Weathering of igneous rocks during shallow burial in an upland peat environment: observations from the Bronze Age Copney Stone Circle Complex, Northern Ireland

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Abstract

The stone circle complex at Copney, County Tyrone is a key Bronze Age site that forms part of the Mid-Ulster stone circle complex. This site was excavated in 1995 and since then, deterioration of the archaeological stonework has been a serious problem. Deterioration is visible as splitting/fracturing of stones, the development of a bleached outer margin, surface scaling and granular disintegration, and, in some cases, complete disintegration of individual stones to sandy regolithic material. Environmental conditions at this site exacerbate the deleterious action of weathering processes, with periodic waterlogging and sub-zero temperatures during winter months. The Copney stones comprise two igneous lithologies: quartz porphyry and porphyritic andesite, both Lower Ordovician (470 Ma) in age. Both rock types show extensive alteration by hydrothermal processes resulting in weakened stone fabrics exploited by weathering processes during burial and subsequent exposure. Mineralogy of buried and exposed material indicates that approximately 2500 years of burial in a peat bog has produced secondary porosity comprising extensive microfracture networks and dissolution voids, which permitted further ingress of moisture and acidic waters, thus, promoting chemical alteration of mineral constituents. The occurrence of completely grussified stones and arenisation of boulder surfaces at Copney indicates that the processes of grussification are not solely restricted to deep weathering environment but can be achieved by burial in a shallow, aggressive environment over periods measured in thousands of years. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The weathering of granitic rocks to form sandy regoliths or grus has attracted considerable attention in recent years (see reviews by Migon´ and Lidmar-Bergström, 2002; Migon´ and Thomas, 2002). Most commonly, studies have concerned deep weathered profiles linked to models of long-term landscape evolution and interpretations are couched in terms of a specific set of climatic conditions responsible for profile formation. For this reason, deep weathered profiles and the presence of reworked grus have historically been associated with a range of palaeoclimatic conditions particularly humid tropical. However, the subsequent widespread discovery and detailed analysis of weathered regoliths on granitic and other rocks across the British Isles and northwest Europe (e.g. Lidmar-Bergström et al., 1997; Smith and McAlister, 1987; Thomas, 1976) have led some authors to identify and distinguish between two profile types. Clay-rich, argillaceous profiles have been interpreted as a more characteristic of former humid tropical climates, whereas it is postulated that sand dominated, arenaceous profiles could have formed under more temperate climates (e.g. Hall and Mellor, 1988). Debate remains, however, as to whether the two regolith types are distinct and can be differentiated on the basis of climate regime and weathering mechanisms, or whether they represent points on a weathering continuum that can only be distinguished in terms of weathering rate and age controls exerted by mineralogical differences between bedrock (Thomas, 1994; Power and Smith, 1994). In addition, local factors such as drainage conditions exert a major influence on weathering patterns and products of granitic rocks. For example, on Dartmoor, southwest England, Ternan and Williams (1979) and Williams et al. (1986) demonstrated that chemical weathering is active and continuous under often-waterlogged acid conditions, which characterise this and many other granite uplands in the British Isles. This contention was further investigated by Power (1989) who buried small granite tablets beneath acid peat within the Mourne Mountains of Northern Ireland for 20 months. Examination by SEM of the retrieved blocks showed etching of mineral grains and exploitation of discontinuities and cleavage planes. However, burial for 20 months, even under such aggressive conditions, is unlikely to produce anything other than superficial modification and for significant alteration and breakdown to occur, it is probable that granite would need to be buried for a significantly longer period. This paper describes just such a study.

This study is centred on the excavation of a group of Bronze Age stone circles at Copney in County Tyrone, Northern Ireland that lay buried beneath a peat cover for up to 2500 years. Attention was drawn to the site when it was observed that, following exposure, many of the smaller stones were rapidly weathering to sand and that the larger boulders were splitting in response to periodic freeze–thaw. The site therefore offers an ideal opportunity to examine the effects of extended burial within a wet, acid environment on the chemical and physical alteration of granite-type rocks.

Evaluation of this historical study will hopefully therefore provide insights into a process by which the ‘arenisation’ of a granite-type rock can be achieved without the necessity for a prolonged period of deep, in situ weathering beneath a stable land surface. Results could have implications for the understanding and interpretation of mixed boulder and grus deposits that mantle upland granite slopes. Previously, these
deposits have been interpreted as deeply weathered material reworked by periglacial processes (e.g. Linton, 1955) and as such have played a central role in the formulation of models of landscape evolution driven by long-term climate change. The possibility that selective grussification could have taken place more recently, without the requirement for climate change, deep weathering or reworking clearly has implications for these models. It is also to be hoped that understanding the weathering processes operating at Copney will be the first step towards the potential preservation of the remaining stones. Failing that, any insights into breakdown of the stones should at least inform future excavation protocols for similarly buried stone so that the accelerated decay seen at Copney can be avoided.

2. The Copney Stone Circle Complex

The Copney Stone Circles are located in County Tyrone, Northern Ireland and represent a key Bronze Age site (ca. 2500 BC) in Mid-Ulster comprising nine stone circles, an alignment and a standing stone (Foley and MacDonagh, 1998). In 1994, two complete circles and part of a third were excavated revealing concentric and radial arrangements of boulders around a central cairn (Fig. 1). The stone circles were constructed using ‘field’ stones gathered from the surrounding areas and are distinctive in the landscape because of their bleached white outer surface (Fig. 2). Excavation involved almost complete removal of peat cover (blanket peat was removed over the last 200–300 years by periodic peat cutting) leaving a layer 10 cm thick overlying the mineral soil (Foley and MacDonagh, 1998). The boulders used to construct the circles are acid and intermediate igneous (subvolcanic) rocks and range in size from small cobbles in central cairns to large perimeter stones up to 1 m in height. The stone circles were constructed ca. 2500 BC and boulders were exposed to approximately 2000 years of subaerial weathering prior to peat burial. Pollen analysis suggests that peat formed in the lake basins of this region at around 450 BC (Pilcher, 1969).

3. Post-excavation deterioration at the site

An archaeological survey approximately 1 year after excavation noted extensive deterioration of stonework at this site with fracturing of the larger boulders and loss of significant amounts of friable sandy material from stone surfaces. Regular site visits have shown that since 1994, deterioration of the archaeological stonework has been a serious and ongoing problem (MacDonagh, 1995). Contributing to the deterioration is the availability of moisture during freeze–thaw episodes. The site is waterlogged for long periods of the year; in addition, the remaining thin layer of peat in which the stones sit acts as a reservoir for moisture drawn into the stone by capillary action. Consequently, during winter frosts, fracturing of boulders together with continual disintegration of stone surfaces is a common occurrence (Fig. 2).

In 1997, the Environment Heritage Service (part of the Department of the Environment, Northern Ireland) commissioned a report to assess the causes and controls of post-
excavation deterioration at this site (Curran et al., 1998). To evaluate the specific controls on stone decay at this site, analyses were divided into three key strategies:

1. Evaluation of current deterioration (post-exavation).
2. Assessment of deterioration incurred during burial in a waterlogged, acidic peatland environment.

Fig. 1. Plan view of the Copney Stone Circle Complex, Tyrone, Northern Ireland (adapted from Foley and MacDonagh, 1998).
Fig. 2. (a) Large-scale splitting of boulders, (b) and (c) scaling and granular disintegration of stone surfaces. Note: Burial in the peat has resulted in a very distinctive bleached outer surface.
3. Analysis of control samples, materials from the surrounding outcrop that were never buried and which can be used to characterise the pre-erosion mineralogy and metamorphic history of the original boulders.

Fig. 3. Hydrothermally altered plagioclase feldspar (a) and biotite phenocrysts (b) in core material from the Copney site. Biotite has been extensively altered to chlorite and oxides and the plagioclase phenocrysts show cores altered to chlorite and sericitised margins.
The techniques used to diagnose and evaluate deterioration at the Copney site included: hand specimen and thin section analysis, Scanning Electron Microscopy (SEM) and X-ray Diffraction (samples were analysed using a Siemens D5000 Diffractometer and XRD patterns were interpreted semiquantitatively using a Siroquant™ software package).

4. Pre-burial mineralogy

The Copney stones consist of two main igneous rock types: quartz porphyry and porphyritic andesite. Both are Lower Ordovician (470 Ma) in age and part of the Tyrone Igneous Complex (Cobbing et al., 1965). Quartz porphyry (rhyolite) is a subvolcanic rock consisting of quartz, biotite and alkali and plagioclase feldspar phenocrysts set in a finer-grained matrix of the same mineralogy. Porphyritic andesite is an intermediate igneous rock dominated by plagioclase feldspar and amphibole as phenocrystal phases with a finer-grained groundmass of plagioclase, amphibole and quartz.

4.1. Post-magmatic mineralogical and fabric changes

Thin section analyses of intact core material from individual boulders and samples from surrounding outcrops indicate that both rock types were extensively modified by hydrothermal alteration associated with their formation and subsequent metamorphic and metasomatic events (Wilson, 1972; Yardley, 1989). For the quartz porphyry rock type, plagioclase feldspar phenocrysts are altered to secondary minerals (chlorite, oxides and epidote), both the cores and rims of potassium feldspar grains are extensively sericitised and biotite shows partial or complete chloritization (alteration to the secondary mineral chlorite) (Fig. 3). Similarly, the major mineral phases of the porphyritic andesite are altered by post-magmatic hydrothermal activity, with sericitisation of plagioclase feldspar and replacement of amphibole and clinopyroxene with secondary minerals. In addition, the quartz present in this rock appears to be of secondary origin occurring as infillings of veins and voids throughout the rock. This secondary mineral assemblage: chlorite, epidote, quartz, sericite and carbonates is characteristic of intense hydrothermal alteration (or propylitization) of andesites (Deer et al., 1966). Throughout both rock types, there is an extensive network of hydrothermal veins and numerous cavities infilled with secondary minerals precipitated from late-magmatic solutions including: quartz, sericite, chlorite, and most notably, calcite. These post-magmatic structural and mineralogical changes indicate that the fabric of both rock types was substantially weakened prior to burial.

5. Post-excavation mineralogy of the Copney boulders

Most Copney stones comprise an intact core of dark grey rock and an outer bleached weathered rind with sandy friable material often released from the stone surfaces and seen as loose material surrounding boulders (Fig. 4). All boulders are extensively veined and
fractured and in many cases, fractures originating from the surface are seen penetrating the main body of the boulders. In contrast, many of the smaller cobbles, especially those in central cairns, have been completely weathered in situ. Studies (e.g. Power and Smith, 1994; Neill and Smith, 1996) have established that a common feature of the weathering of igneous rocks is the development of a secondary porosity created by mineral dissolution (dissolutional porosity) and/or the formation and enhancement of microfracture systems (fracture porosity). To highlight the extent of secondary porosity development, all samples were cut and then impregnated under vacuum with blue-dye resin to highlight voids created by dissolution, re-opening of hydrothermal veins and microfractures (Fig. 5).

5.1. Outer margin

The surfaces of the Copney stones are bleached, extensively fractured and highly porous. For both rock types, the outer margin consists of an open network of fractures and voids forming a secondary (dissolutional and fracture) porosity. In many samples, the blue-dye resin used to impregnate thin sections penetrates to a depth of up to 10 mm reflecting the open porous fabric of the outer margin (Fig. 5). Outer surfaces of quartz porphyry boulders consist of quartz grains set in a fine-grained clay matrix. Quartz phenocrystals are highly fractured and large voids are present where quartz and other phenocrysts (biotite, plagioclase and potassium feldspar) have been removed by physical or chemical processes (Fig. 6). Although designed primarily for outcrop scale exposures, according to Irfan and Dearman (1978) who defined six stages of weathering from fresh rock (I) to residual soil (VI), the bleached outer zone could be classified as stage (IV): highly weathered, comprising ‘a weakened and iron-stained rock in which the main petrological changes have led to a nearly complete alteration of plagioclase and biotite’.

Fig. 4. Cross-section of an intact stone sample of quartz porphyry from Copney showing the weathering rind (0.5–1 cm) enclosing a dark inner core. An array of microfractures crosscuts this sample.
In quartz porphyry samples, quartz phenocrysts are highly fractured and chloritised biotites are weathered and open along cleavage planes (Fig. 6). For both rock types, secondary products (chlorite and oxides) within plagioclase and potassium feldspar phenocrysts have been removed by dissolution enhancing secondary intergranular porosity (Fig. 7). Similarly, some of the secondary (hydrothermal) minerals infilling veins and voids have been removed by dissolution.

XRD analysis (Table 1) reveals that for both rock types, the mineralogy of this weathering rind differs from that of the inner core. For most samples, the porous outer margin tends to have higher quartz content and lower plagioclase feldspar and chlorite relative to other mineral constituents. Similarly, for porphyritic andesite, the bleached outer margins of samples tend to have higher proportions of quartz and lower plagioclase and chlorite compared to core material. The amount of clay minerals (predominantly illite) is relatively small for both rock types and the proportions do not appear to change significantly between the outer margin and intact inner core.

5.2. Limonite band

In many cases, a band (0.2–1 mm thick) of iron staining occurs a few millimetres from the boulder surface beneath the bleached layer (Fig. 8). This ‘limonite band’ (Kennan,
1973; Dearman, 1976; Irfan and Dearman, 1978) comprises reddish brown material and consists of limonite (a general term used for iron oxyhydroxides), which coats surrounding grains and infills microfractures. Iron is leached from mafic silicates such as biotite in quartz porphyry and hornblende in the porphyritic andesite (and secondary chlorite) as ferrous iron under reduced conditions and subsequently oxidised to ferric iron. Heavy staining around partially altered biotite indicates that precipitation of secondary ferric iron

Fig. 6. Alteration of biotite phenocrysts at the surface (a) and within the bleached outer margin of quartz porphyry sample (b).
is rapid and occurs before the constituent elements (Fe and Ti primarily) are transported in significant distances (Nesbitt and Markovics, 1997).

There is a reduction in porosity below the limonite band; however, secondary porosity still occurs as re-opened hydrothermal veins and occasional dissolution voids (Fig. 7). This indicates that planes of weaknesses exist throughout the stones, which form pathways for fluid ingress and, therefore, potential sites of further rock disintegration.

5.3. Material loss

A common feature of the outer margin is the frequent occurrence of a fracture up to 10-mm depth, and in many cases, at the base of the limonite band (Fig. 8). This fracture runs

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Semiquantitative XRD analysis of exposed boulders from the Copney Stone Circles: outer bleached margins and inner cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock type</td>
<td>Quartz porphyry (1) Outer margin (wt.%) Inner core (wt.%)</td>
</tr>
<tr>
<td>Quartz</td>
<td>60</td>
</tr>
<tr>
<td>Plagioclase feldspar</td>
<td>18</td>
</tr>
<tr>
<td>Potassium feldspar</td>
<td>4</td>
</tr>
<tr>
<td>Biotite</td>
<td>2</td>
</tr>
<tr>
<td>Hornblende</td>
<td>6</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>–</td>
</tr>
<tr>
<td>Epidote</td>
<td>–</td>
</tr>
<tr>
<td>Chlorite</td>
<td>2</td>
</tr>
<tr>
<td>Clay minerals</td>
<td>7</td>
</tr>
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Fig. 7. Thin section photomicrograph showing a hydrothermal vein re-opened by dissolution within porphyritic andesite.
parallel to the outer surface margin and represents a major site for exfoliation and granular disintegration. The material released from the surface is bleached, weakly cemented and friable, consisting of a framework of fractured mineral grains set in a highly porous and microfractured sandy matrix. Within this sandy material, quartz grains are the only remnants of the original mineralogy and, according to Irfan and Dearman (1978), this material released from the boulders is classified as stage (V): completely weathered. Once released from the boulders, this material is broken down further by reworking on the peat surface, as well as by in situ weathering processes.

6. Mineralogical and physical changes during burial

Studies such as that of Ternan and Williams (1979) and Williams et al. (1986) have shown that weathering is active and ongoing during burial in acid peat upland areas. To assess the extent of in situ weathering due to burial for approximately 2000–2500 years in a peat bog, permission was granted by the Environment and Heritage Service (Historic Monuments Division, DoE, NI) to excavate a small section of circle ‘C’ and several freshly exposed stones were sampled and analysed. At present, burial conditions for the remaining circles are acidic (pH ranges from 3.3 to 3.9; Curran et al., 1998) and aerobic rather than anaerobic due to the throughflow of subsurface water. It is not known how long anaerobic conditions have existed, however, peat cutting during the 18th and 19th centuries would have affected water table level and may have created locally aerobic conditions.

In all freshly exposed material analysed, a bleached outer margin occurs with a distinctive limonite band at depth (Fig. 9). In addition, many of the smaller stones are
completely disintegrated (grussified) to cream coloured sandy material. Some of the larger stones excavated display prominent fractures created by the exploitation of inherent weaknesses by organic acids. Thin section analysis of the newly excavated material highlights the changes that occurred during burial beginning approximately 2000 years ago in an aggressive, acidic peatland environment. Microstructural and mineralogical transformations that are seen throughout the freshly exposed boulders include:

- Transformation of biotite and secondary (deuteric) chlorite to fine-grained micaceous products and clay minerals along cleavage planes and grain boundaries causing expansion along cleavage planes and partial decomposition.
- Alteration of sericitised potassium feldspars to clay minerals.
- Decomposition of plagioclase feldspars to iron oxyhydroxides.
- Removal of alteration products in solution: voids in the sericitised plagioclase feldspars and along veins crosscutting the stones due to the removal of secondary calcite and other soluble products.

In addition, within the outer bleached layer of freshly exposed boulders, mineralogical and structural changes include:

- Decomposition of remnant biotite, secondary chlorite and oxides (re-deposition as limonite) leading to the release of Fe and formation of a limonite band several millimetres below the surface, together with general brown staining of grains and infilling of microcracks (Fig. 9).
• Reduction in size of quartz by progressive microfracturing, opening up of grain boundaries and formation of voids by physical disaggregation of mineral grains.

The mineralogical changes identified suggest that during burial, weathering was selective. Biotites, plagioclase feldspars and their secondary hydrothermal products altered before potassium feldspars and quartz. Overall, high levels of organic acids and low pH (pH 3.3–3.9) within this aggressive environment exploited inherent weaknesses within these igneous lithologies leading to the development of secondary porosity through progressive dissolution and microfracturing (Power and Smith, 1994). In comparison to the boulders now exposed at this site, microfracture networks are less well developed. However, the products of in situ weathering are similar; all samples have bleached, porous outer margins and the material released from stone surfaces is sandy, regolithic with some primary minerals (e.g. quartz) still identifiable. As suggested in other studies (e.g. Ternan and Williams, 1979; Williams et al., 1986), analysis of buried samples indicates that chemical and physical processes were active during burial with exploitation of fractures, scaling and granular disintegration of boulder surfaces and complete in situ disintegration of individual stones. The subsequent exposure of boulders to subaerial conditions with periodic freeze–thaw episodes led to rapid deterioration as the structural and mineralogical weaknesses acquired during burial were exploited with further splitting of boulders and loss of significant amounts of sandy regolithic material within a few months of exposure.

7. Discussion: products, mechanisms and controls of weathering

The products from both in situ weathering during burial and subsequent deterioration on exposure show many similarities to deep weathering of granites in temperate climates despite having different textures (e.g. Bisdom, 1967; Taboada and García, 1999). For example, material at Copney has a porous matrix, low clay fraction and preserves the original structure and can be classified as sandy regolith. In a fashion similar to the deep weathering of many granites, the formation of regolith at Copney has involved the development of a secondary porosity through progressive microfracturing together with selective and sequential decomposition of different minerals (Dearman et al., 1978). This results in the formation of a distinct bleached weathering rind and ultimately, sandy material (grus) either in situ or released from the stone surfaces. At Copney, in situ grussification appears to correlate with specific surface, with stones and cobbles completely disintegrating to grus while larger blocks (> 30 cm) typically fracture and split into discrete angular boulders.

Thin section analysis indicates that the mineralogy of the exposed stones and the mineralogical transformations seen in boulders still buried beneath the peat at Copney are consistent with the processes of grussification and arenisation (Le Pera et al., 2001; Gerrard, 1994; Thomas, 1976; Tardy et al., 1973). The mineralogical changes identified suggest that during burial, in situ weathering was selective with biotites, plagioclase feldspars and their secondary hydrothermal products altering before potassium feldspar and quartz (Fookes et al., 1971; Irfan and Dearman, 1978). In addition, similar to granite weathering in other regions (e.g. Taboada and García, 1999; Power and Smith, 1994),
arenisation was induced and enhanced by chemical and physical alteration of biotite and plagioclase. Dissolution and expansion of secondary mineral phases along cleavage planes and grain boundaries controlled deterioration of the microfabric by causing transgranular cracking and the opening of grain boundaries ultimately causing disintegration of the rock. Later stage weathering is represented by further microfracturing of grains and rock fabric together with mineral dissolution resulting in the formation of authigenic clays and ferruginous products occurring as pseudomorphous replacements of feldspar, biotite (and their secondary minerals) and infilling microcracks.

While products and mechanisms are similar to those for deep weathering of granitic rocks, the controls on the arenisation process at this upland site are different. Saprotilite and grus formation in other temperate regions is normally associated with deep weathering over long time periods and/or reworking of material. At Copney however, selective grussification of igneous rocks is achieved by burial in a shallow, aggressive peatland environment over a relatively limited period of up to 2500 years. The results from this study indicate that arenisation of acid igneous rocks can be achieved without the necessity for a prolonged period of deep, in situ weathering beneath a stable land surface, climate change or reworking.

At Copney, the combination of inherent geological weaknesses, acidic burial conditions and current site conditions controls deterioration of the archaeological stonework. Mineralogical evidence indicates that acid igneous rocks were extensively modified by hydrothermal processes prior to burial, resulting in substantially weakened rock fabric with a relatively high proportion of soluble secondary products. Leaching of secondary minerals during burial under acidic conditions produced a high proportion of dissolution void and re-opened veins throughout the stone causing further fracturing of mineral grains and microfabric. When the site was exposed to subaerial conditions following excavation in 1994, these structural and mineralogical weaknesses were further exploited particularly during freeze–thaw episodes.

8. Conclusions

The mineralogical changes observed in the buried and exposed igneous archaeological stonework at Copney in County Tyrone provide further insights into the processes responsible for the in situ production of detritus in weathering profiles. This historical experiment indicates that the formation of grus and the process of arenisation are not solely restricted to deep weathering environments. The occurrence of completely grussified stones and arenisation of boulder surfaces at Copney indicates that selective grussification of igneous rocks can be achieved by burial in a shallow, aggressive acid-organic environment over periods measured in thousands of years.

The evidence from this study and observations from similar stone circle sites suggest that, if conditions at this site were improved and better managed (for example, installing appropriate drainage systems and adequate protection from dislodgement by grazing animals), over time, the rate of post-excavation accelerated decay may decrease. However, given the inherent structural and mineralogical weaknesses within the rock types at Copney together with the relatively frequent occurrence of freeze–thaw episodes in this
upland region, deterioration of this archaeological stonework through fracturing and granular disintegration is likely to continue.

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