change recorded at Bentyfield Mine was due to a shallow landslide occurring on the north-facing slope of the main bench-style spoil heap (Figure 10). Monitoring of this slope indicated that the failure itself is slow moving and does not represent an immediate threat of major blockage to the main channel of Garrigill Burn, which is located directly at the base of the landslide. However, the landslide appears to be a rotational failure and downslope movement did result in the erosion of c.7 m^3 of material from the spoil heap over the 18 months of fieldwork. The archaeological significance of this erosion is heightened by its proximity to the only surviving section of original intact culvert across the entire site. Material eroding from the spoil heap is deposited directly into Garrigill Burn and therefore has the potential to block the downstream culvert and lead to further channel instability and structural collapse.

Temporal variation in surface change at Bentyfield Mine during the 18 month monitoring period again demonstrated that the erosion of archaeological remains is highly episodic in nature. As with Whitesike Mine, the main period of high magnitude change was between May and June 2013 and was particularly prominent for locations close to Garrigill Burn, again suggesting that a significant rainfall event occurred at this time.

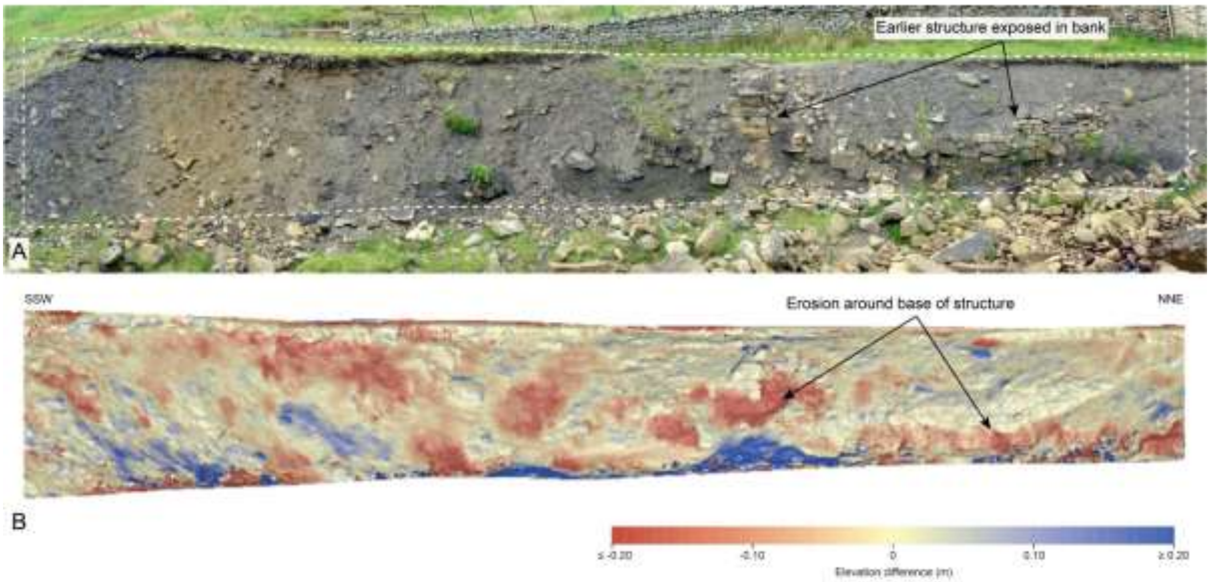

Figure 9 – Field photograph (A) and DEM of Difference representing total elevation changes during the period September 2012 to March 2014 (B) for the south-facing stream bank adjacent to the Bentyfield mine shop.

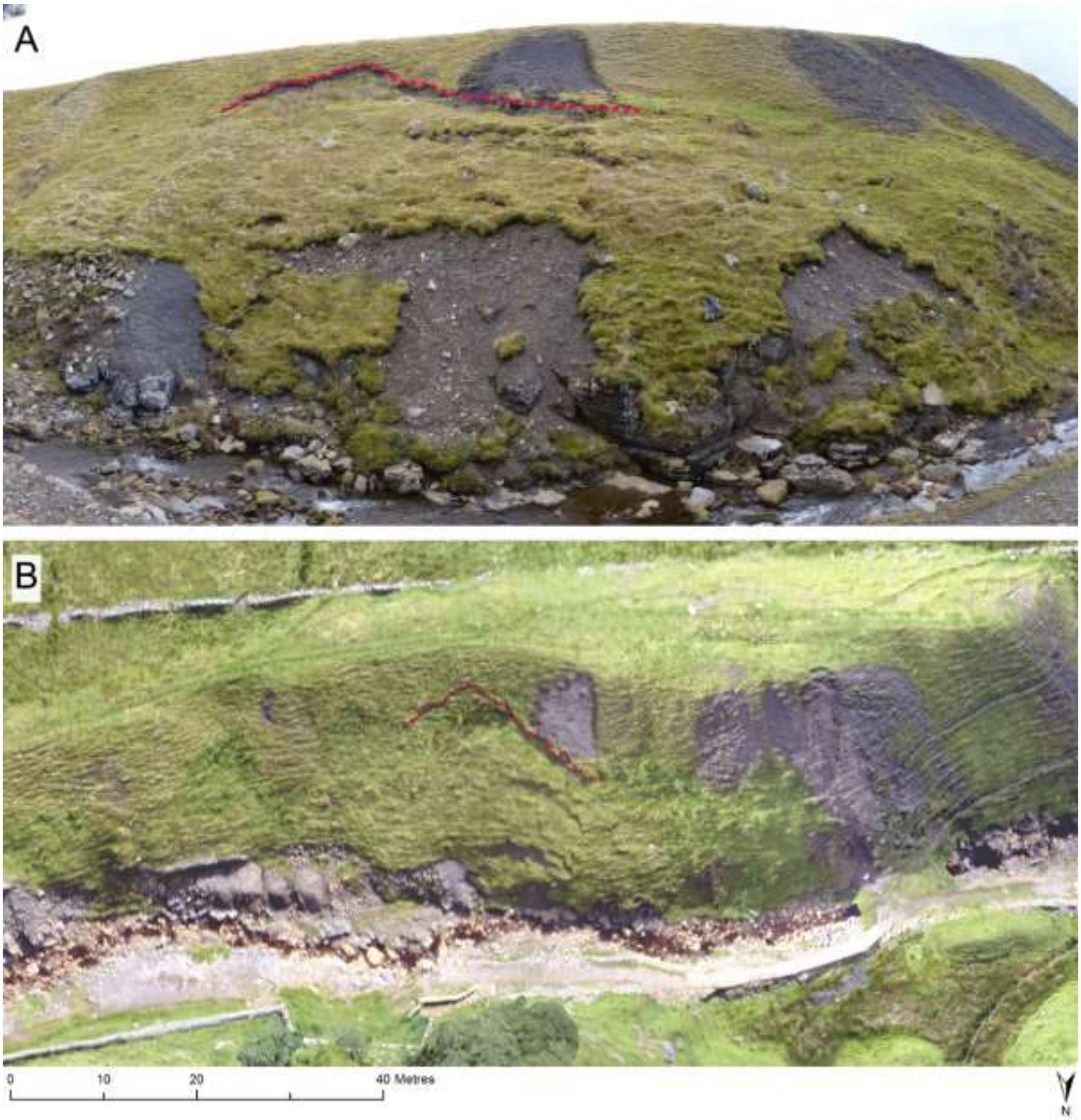

Figure 10 – Field photograph (A) and UAV aerial image (B) showing the slow-moving landslide on the main southern spoil heap at Bentyfield Mine. The UAV imagery was captured in September 2012 while the field photograph was taken in March 2014 during the final TLS survey. The main failure scarp is highlighted with a red dashed line. Garrigill Burn flows from left to right (east to west).

4.1.3 Tailings heaps

The largest morphological changes identified across the entire site were recorded on the western tailings heaps. These waste heaps were historically utilised by both mines, being linked to Whitesike Level, Bentyfield Low Level and the Whitesike dressing floors via a system of partially extant tramway routes. Despite representing only 8% of the total survey area, these tailings heaps accounted for 64% of the total net volumetric change, with 165.7 m^3 of erosion recorded over 18 months. The main cause of this change was the development of a large gully on the west-facing slopes; the same location showing longer-term progressive gullying on earlier aerial photographs (Section 4.2). This single gully recorded 156.7 m^3 of sediment loss over the 18 month period, which was equivalent to 95% of the total net erosion from the entire tailings heaps. Temporal variation in erosion from this gully was again dominated by the major event identified in May – June 2013, although intermittent erosion and temporary sediment storage were also recorded throughout the remainder of the monitoring period (Figure 11).

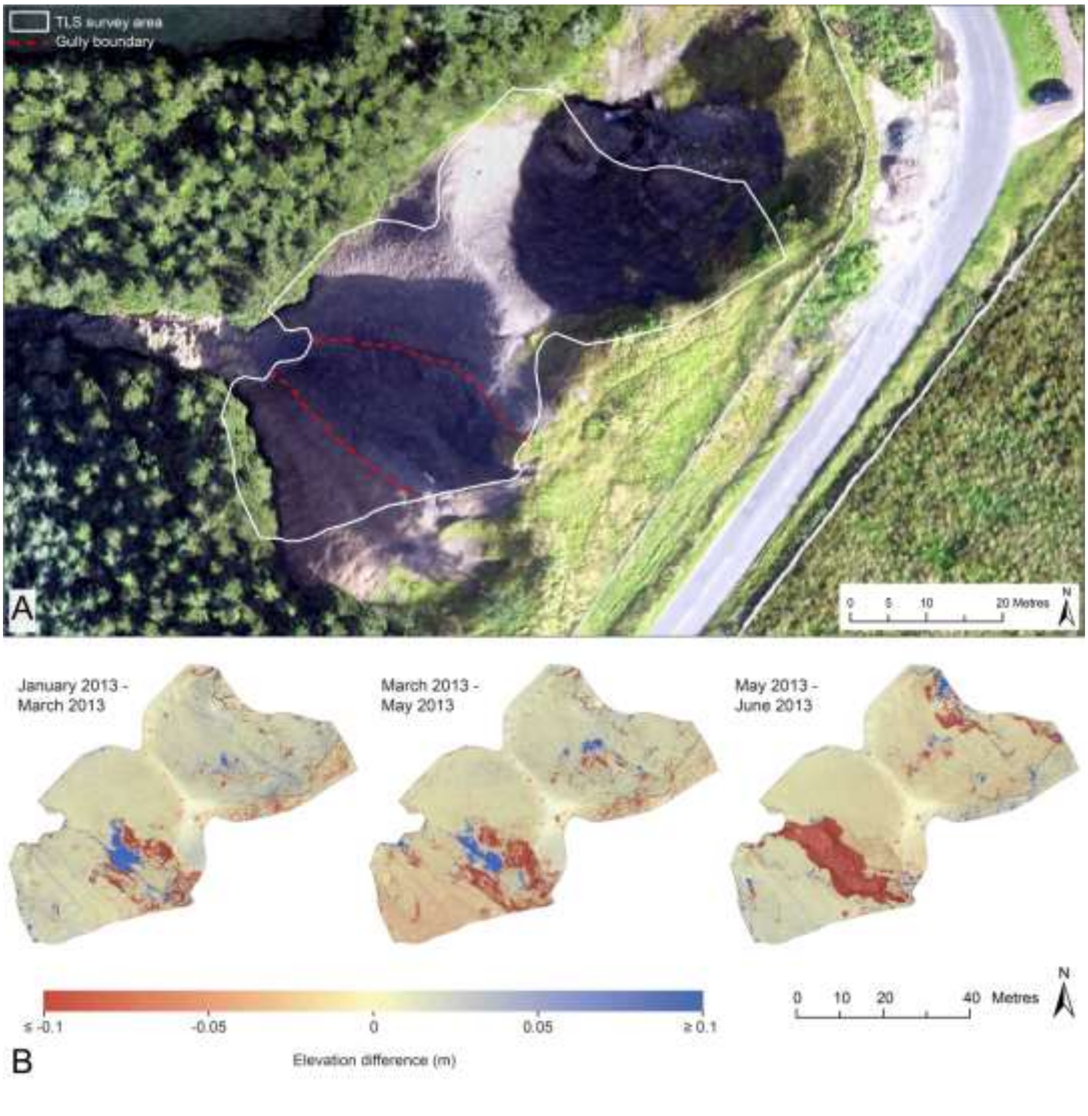

Figure 11 – UAV aerial image showing the extent of the tailings heaps TLS survey area and with the approximate boundary of the main gully defined (A). DEMs of Difference are shown for three survey intervals during early-to-mid 2013 (B). Although the earlier intervals demonstrate a pattern of intermittent erosion and temporary storage, the main erosional changes again occurred between May and June 2013.

From a heritage management perspective, this erosion represents the loss of an integral component of the surface archaeology of these two historical lead mines. However, the erosion of these waste heaps is also of considerable significance in terms of the volume of heavily contaminated sediments which are being mobilised and their potential environmental impact on local river systems. Importantly, Garrigill Burn flows through a culvert directly beneath the tailings heaps, meaning that any sediment eroded from the slopes is directly connected with the stream and the wider South Tyne catchment.

4.2 Longer-term post-abandonment morphological change (c.1868 – 2010)

Analysis of historic maps and aerial photographs depicting Whitesike and Bentyfield mines between 1868 and 2010 (Table 1) indicates that the main longer-term morphological changes relate to alterations to the course of Garrigill Burn as it flows through the mined area and the progressive modification of some of the waste heaps. This longer-term trend correlates well with the results of the repeat TLS monitoring. The culverting of Garrigill Burn visible on the 1868 map was a fundamental component of the mining operations, involving the use of drystone revetments to manage the flow of water to power machinery and provide additional working surfaces for ore dressing. However, the cartographic evidence suggests that the stream began to revert to a more natural, sinuous course almost immediately after the mines were abandoned, with areas of the covered Bentyfield channel having already become exposed by 1900 (Figure 12).

By the 1950s, most of the historical culverted sections of channel had collapsed, with only five narrow stream crossings still in existence. This process of stream adjustment continued into the later 20th century, with extensive areas of bankside erosion and the collapse of further mining-era channel management structures by the time of the 1976 aerial photograph. Only two culverted sections of stream remained by 1999, with the eastern example collapsing at some point prior to 2009 and being replaced by a wooden footbridge in 2012. Although difficult to quantify due to the variable resolution of the available data sets, these trends strongly suggest that fluvial processes linked to the flow of Garrigill Burn through the centre of the two mines are the dominant drivers of large-scale, long-term morphological change. This longer-term perspective corresponds well with the results of the repeat TLS surveys, which also emphasised the prominent role of bank erosion in driving surface topographic change.

The surveys also indicated that several of the major waste heaps are experiencing ongoing erosion, including the large bench-style spoil heap associated with Bentyfield Mine and the extensive unvegetated tailings heaps located to the west of Whitesike. The longer-term record actually suggests that the main Bentyfield spoil heap appears to have remained relatively stable during the period 1868 – 2010. However, there has been significant modification of the western slope of the shared tailings heaps since at least the mid-20th century (Figure 13). The resolution of the 1958 aerial photograph is fairly low but there do not appear to be any major gullies visible on the western slopes. In contrast, the 1976 photograph shows the development of a series of narrow gullies extending from the southern crest to the outlet of a culvert which carries Garrigill Burn beneath the tailings heaps. By 2009 the main central gully had deepened and widened significantly, with a corresponding extension of the smaller parallel gullies to the southwest. This central gully is the same one that recorded the highest magnitude morphological change during the TLS monitoring period (Section 4.1.3), suggesting a long-term and persistent focus of erosion.

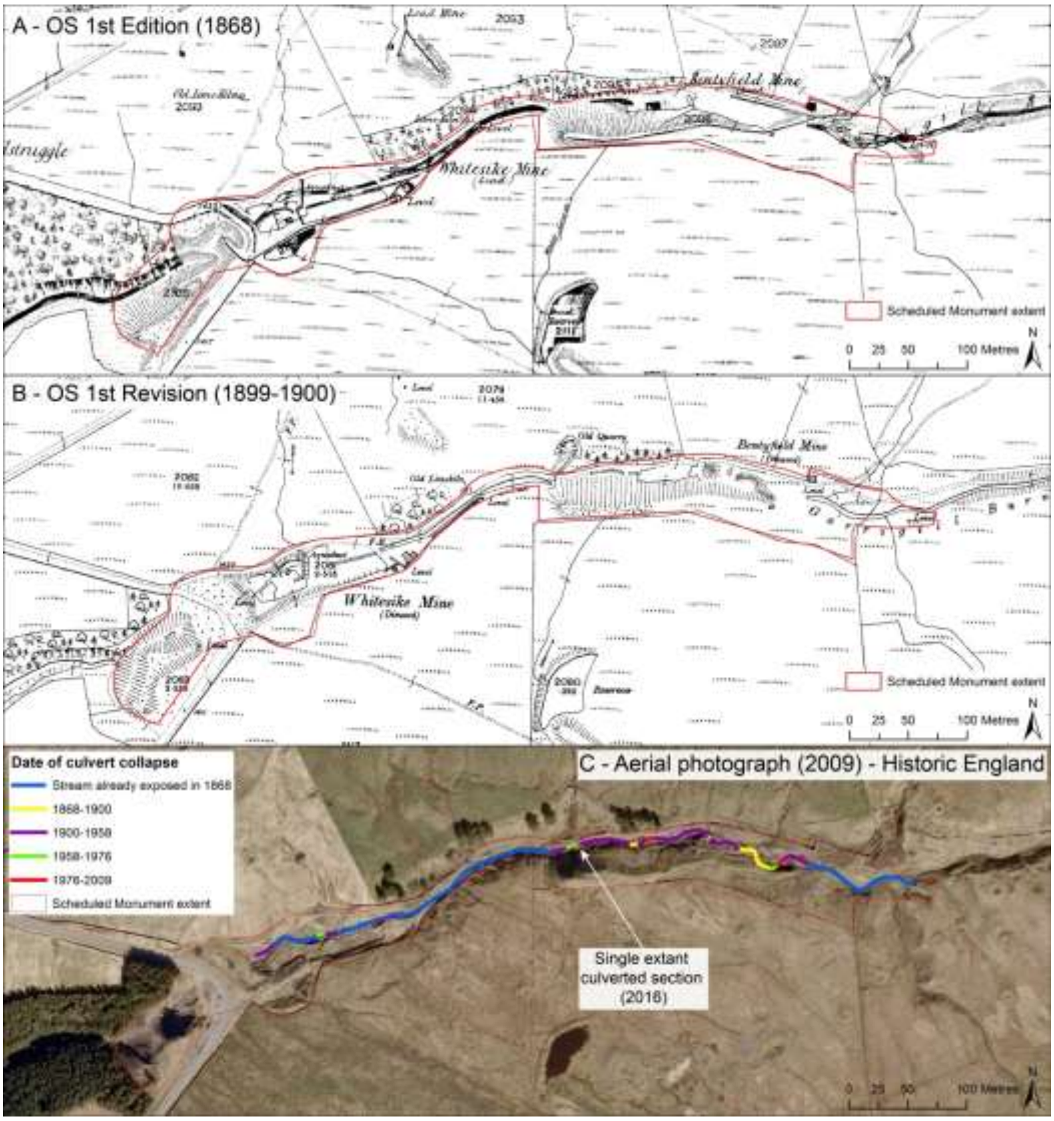

Figure 12 – Historic Ordnance Survey maps from 1868 (A) and 1900 (B), showing how the mines appeared towards the end of their operational life. The progressive collapse of the culverted sections of Garrigill Burn began almost immediately after abandonment and continued throughout the 20th century (C) (Historic OS maps © Crown Copyright and Landmark Information Group Limited 2016. Aerial photograph © Historic England).

Figure 13 – Slope erosion and gully development on the tailings heaps between 1958 and 2009 (Aerial photographs © Historic England).

5. Discussion

5.1 Drivers and spatial distribution of damage to archaeological remains

The high resolution TLS change detection for the period from September 2012 to March 2014 indicates that the overall net volumetric change for these archaeological sites is overwhelmingly erosional, with a total change of 259.5 m^3 from an area of just ~27500 m^2. Total net erosion was actually highest from the tailings heaps, the smallest survey area (2144 m^2), and lowest from Bentyfield Mine, the largest survey area (18905 m^2) (Table 2; Figure 14). However, the results also indicate clear variation in the spatial distribution and causes of documented erosion. Interestingly, the monitoring demonstrated minimal anthropogenic disturbance along established footpaths and on the slopes of the tailings heaps. This demonstrates that, in this context at least, natural geomorphic processes are the primary drivers of erosion, with the results allowing the relative impact of each individual process to be assessed (Figure 15).

Table 2: Comparison of TLS-derived surface volumetric change and survey area size

Mine area	Total net change (m^3)	Percentage of total change (%)	Size of area (m^2)	Percentage of total area (%)	Net erosion per unit area (m^3/m^2)
Whitesike	-62.3	24	6538.9	24	0.010
Bentyfield	-31.5	12	18905.3	68	0.002

Tailings heaps	-165.7	64	2144.0	8	0.077
Total area	-259.5	100	27588.2	100	0.010

Although gullying was recorded as the geomorphic process causing the most significant amount of erosion (~166 m^3; 64%), this was almost entirely the result of the progressive incision of one large gully located on the western tailings heaps. This gully has clearly been developing for several decades (Section 4.2) and represents a long-term source of erosion at the site. In this particular archaeological context, gullying therefore represents a high magnitude but spatially restricted driver of erosion; a finding that corresponds well with studies of more recent mining landscapes (Hancock *et al.*, 2008).

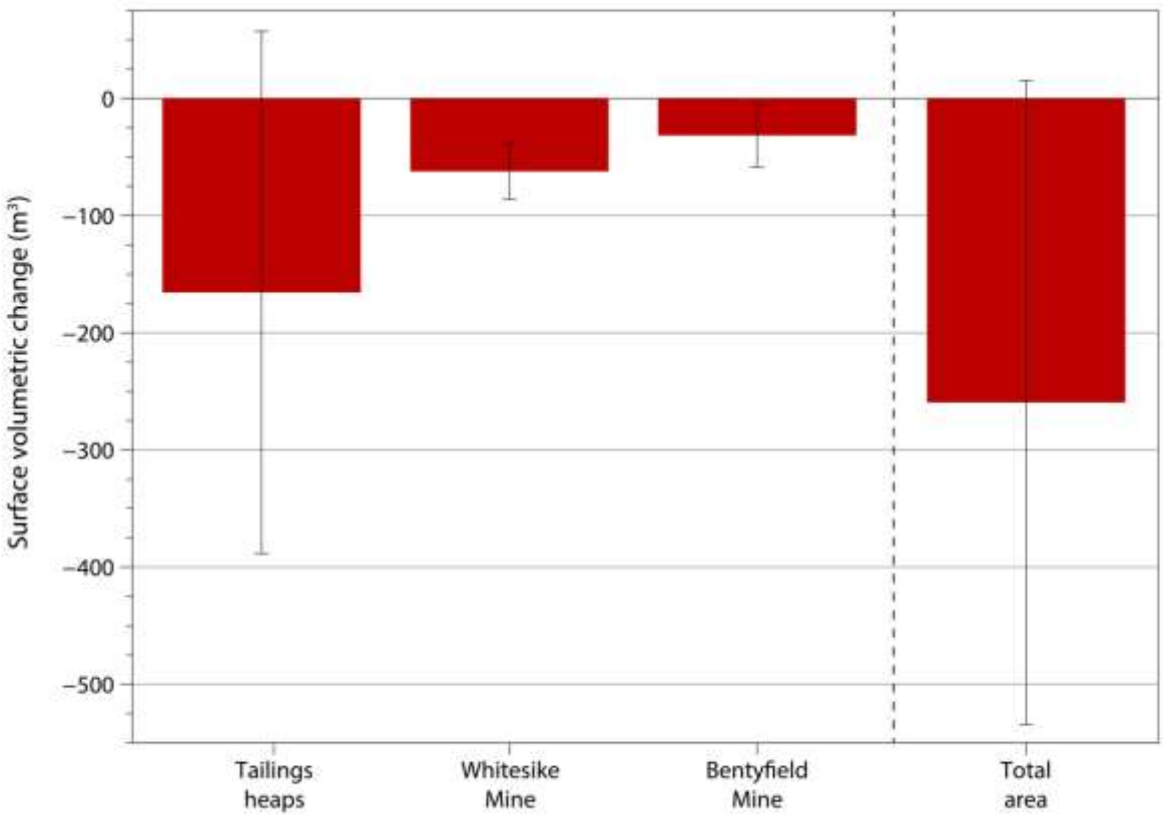

Figure 14 – Comparison of total net volumetric change from each of the main survey areas during the period from September 2012 to March 2014, based on the results of the repeat terrestrial laser scanning. Error bars are based on the spatially variable change detection analysis conducted at a 95% confidence interval outlined in the methodology.

In contrast, bank erosion resulted in less overall morphological change (~80 m^3; 31%) but damage caused by this process was more spatially extensive with particular concentrations throughout the main working areas of both Whitesike and Bentyfield. Importantly, bank erosion was also recorded as being the cause of considerable damage to the dressing floors at both mines, the collapse of upstanding architectural features and the exposure of previously buried structural remains. The significance of bank erosion as a key driver of change on upland mine sites was further emphasised by the results of the longer-term analysis (Section 4.2) and by earlier studies of historical metal mines in other locations (Haigh, 1980; Gao and Bradshaw, 1995).

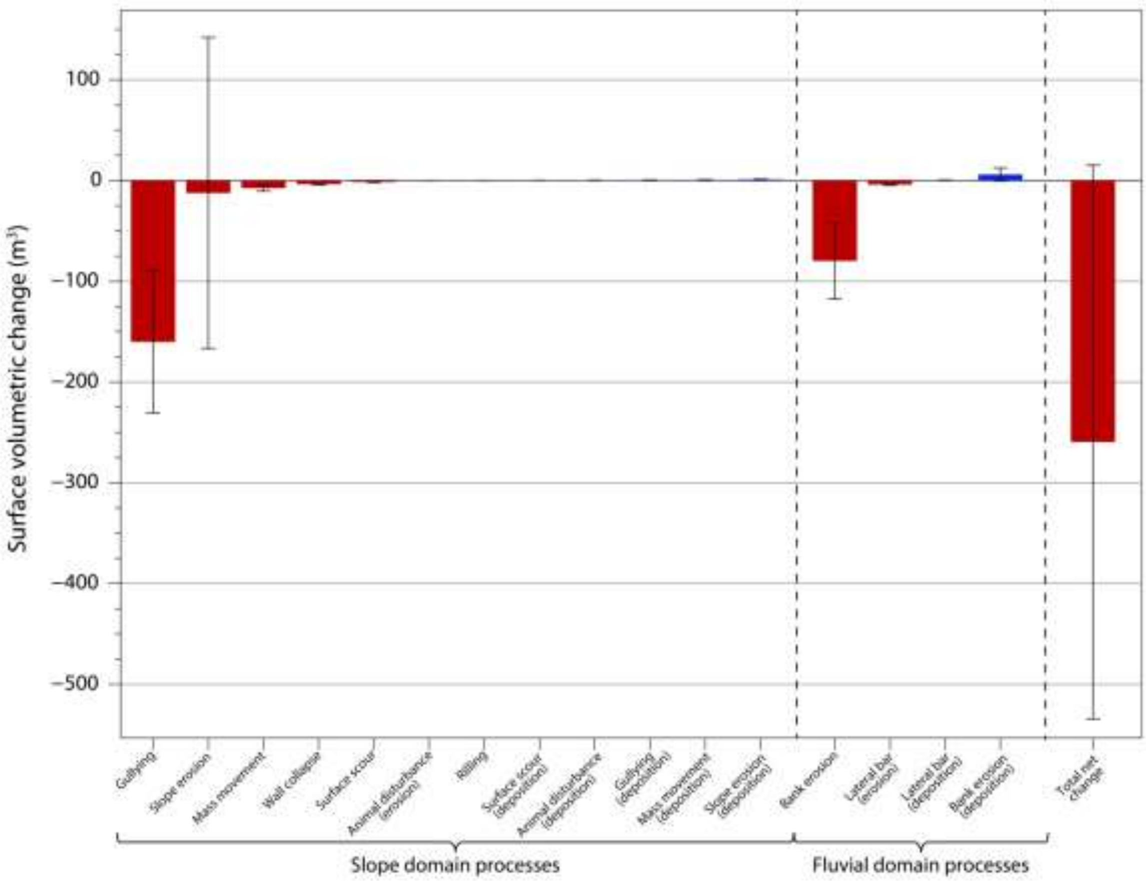

Figure 15 – Net volumetric change for the period from September 2012 to March 2014 for the total combined TLS monitoring area, distinguished by geomorphological process type. Red bars indicate negative change (erosion) and blue bars indicate positive change (deposition). Error bars are based on the spatially variable change detection analysis conducted at a 95% confidence interval outlined in the methodology.

The TLS monitoring did record a wide range of other geomorphic processes but the magnitude of change resulting from these was generally limited in comparison (Figure 15). Diffuse slope erosion was recorded across large spatial extents but actually resulted in a relatively low overall magnitude of change (~12 m^3). Such spatially extensive slope erosion is typically the result of one or more diffusive processes, such as wind erosion, sheetwash, soil creep and freeze-thaw. Actually identifying the relative contribution of these drivers of diffuse change is extremely difficult, though needle ice development and freeze-thaw erosion were observed during field monitoring. Mass movements on unstable slopes (e.g. spoil heaps) are also known to represent a significant geomorphic process at recently abandoned mines (Esling and Drake, 1988). However, the only significant example was recorded on the main Bentyfield spoil heap. Although this landslide only resulted in ~7 m^3 of erosion over 18 months, indicating that it is a slow moving failure, there is some concern over the potential impact it may have on the only surviving section of drystone culvert located immediately downstream.

5.2 Short-term temporal variation in rates of surface change

Repeat laser scanning on a monthly basis allows high temporal resolution patterns of change to be identified, including the analysis of seasonal variation in the magnitude of different geomorphic processes. This information is of considerable value for predicting the likely timing of large-scale morphological changes and the response of upland archaeological sites to particular extrinsic factors, such as high magnitude storm events. The results of the monitoring demonstrate that erosion of abandoned mines in upland contexts is highly episodic, with a pronounced peak in surface change between May - June 2013 but only smaller secondary peaks occurring at other times (Figure 16). During this one notable survey interval, large-scale topographic changes were identified throughout the entire mined area, generally in close proximity to the main stream channel or along concentrated flow paths. For example, 70% of all bank erosion on the lower dressing floor occurred during this one monthly interval, with a similar pattern occurring elsewhere across much of the site.

Comparison with local weather data indicates that this was the consequence of a single rainfall event on 18th May 2013. This event resulted in the highest river level ever recorded for the upper South Tyne (2.85 m) and caused extensive flood damage elsewhere in Northern England (Durham County Council, 2013; Environment Agency, 2015). Although recorded rainfall levels were actually relatively moderate (33.5 mm at Alston Springhouse Park), this was the first significant storm impacting on ground still saturated by recent snow melt and antecedent rainfall (Figure 17).

The significance of this pattern is that erosion of upland mine sites is clearly dominated by low frequency, high magnitude rainfall events, such as that recorded on 18th May 2013 or more recently by Storm Desmond (3rd-8th December 2015). With the frequency and intensity of such storm events predicted to increase in relation to a changing climate, it is likely that corresponding damage to upland archaeology will also intensify; presenting significant long-term challenges to the heritage community

(Howard *et al.*, 2008; Howard, 2013). Such high intensity storms are not the only source of intra-annual variation in erosion rates, however, with the TLS results also recording intervening topographic changes. This higher frequency, lower magnitude erosion does play an important preparatory role in terms of destabilising surface deposits in advance of large-scale storm-driven changes. To be fully effective, future monitoring of upland archaeological sites must therefore concentrate on both the aftermath of large storm events, when the greatest magnitude of erosion is likely to occur, and on the lower magnitude land surface changes occurring throughout a typical year.

5.3 Wider implications of the erosion of abandoned metal mines

Understanding the geomorphological processes encountered in particular landscape contexts is fundamental to developing effective heritage management strategies. In upland environments in particular, the potential for the widespread and damaging erosion of nationally significant industrial archaeological remains is considerable. This is in part due to the increased erosion rates typically encountered in the uplands, but also the result of the high density of industrial archaeological remains now known to survive in such areas. For example, recent research into the mining landscapes of Alston Moor and the adjacent Upper Tees catchment recorded 465 named historical lead mines from an area of only ~200 km^2 (Kincey, 2016).

Historical mining operations clearly had a significant impact on the physical environment, with estimates for the UK suggesting that approximately 38.5 km^3 of mining-related material has been mobilised since 1850 (Price *et al.*, 2011). However, an important additional point is that, due to the highly erodible and contaminated nature of their deposits, the erosion of abandoned metal mines is an ongoing legacy problem also facing a range of other stakeholder groups, including geomorphologists, ecologists and water quality specialists (Miller, 1997; Batty, 2005; Mayes *et al.*, 2015). The persistent release and redistribution of heavy metal contaminants to upland river systems poses especially significant risks to natural ecosystems and human health.

In the UK, legislative responsibility for managing the considerable legacy problems of historical metal mining lies primarily with the Environment Agency, DEFRA and the Coal Authority (Potter *et al.*, 2004). Although European legislation, such as the Water Framework Directive and the associated Mining Waste Directive, has led to increased research into the environmental impacts of historical mining, much of this has focused on contaminated water draining from mine adits. However, since ~90% of metal contaminants in former mining catchments are associated with sedimentary rather than aqueous forms (Hudson-Edwards *et al.*, 2008), quantifying the ongoing erosion of abandoned mines is crucial in developing a comprehensive understanding of contaminant flux. Archaeologists therefore have a fundamental role to play in both the preservation of abandoned mines as heritage sites and the furthering of interdisciplinary knowledge regarding the ongoing erosion of heavily contaminated legacy sediments.

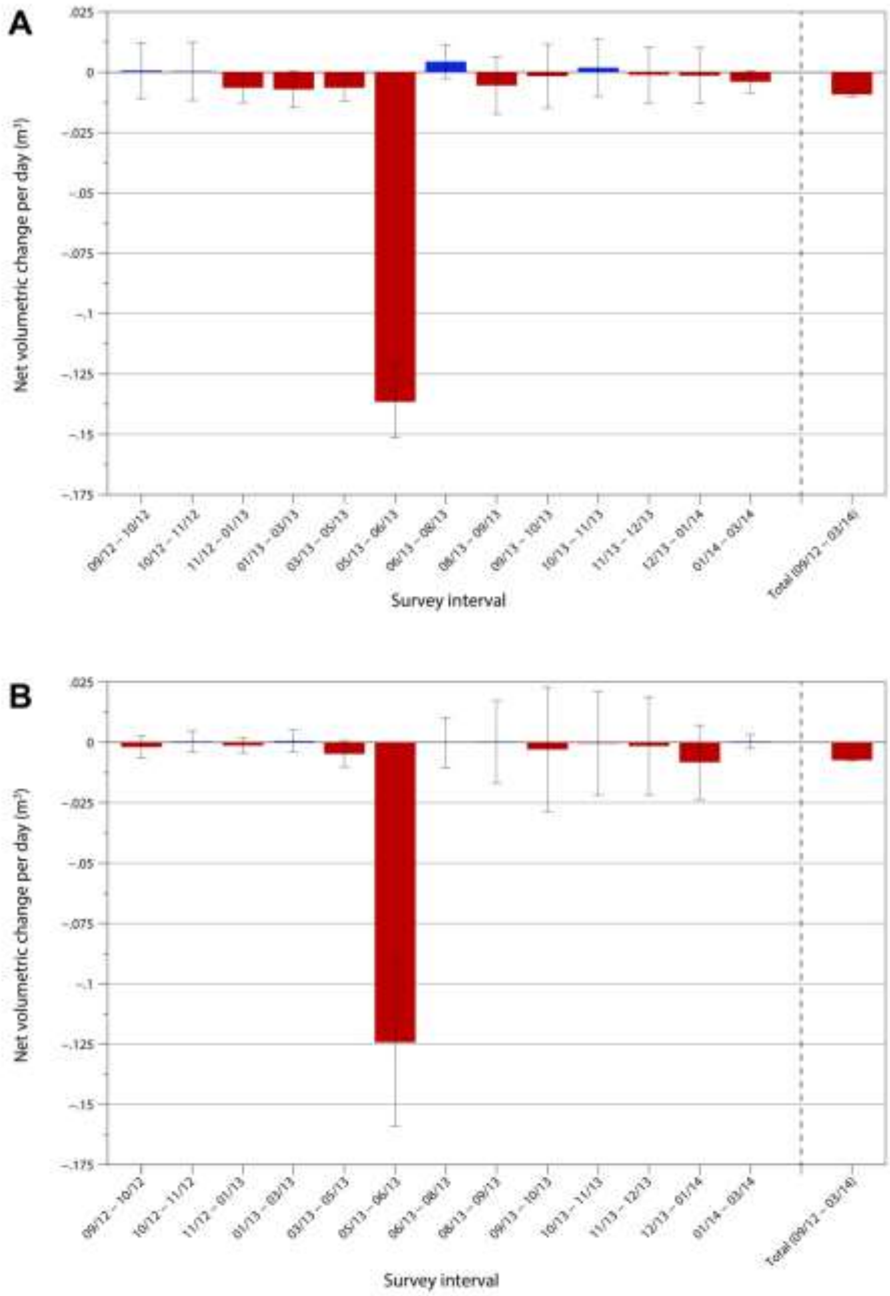

Figure 16 – Net volumetric change per day resulting from erosion of the lower dressing floor (A) and upper dressing floor retaining wall (B) at Whitesike Mine. Data are shown for each of the individual survey intervals and for total change across the entire monitoring period. The episodic nature of the erosion and dominance of the May 2013 event can be clearly seen for both areas. Red bars indicate negative change (erosion) and blue bars indicate positive change (deposition). Error bars are based on the spatially variable change detection analysis conducted at a 95% confidence interval outlined in the methodology.

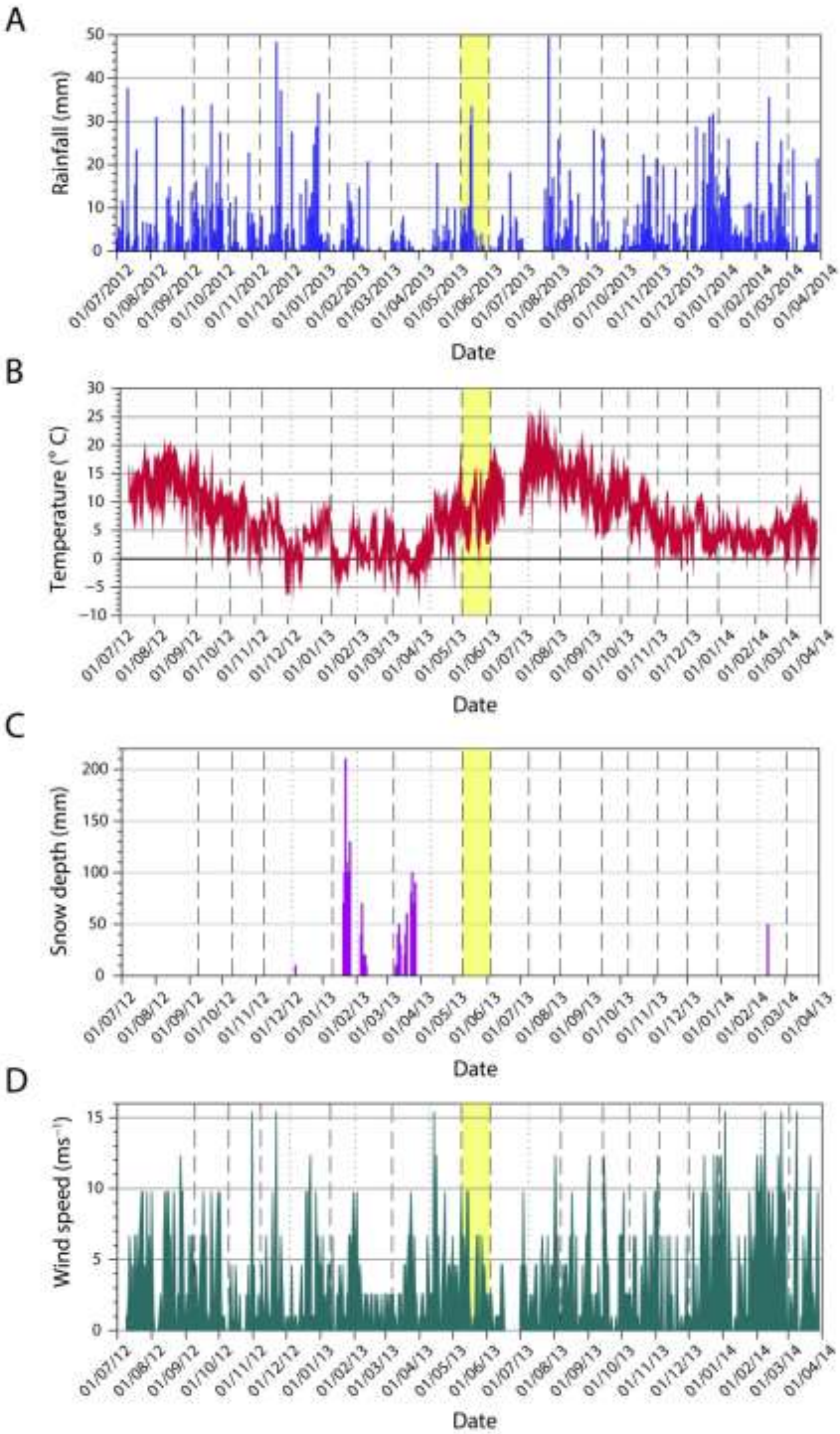

Figure 17 – Daily weather station data from Alston Springhouse Park (<6 km from the field site) covering the period from 01/07/2012 to 01/04/2014. Data shown include rainfall (A), temperature range (B), snow depth (C) and wind speed (D). Vertical dashed lines represent TLS survey dates, vertical dotted lines indicated dates when field visits occurred but no TLS data were collected. The May-June 2013 interval when most of the topographic changes were recorded is highlighted in yellow for reference. Data courtesy of the Met Office Integrated Data Archive System (MIDAS), made available via NERC’s British Atmospheric Data Centre (BADC)

6. Conclusion

Despite being removed from the 'Heritage at Risk' register in 2012, the surface archaeology at Whitesike and Bentyfield is undoubtedly still experiencing ongoing and significant erosion. Gullying was recorded as the geomorphic process causing the largest amount of erosion (166 m^3), although this was almost entirely the result of the incision of a single large gully located on the slopes of a tailings heap. Bank erosion resulted in less overall morphological change (80 m^3) but was far more spatially extensive and damaging to both important archaeological deposits and upstanding structural remains. The results demonstrate that the erosion of upland mine sites is highly episodic and is primarily driven by low frequency, high magnitude storm events. For example, the rainfall event on 18th May 2013 was responsible for 70% of all recorded bank erosion on the lower dressing floor at Whitesike Mine; one of the most archaeologically significant components of the entire site. However, the results also indicated that year round higher frequency, lower magnitude erosion plays an important role in terms of destabilising surface deposits in advance of large-scale storms.

The consolidation works implemented as part of the HAR scheme were partially successful; reducing surface scour on the Whitesike dressing floors and stabilising structures and areas of bankside archaeology at Bentyfield. However, other aspects of the repair scheme were clearly less beneficial, including the repeated collapse of the repaired retaining walls adjacent to the upper dressing floor at Whitesike. Elsewhere considerable damage occurred in areas which the HAR scheme did not attempt to consolidate, such as the bank erosion of the lower dressing floor and the extensive gullying of the tailings heaps.

These observations highlight a number of pressing concerns with the way in which the risk of erosion on archaeological sites is currently characterised, designated and managed. The limited success of the repair scheme at Whitesike and Bentyfield was at least partially the result of not fully understanding the causes and rates of erosion at the site and the repeat TLS surveys now provide a baseline of information with which to develop an appropriate and targeted management scheme. Subsequent consolidation work will have to balance the need for further works against the need to be sensitive to the original archaeological character of the site. For example, although the repair of the retaining wall at the upper dressing floor utilised drystone techniques and was therefore historically authentic, the structure has already collapsed twice since 2011 and so this is clearly not a long-term solution. Since archaeological sites will never remain fully static and unchanging, it can also be argued that the use of binary designation terms (i.e. 'at risk' or 'not at risk') is somewhat misleading and a more nuanced approach needs to be developed by the heritage management community.

The combined use of repeat terrestrial laser scanning, UAV survey and archival research has provided an effective methodology for monitoring the nature and causes of change at these important archaeological sites. Furthermore, the monthly frequency and length of the monitoring programme have allowed temporal variation in erosion rates to be quantified at a unique level of detail. Walkover surveys of numerous other abandoned mines in the North Pennines have indicated that a similar range of erosion processes are being encountered and that the results can therefore be extrapolated to other similar upland contexts. However, it is acknowledged that the survey methods employed by this study require a significant investment of time and money and therefore cannot be applied extensively across numerous archaeological sites in different landscape contexts. Nevertheless, given similar high resolution assessments of other sites in contrasting locations, the relative significance of the different physical and environmental factors influencing the erosion of archaeological sites could be established. Once this baseline information has been gathered, the results would better inform and enhance the efficacy of conservation works elsewhere, without the need for additional detailed monitoring.

Although specific priorities and management strategies undoubtedly vary between disciplines, this research has emphasised the need for interdisciplinary approaches to the research and management of industrial sites (Howard *et al.*, 2015). Open engagement between researchers and practitioners in relevant disciplines is the only way in which the diverse range of issues facing the long-term stability of abandoned historical mines can be fully understood and appropriate future mitigation strategies designed and implemented.

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