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The weathered Carboniferous limestone at Bullslaughter Bay, South Wales: the first example of ghost-rock recorded in the British Isles

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ABSTRACT: The Carboniferous Limestone at Bullslaughter Bay hosts some of the most notable examples of deep weathering in the British Isles as well as two members of an enigmatic suite of breccias known as the Gash Breccias. The weathered limestone has been investigated thoroughly in order to identify the process responsible for the weathering. In this paper it is demonstrated that the weathering is isovolumetric but the weathering profile is not characterised by a vertical gradient and its depth suggests that meteoric waters did not contribute significantly to the weathering process. The weathered limestone has lost significant amounts of calcium and parts are virtually decalcified. It is seen that the dominant primary minerals of illite and quartz have been preserved while secondary clay minerals are generally absent. The weathered limestone cannot be a saprolite *sensu stricto* as it has been subjected to only restricted chemical processes. It is, therefore, interpreted as a "ghost-rock". This type of weathering results from chemical dissolution by slow moving waters in the saturated zone. It is suggested that the weathering may have taken place during periods of emergence in the Carboniferous, at the same time as the cyclothem tops were exposed to subaerial modification, as evidenced by omission surfaces and palaeokarstic solution features. This is the first time that ghost-rock weathering has been reported from the British Isles.

KEYWORDS: Deep weathering, saprolite, ghost-rock, Gash Breccia, Carboniferous Limestone, Wales.

RÉSUMÉ: L'altération du calcaire carbonifère en Baie de Bullslaughter, Pays-de-Galles méridional : la première description de « roche-fantôme » dans les Iles Britanniques. Le Calcaire Carbonifère de la baie de Bullslaughter offre un exemple de profonde altération, parmi les plus significatifs des Iles Britanniques, ainsi que des éléments d'une série énigmatique de brèches connues sous le nom de « Gash Breccias ». Le but de cette étude était d'identifier les processus responsables de l'altération du calcaire. Il est clair que l'altération est isovolumétrique mais sa diffusion dans l'espace ne montre pas de gradient vertical et sa position en profondeur suggère que les eaux météoriques n'ont pas contribué aux processus d'altération. Cette dernière s'est traduite par une perte importante de calcium pouvant aller jusqu'à une décalcification presque totale. Les minéraux primaires dominants, illite-mica et quartz ont été conservés, tandis que les minéraux argileux secondaires sont généralement absents. Le calcaire altéré n'est pas un saprolite *sensu stricto,* car il n'a été que peu affecté par les processus d'altération chimique. Aussi est-il considéré comme une « roche-fantôme ». Ce type d'altération résulte de la dissolution du calcaire dans la zone saturée à faible gradient hydraulique, caractérisée par une lente circulation des eaux. On avance l'hypothèse que cette altération a pu se produire très précocement pendant les périodes d'émersion du Carbonifère, lorsque le toit des unités cyclothémiques était exposé à l'érosion continentale, comme le prouvent les lacunes stratigraphiques et les formes paléokarstiques de dissolution superficielle. C'est la première fois que ce type d'altération en « fantômisation » est décrit dans les Iles Britanniques.

MOTS-CLÉS: Altération profonde, saprolite, roche-fantôme, Gash Breccia, Calcaire Carbonifère, Pays-de-Galles.

1. Introduction

It is often necessary to reappraise individual strands of geomorphological evidence so as to reconstruct the landscape development of a given region more accurately. These strands may include the study of denudation surfaces (e.g. Rowberry et al., 2007; Rowberry, 2012), inherited sedimentary deposits (e.g. Morawiecka et al., 1996; Walsh et al., 1996), and ancient landforms (e.g. Battiau-Queney, 1987; Štěpančíková & Rowberry, 2008). The weathered rocks of the British Isles have not attracted a significant amount of research over the years despite their fairly widespread distribution (Walsh et al., 1999). It is thought that this reflects the fact that they have seldom been a problem during engineering work and generally have little commercial value at present. There are, however, known to be a number of *in situ* regoliths, both palaeosols and saprolites, which developed prior to the onset glaciation during the Pleistocene. These are commonly found to occur on rocks rich in silicates (Battiau-Queney, 1996). The weathering processes that came to form these regoliths resulted from the action of meteoric waters (Nahon, 1991) with the weathering depth ultimately controlled by the permeability of the bedrock (Battiau-Queney, 1987). The preserved weathering profiles are generally incomplete: the shallower soils have already been removed by surface erosion while the deeper saprolites remain (Battiau-Queney, 1984). It is, however, clear that the action of meteoric waters cannot account for all the weathered rocks of the British Isles. There are some weathering phenomena that have been ascribed to hydrothermal processes (Sheppard, 1977) while there are also examples of exceptionally deep weathering in which derived fossils indicate that the weathering process may have begun earlier than normally thought, during the late Cretaceous (Hamblin, 1973).

The Carboniferous Limestone of southern Pembrokeshire is represented by the Pembroke Limestone Group, of Courceyan to Brigantian age, which predominantly comprises skeletal and ooidal limestones with some calcite and dolomite mudstones, sandstones and mudstones, and a few coals and cherts (Waters et al., 2009). This group has long been known to host a number of examples of deep weathering including those found at Lydstep Iron Ore Mine (Dixon, 1921), Pole Reef Cove (Dixon, 1921), West Angle Bay (Cantrill et al., 1916; Dixon, 1921), and Pembroke Power Station (Higginbottom & Fookes, 1971). It may be that this list should also include the Flimston Basin but the role of weathering has yet to be established satisfactorily, neither with regard to basin formation nor subsequent deposition (e.g. Jenkins et al., 1995; McLean, 2002). However, some of the most notable examples of deeply weathered limestone in the British Isles are to be found in the cliffs at Bullslaughter Bay in south Wales. These cliffs also host two members of an enigmatic suite of breccias known as the Gash Breccias (Dixon, 1921). The weathered limestone has been investigated thoroughly

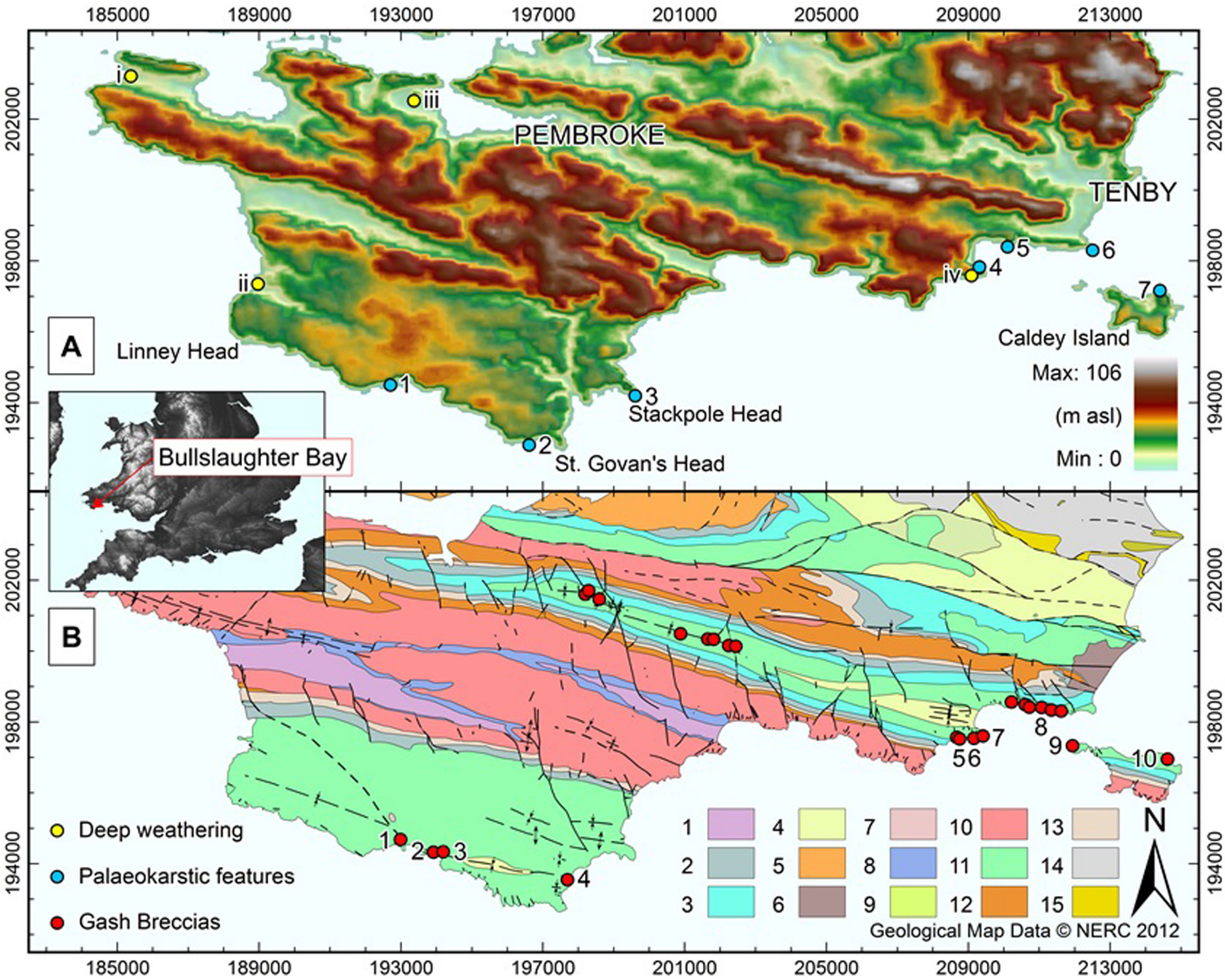

Figure 1. (A) The topography of southern Pembrokeshire constructed using SRTM data from the CGIAR-CSI GeoPortal (srtm.csi.cgiar.org). The yellow dots represent the location of potentially analogous weathering sites (i: West Angle; ii: Pole Reef Cove; iii: Pembroke Power Station; iv: Lydstep Mine) while the blue dots represent the location of palaeokarst sites (1: Elegug Stacks; 2: St. Govan's Chapel; 3: Stackpole Head; 4: Lydstep Cleft; 5: Proud Giltar; 6: Giltar Point; 7: Highcliff Quarry). (B) The regional geology constructed using data from the British Geological Survey (1: Aber Mawr Shale Fm.; 2: Avon Group; 3: Black Rock Subgroup & Oolite Fm.; 4: Bishopston Mudstone Fm.; 5: Cosheston Group; 6: Devonian and Carboniferous (undifferentiated); 7: Palaeogene and Neogene (undifferentiated); 8: Ludlow Rocks (undifferentiated); 9: Millstone Grit Group; 10: Milford Haven Group; 11: Pembroke Limestone Group; 12: Ridgeway Conglomerate Fm.; 13: Shrinkle Sandstone Fm.; 14: South Wales Lower Coal Measures Fm.; 15: Telpyn Point Sandstone Fm.). The red dots represent the location of major bodies of Gash Breccia (1: Flimston; 2: Bullslaughter Bay West; 3: Bullslaughter Bay East; 4: Trevallen; 5: Draught; 6: Whitesheet Rock; 7: Lydstep Point; 8: Valleyfield Top; 9: St. Margaret's Point; 10: Den Point) (© Crown Copyright 2013: a British Geological Survey/EDINA supplied service).

through field observations and laboratory analyses in order to identify the process responsible for the weathering. In addition, the relationships between the weathered limestone and the two large breccia masses exposed at both ends of the bay have been considered.

2. The geology at Bullslaughter Bay

The study area of Bullslaughter Bay is located within an area of outstanding natural beauty in the southern part of the Pembrokeshire National Park (Fig. 1). The cliffs around the bay are built from limestones of the Oystermouth Formation (Brigantian) and mudstones of the Aberkenfig Formation (Pendleian-Arnsbergian) (Figs 2 & 3). The Oystermouth Formation comprises thin- to medium-bedded dark grey argillaceous limestones and mudstones (Waters et al., 2009). It is also common to find chert nodules or beds as well as sandy limestones. The interbedded argillaceous limestones and mudstones are often decalcified or deeply weathered to pale grey, white, yellow, or reddish silty clays. The colour of these clays reflects the parent material. There are also units of medium- to thick-bedded skeletal packstones and oolitic limestone with cherts in the lower part of the formation in southern Pembrokeshire. The Aberkenfig Formation comprises dark grey fissile mudstones with thin-bedded radiolarian cherts and siliceous mudstones (Waters et al., 2009). However, as a result of weathering, every part of this outcrop currently exposed around the bay comprises a stiff yellow-buff clay with residual chert clasts. To the north and south of Bullslaughter Bay the Oxwich Head Limestone Formation (Asbian-Brigantian) underlies the Oystermouth Formation. This succession comprises thick-bedded fine- to coarse-grained, recrystallised, bioturbated skeletal packstones with distinctive pale to dark grey mottling (Waters et al., 2009). It is also common to find pseudobrecciation and ooidal limestones as well as units of dark grey irregularly bedded skeletal packstones with shaly partings.

The cliffs around the bay also host two large members of an enigmatic suite of breccias known as the Gash Breccias (Dixon, 1921) (Figs 4A & 4C). The origin and age of the suite remains poorly constrained despite recent attempts to understand better their geological history (Larvin, 2010; Miller, 2011; Woodhouse, 2011). These are major bodies of fragmented limestone in otherwise unbroken sequences of Carboniferous Limestone (Fig. 4B). The suite comprises about twenty five members and all occur within an area of about 110 km^2 in the eastern part of the Pembroke Peninsula (Walsh et al., 2008). The breccias are only found where the dip of the strata exceeds 50° and they are often coarse, chaotic, and clast-supported. The shapes of the individual breccias may vary considerably. The clasts are invariably highly angular and at some sites they have been cemented with various degrees of firmness by additions of secondary calcite, although not noticeably so at Bullslaughter Bay. The largest clasts may

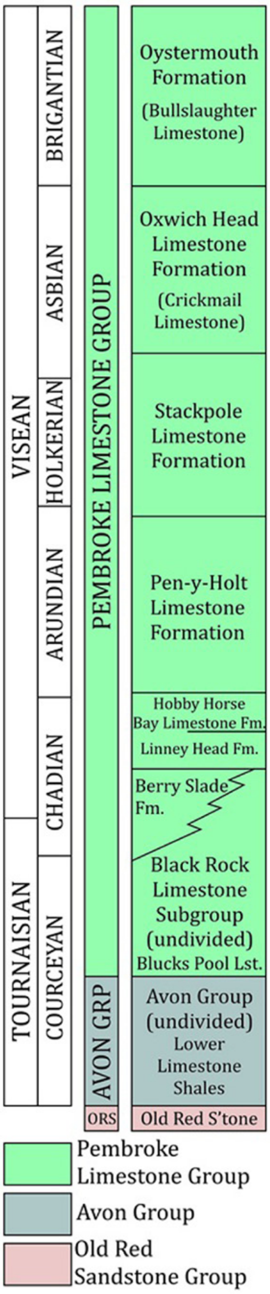

Figure 2. The Tournaisian and Viséan lithostratigraphy and nomenclature of the Pembroke Limestone Group (modified from Waters et al., 2009). This group is overlain by the mudstones of the Aberkenfig Formation, part of the Marros Group of South Wales.

weigh as much as several hundred tonnes whilst the smaller clasts irregularly fill the voids between the larger ones until they are sufficiently small to be regarded as a matrix. It is difficult to assess whether subsidence has occurred within the breccias and to quantify its depth as the immediate wall rocks are normally near vertical and therefore the constituent clasts simply match those in the walls (Walsh et al., 2008). The adjacent siliciclastic outcrops of Old Red Sandstone and Upper Carboniferous are not known to host analogous features nor are the more distal Carboniferous Limestones of the Gower Peninsula or Pembrokeshire Coalfield. There is no information about what underlies the modern exposures of Gash Breccia nor is there information about what has been removed by erosion above them (Walsh et al., 2008).

3. Methods

The field observations focused on investigating the physical relationships that exist between the unweathered and weathered limestone in both the unbrecciated and brecciated rocks. These observations were supplemented by data pertaining to compressive strength obtained using a Schmidt Hammer. The standard method for testing was applied at ten sites with disparate geological characteristics and the presented results reflect the mean values obtained at each site, minus the highest and lowest readings. The main cove in the central part of the bay was also mapped in terms of rock weathering grade following the standard method described by the Geological Society of London (1990). This method focuses on the degree of iron staining, the approximate proportion of clay in the sediment, and the degree to which corestones and residual particles such as chert blocks are present. It has not yet been possible to conduct a survey in order to investigate the microtectonic structures both near and within the weathered limestones although it could also yield some interesting results.

The laboratory analyses comprised calcimetry, granulometry, x-ray diffraction, and exoscopy. The calcimetric analysis provides information regarding the selective loss of calcium from an impure parent limestone, the granulometric analysis differentiates between collapsed material and material that has weathered *in situ*, the x-ray diffraction provides information regarding secondary clay formation, and the exoscopy of individual quartz grains provides information regarding both the primary sedimentation environment and the secondary effects of the weathering environment. The calcium carbonate content was determined by calcimetric analysis on samples of weathered limestone using a Bernard Calcimeter. The grain-size distribution was determined through microgranulometric analysis (< 900 µm) on samples of weathered limestone using the laser diffraction particle size analyser Malvern Mastersizer 2000. The clay mineral associations were determined through x-ray diffraction on samples of weathered limestone using a Bruker D4 Endeavor coupled with a fast LynxEye Detector. The surface morphologies of individual grains within two samples were analysed using the scanning electron microscope JEOL 6380 LV.

4. Results

4.1. Field observations

The thin- to medium-bedded dark grey argillaceous limestones and mudstones of the Oystermouth Formation that form most of the cliffs at Bullslaughter Bay are both unweathered and weathered while the mudstone cliffs of the Aberkenfig Formation are all deeply weathered. The Oystermouth Formation was deposited in shallow marine waters and it presents a wide range of facies that reflect the rapidly changing sedimentary environment.

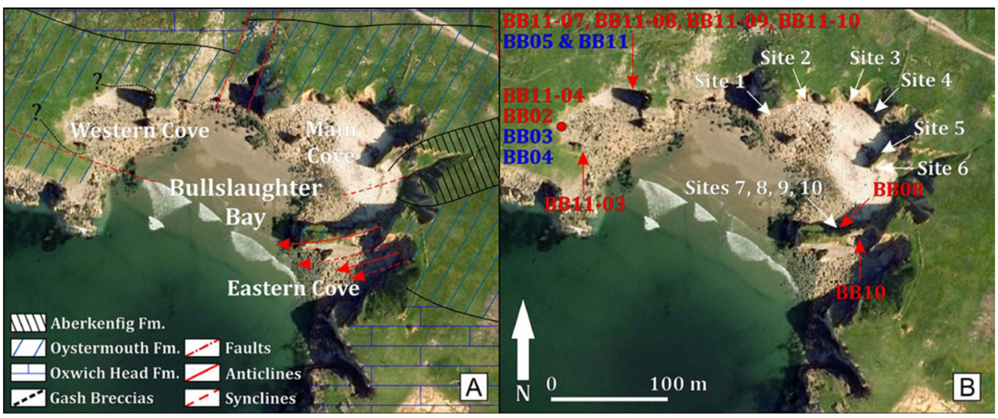

Figure 3. (A) The lithologies and main geological structures around Bullslaughter Bay (modified from Thomas 1971); a detailed geological cross-section through the eastern part of the bay was recently presented by Błażejowski & Walsh (2013). (B) The location of the Schmidt Hammer test sites (indicated by white lettering) and sample sites (red lettering refers to the samples subjected to calcimetric analysis while the blue lettering refers to samples subjected to granulometry, x-ray diffraction, and/or exoscopy) (satellite image from Google Earth).

Figure 4. A photographic overview of the study area at Bullslaughter Bay. The cliffs around the bay attain a maximum height of approximately 40 m while its widest part is approximately 300 m. (A) The deep weathering and Gash Breccia in the western part of the bay; it should be noted that the breccia is not developed in the main axis of the syncline but slightly to the north. (B) The generally unweathered limestone in the central part of the bay; a prominent fault is visible due to weathering along the fault plane. (C) The deep weathering and Gash Breccia in the eastern part of the bay; weathering processes hereabouts have altered both the limestones of the Oystermouth Formation as well as the overlying dark grey fissile mudstones of the Aberkenfig Formation.

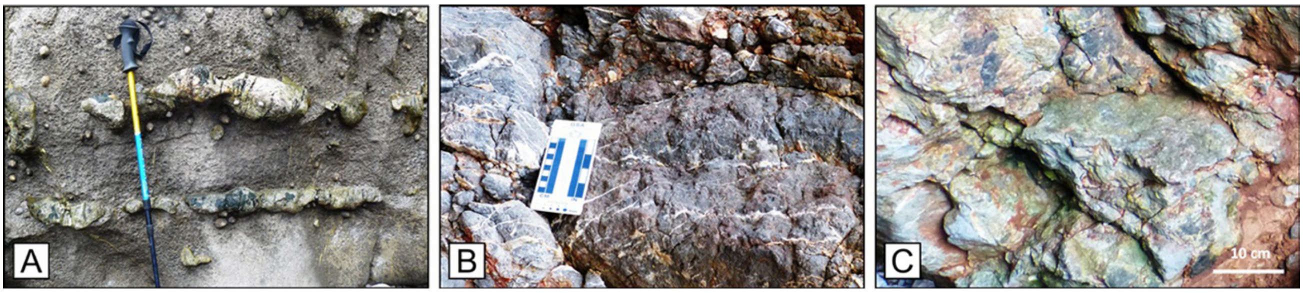

Figure 5. The thin- to medium-bedded dark grey argillaceous limestones and mudstones of the Oystermouth Formation at Bullslaughter Bay. The limestone is highly heterogeneous and it is common to find chert nodules and beds (A), calcite veins (B), and argillaceous limestone (C). These sharp lateral and vertical variations in texture, mineralogy, and permeability ensure that it is not affected uniformly by weathering processes; the degree of weathering may vary greatly from place to place.

Lithologically, the formation is highly heterogeneous and it is common to find chert nodules and beds (Fig. 5A), calcite veins (Fig. 5B), and argillaceous limestone (Fig. 5C). These sharp lateral and vertical variations in texture, mineralogy, and permeability ensure that it is not affected uniformly by weathering processes. The affect of weathering on such an anisotropic rock may vary considerably from place to place so that the weathered limestone may appear as either isolated decalcified blocks or banded ochreous and slightly calcareous sands and silts. However, the isovolumetric nature of the weathering is readily recognisable as it is often possible to trace calcite veins, bedding planes, cracks or cleavage from the unweathered limestone and into its weathered counterpart and from there into loose material.

The weathered Carboniferous Limestone is exemplified at the two sites shown in Fig. 6 (A-C & D-F) where it is frequently possible to trace geological features from unweathered to weathered limestone and onto loose material without interruption. The banded facies have often weathered into a laminated loose rock which has previously been assumed to represent fill sediment. The highly weathered material also contains isolated unweathered or less weathered “corestones” that may or may not be decalcified but are almost always highly angular. The

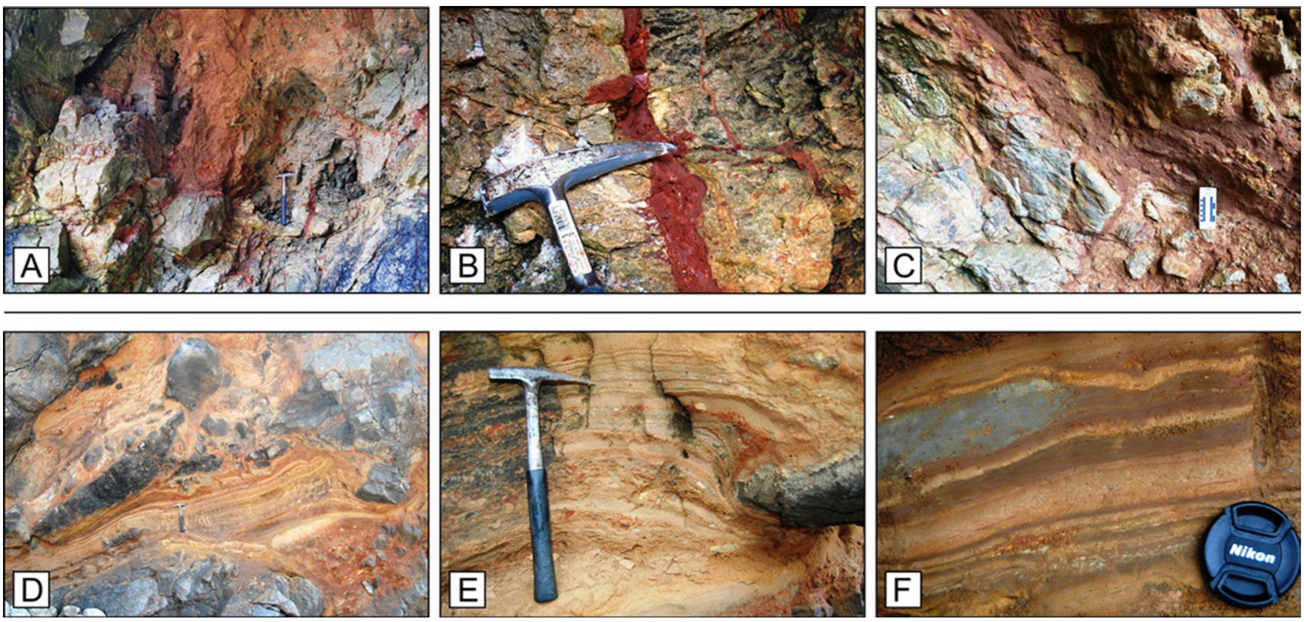

Figure 6. The weathered Carboniferous Limestone at two sites within Bullslaughter Bay. The affect of weathering on such an anisotropic rock may vary considerably from place to place so that the weathered limestone may appear as either isolated decalcified blocks or banded ochreous and slightly calcareous sands and silts. The examples in A-C occur in the western part of the bay while the examples in D-F occur in the main cove in the eastern part of the bay (see Fig. 2). It is frequently possible to trace geological features from unweathered to weathered limestone and onto loose material without interruption (e.g. calcite veins, bedding planes, or cleavage).

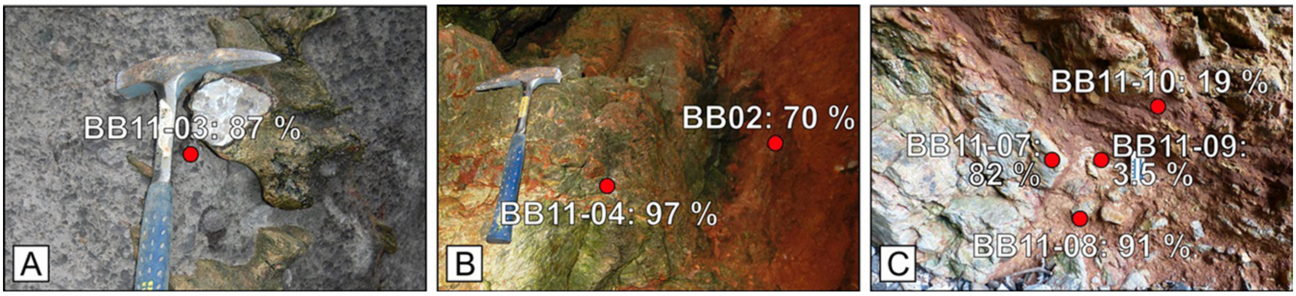

Figure 7. The results of the calcimetric analysis for seven samples from the western part of the bay shown within their field setting. This analysis provides information regarding the selective loss of calcium from an impure parent limestone. The three sites are separated by less than 50 m and the results clearly illustrate that changes in the calcium carbonate content occur at the centimetre scale.

Table 1. The results of Schmidt Hammer Tests conducted around the main cove in the eastern part of Bullslaughter Bay. These measurements were obtained from a number of places in which the limestone appeared to be weathered, as assessed visually or audibly by striking the rock with a hammer, and their significance stems from the fact that they confirm that a loss of compressive strength may occur without a change in the physical appearance of the limestone.

Reading	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10
1	59	64	52	-	58	66	41	52	15	48
2	58	62	39	-	55	63	40	50	14	46
3	58	62	38	-	54	62	29	25	12	44
4	58	57	30	-	50	56	24	24	11	44
5	56	55	27	-	48	56	24	16	-	37
6	55	54	24	-	46	50	24	16	-	36
7	54	53	23	-	40	48	22	15	-	34
8	52	48	14	-	34	40	22	13	-	22
9	46	44	12	-	34	38	20	13	-	18
10	46	40	12	-	28	30	14	13	-	16
Mean*	**54.625**	**54.375**	**25.875**	**-**	**45.125**	**51.625**	**25.625**	**21.5**	**12.333**	**35.125**
Std. Dev.*	4.10	6.25	9.88	-	8.31	9.35	6.37	12.41	1.53	10.33

* The second to eighth readings have been used to determine the mean and standard deviation

Site 1: sub-vertical horizontally bedded limestone on the western side of BBE; Site 2: clast-supported limestone boulders in the breccia on the western side of BBE; Site 3: matrix-supported limestone boulders in the breccia on the western side of BBE; Site 4: red clay matrix on the western side of BBE; Site 5: matrix-supported limestone boulders in the breccia in the central section of BBE; Site 6: matrix-supported limestone boulders in the breccia in the central section of BBE; Site 7: large limestone blocks beneath deep weathering on the eastern side of BBE; Site 8: large limestone blocks within the deep weathering on the eastern side of BBE; Site 9: deeply weathered sands and clays on the eastern side of BBE; Site 10: sub-vertical horizontally bedded limestone on the eastern side of BBE.

angularity of these corestones contrasts to the rounded corestones normally found within weathered granite or other igneous rocks. It is clear from Schmidt Hammer Tests that the weathering has caused a loss of compressive strength (Table 1). These measurements were obtained from a number of places in which the limestone appeared to be weathered, as assessed visually or audibly by striking the rock with a hammer. Their significance stems from the fact that they confirm that a loss of compressive strength may occur without a change in the physical appearance of the limestone.

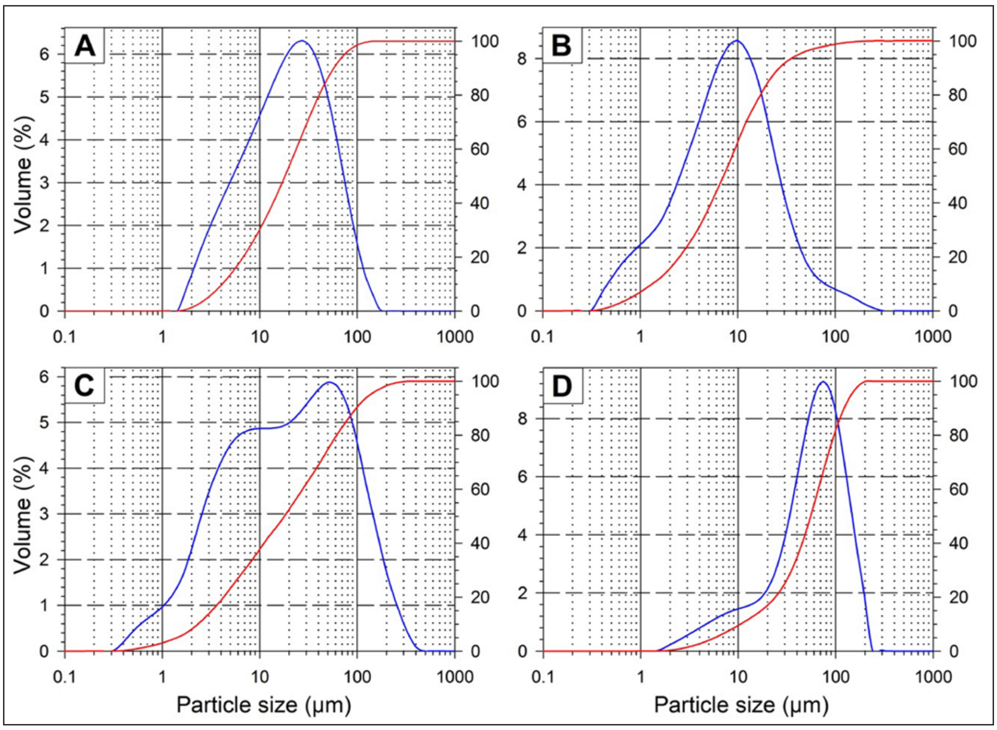

Figure 8. The granulometric particle size distribution graphs for the following samples: (A) BB03; (B) BB05; (C) BB10; (D) BB11. This analysis differentiates between collapsed material and material that has weathered *in situ*; poorly sorted grains are indicative of collapse while better sorted grains are indicative of weathering. The results for each of the samples show well sorted grains that are considered to reflect *in situ* weathering processes.

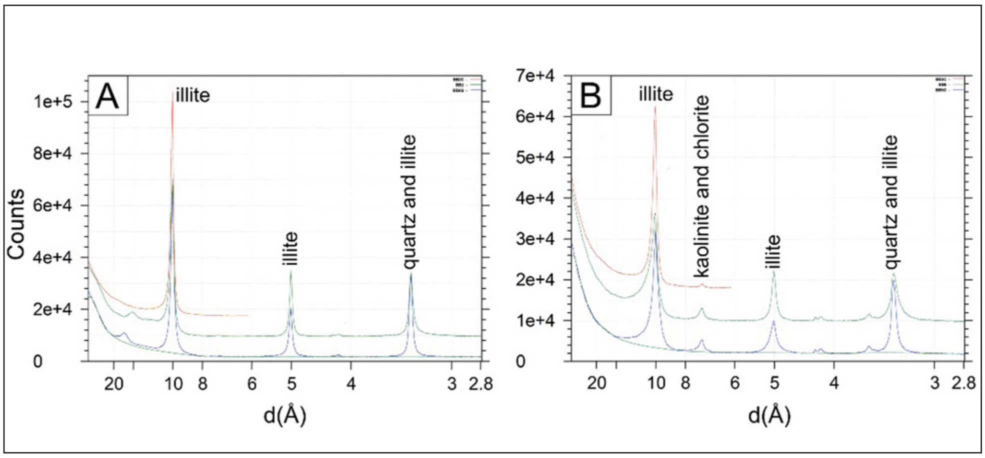

Figure 9. The x-ray diffraction graphs for samples BB02 (A) and BB05 (B). This provides information regarding possible secondary clay formation: the green line represents the normal run with the air-dried sample, the black line represents the glycol run following ethylene-glycol vapour saturation for twelve hours, and the red line represents the heating run following two hours of heating at 490°C. The primary minerals are preserved in the weathered samples and it is clear that the parent rocks were either impure limestone or shale rich in quartz, illite, and goethite.

Table 2. The results of the calcimetric analysis undertaken on seven samples from the western part of Bullslaughter Bay. The precise sample locations are shown on Fig. 7.

Sample	V Initial (mL)	V Final (mL)	Mass (g)	$CaCO_3$ (%)
BB11-03	2.5	57.5	0.2686	86.88
BB02	2.5	71	0.4225	69.73
BB11-04	8.5	76	0.2967	96.53
BB11-07	8	62.5	0.2834	81.60
BB11-08	3	68	0.3016	91.44
BB11-09	3	6	0.3614	3.52
BB11-10	2	18	0.3615	18.78

A weathered laminated material derived from shale and siltstone within the main cove of the bay has revealed crinoid remains. These are generally disarticulated and represented by isolated columnals or brachials with the crinoid ossicles offering evidence for temporary burial, reworking, transportation, and reburial (P. Gorzelak, pers. comm.). This weathered material has also preserved a residual Brigantian conodont assemblage (Błażejowski & Walsh, 2013). The weathering grade map drawn around the main cove corresponds well to the results of the compressive strength tests but not to previous geological mapping of the breccia margins. It is, therefore, clear that the relationship between the weathering and the brecciation is far from straightforward. The rocks near the synclinal axes may be more weathered than those situated further away but there are also examples from both sides on the bay where the converse is true. There is also no simple relationship between the weathering grade and the proximity of the syncline axis. It is, however, clear that there are no rocks within the study area that have been completely altered within the framework set out by the Geological Society of London (1990).

4.2. Laboratory analyses

The samples used for laboratory analyses were taken from sheltered sites at the base of the cliffs, many tens of metres below the ground surface. The calcimetric analysis was undertaken on seven samples from the western part of the bay (Table 2 & Fig. 7A-C). It has been found that the calcium carbonate content within these samples ranges from 97 % in the unweathered limestone to 3.5 % in the deeply weathered material. There may be an abrupt transition from unweathered limestone with a high calcium carbonate content to decalcified clays, such as between samples BB11-08 and BB11-09 (Fig. 7C). These results clearly illustrate that changes in the calcium carbonate content occur at the centimetre scale. The granulometric analysis was undertaken on four samples of weathered material (Fig. 8). The first, BB03, was taken from a fissure filled with a loose reddish material that was found to be composed of silts with only subordinate clays and fine sands (Fig. 8A). The second, BB05, was taken from a compact reddish weathered limestone that was found to be composed of silts with subordinate clays (Fig. 8B). The third, BB10, was taken from a compact yellow weathered limestone that was found to be composed of silts with subordinate clays and sands (Fig. 8C). The fourth, BB11, was taken from a compact reddish material that was found to be composed of silts and fine sands (Fig. 8D). The fact that each curve is dominated by fine silt with low or very low quantities of clay and sand indicates that the sediments have not been transported after weathering; the paucity of sand and clay suggests inheritance from the parent rock, rather than collapsed material, and reflects an *in situ* weathering process. It should be noted that, in contrast, the Trask Sorting Index does not indicate well-sorted material, a fact that is thought to reflect the frequent fine lamination of the rock; it was simply not possible to sample material from only one lamina. The x-ray diffraction was undertaken on five samples of weathered material as well as one sample of unweathered limestone (Table 3 & Fig. 9A-B). The weathered samples all have their primary minerals preserved and it is clear that their parent rocks were either impure limestone or shale rich in quartz, illite, and goethite. There is little evidence for secondary clay formation. The exoscopic analysis was undertaken on two samples of weathered limestone (Fig. 10). The first, BB04, was taken from an intensively weathered limestone (Fig. 10A-B). The sands within this sample are generally rounded with a low relief and their surface morphology is typical of marine grains. The second, BB08, was taken from a partly weathered limestone (Fig. 10C-D). The sands within this sample are generally sub-rounded with a medium relief and their surface morphology is typical of fluvial grains. It is suggested that both samples reflect transport processes prior to sedimentation and later lithification. These contrasting results reflect the wide range of facies within the Oystermouth Formation.

Table 3. The mineralogical analysis of the clay fraction < 2 μm.

Sample	Illite (%)	Kaolinite (%)	Chlorite (%)	Mixed-layer clay (%)	Accessory minerals
BB02	90	-	-	10	quartz & goethite
BB05	90	7	3	-	quartz & goethite

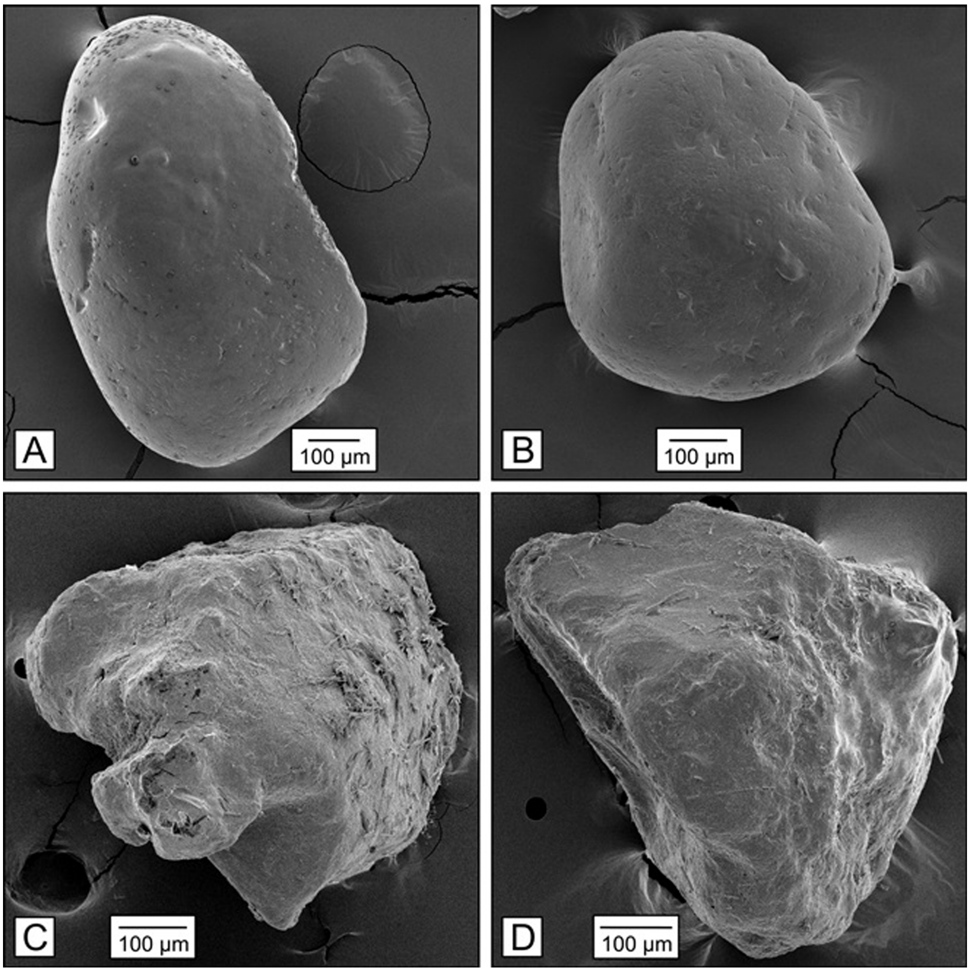

Figure 10. The exoscopic analysis of individual quartz grains from samples BB04 (A & B) and BB08 (C & D). The surface morphologies within the former sample are generally rounded with a low relief, typical of marine grains, while those within the latter are generally sub-rounded with a medium relief, typical of fluvial grains. It is considered that these morphologies were etched prior to initial lithification and do not indicate more recent transportation.

5. Discussion

5.1. The weathering characteristics

The isovolumetric nature of the weathering has been demonstrated through field observations while the loss of density associated with the weathering has been indirectly confirmed by results obtained with the Schmidt Hammer. The weathered limestone, therefore, appears to have certain physical characteristics that are typical of a saprolite. There are, however, two fundamental objections to this interpretation. The first is that a typical regolith weathering profile is marked by a vertical gradient in which the intensity of the weathering increases upwards through the profile. This vertical gradient has not been observed anywhere in the cliff sections at Bullslaughter Bay. The second is that, given the present sheltered position of strata, the weathering is thought to extend to far greater depths than can be attributed to a surficial weathering process. The laboratory analyses enable us to define the process responsible for this weathering. It is clear that there has been a considerable loss of calcium and much of the weathered rock is essentially decalcified. The primary minerals, mainly quartz and illite, have been preserved while secondary clay minerals are generally absent. The comparatively small amount of kaolinite found within the weathered rock contrasts markedly to previous studies undertaken on nearby saprolites (Battiau-Queney, 1980). There are small quantities of goethite within all the samples and this explains the red or ochreous colour of the rock. The exoscopy also provides interesting information about the history of the rock as the images do not show the deep corrosion pitting that has hitherto been seen on other saprolitised grains from Wales or elsewhere in the British Isles (Battiau-Queney, 1980 - for corrosion pitting, see, for example, p. 300, p. 310, p. 318, p. 330-332). Furthermore, euhedral crystal overgrowths are very rarely seen in contrast to those saprolites previously analysed from the Marros Group (the Welsh “Millstone Grit”) (Battiau-Queney, 1984).

5.2. The weathering process

The results suggest a different weathering process to that responsible for forming saprolite. It appears that the weathered limestone was subjected to only restricted chemical processes. The majority of the mineralogical characteristics of the host rock have been preserved except that there has been a considerable loss of calcium and, indeed, much of the weathered limestone is completely decalcified. It is proposed that the weathered limestone is a “ghost-rock” (*sensu* Quinif, 2010; Laverty, 2012). This is the first time that this type of limestone weathering has been reported in the British Isles. These weathered rocks have the same isovolumetric structure as saprolites but differ with respect to their chemical and mineralogical properties. They form as a result of chemical dissolution caused by slow moving waters deep within the saturated phreatic zone. The slow moving waters preferentially flow along perpendicular joint systems and are able to isolate intact blocks of limestone and other parent rock in much the same way as occurs during the first stage of biostasy (Erhart, 1955). The ghost-rock presents almost no vertical changes in the weathering profile because of the very low hydraulic gradient in the phreatic zone. It has been observed to depths of more than 100m below the surface and may attain depths of more than 500 m given suitable hydrodynamic conditions (Quinif, 2010). The ghost-rock becomes prone to mechanical erosion when it passes from the phreatic zone into the vadose zone. It is at this time that pseudoendokarstic features may develop in the unweathered limestone and cave systems may develop in the ghost-rock. The Carboniferous Limestone of the Pembroke Limestone Group may also host further examples of ghost-rock weathering such as, for example, the weathering seen on an exposed face at Bosherston Quarry (Fig. 11A-C) and that seen on the cliff face at Pen-y-Holt (Fig. 11D-F). These sites contrast to the study area at Bullslaughter Bay in that the beds dip far more gently. Samples from these sites are currently being analysed in the laboratory so as to determine if this weathering was also initiated within the saturated phreatic zone. It is also possible that ghost-rock may

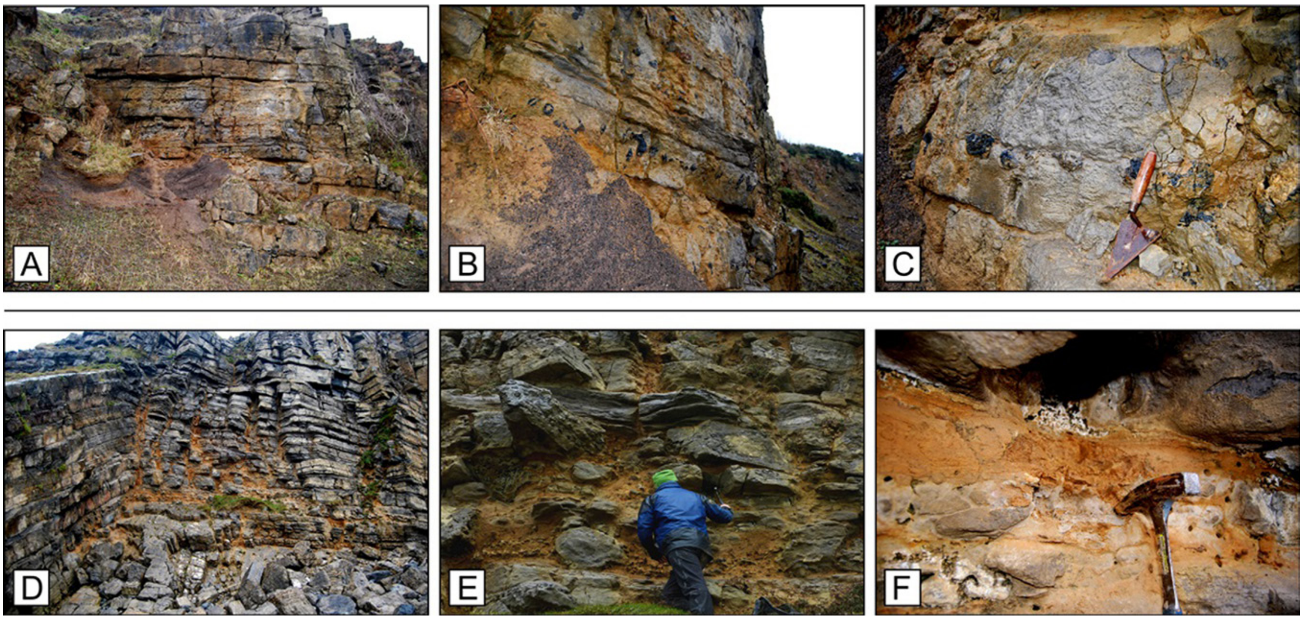

Figure 11. The Carboniferous Limestone of the Pembroke Limestone Group hosts further examples of deep weathering such as those seen within an exposed quarry face at Bosherston Quarry (A-C) and those within the cliff face at Pen-y-Holt (D-F). These sites contrast to the study area at Bullslaughter Bay in that the bedding dips far more gently. Samples from these sites are currently being analysed in the laboratory so as to determine if this weathering was also initiated in the phreatic zone.

occur in more distal quarries such as those along the North Crop of the South Wales Coalfield (e.g. Cwar yr Ystrad and Vaynor Quarries) and in the area around Great Doward in the Forest of Dean (e.g. Scowles Quarry) (Battiau-Queney, 1986).

5.3. The timing of the weathering

The geomorphological and geological history of the Welsh region during the Mesozoic is largely conjectural due to the general paucity of appropriately aged rocks (Cope, 1984; Walsh et al., 1999). There is, perhaps unsurprisingly, no evidence to suggest that ghost-rock weathering took place in the Jurassic or Cretaceous. There is, however, sufficient evidence to suggest that the weathering may have occurred prior to brecciation due to the fact that the same ghost-rock weathering processes have clearly affected both the unbrecciated limestone host and isolated clasts or blocks within the breccias themselves. These breccias are closely associated with fold structures and it seems reasonable to suggest that brecciation also occurred during late Carboniferous-early Permian folding of the Variscan Orogeny (cf. Wright et al., 2009). It follows that the weathering is most likely to have occurred during the Carboniferous. However, ghost-rock weathering processes cannot operate under the sea, and therefore there has to be independent evidence to demonstrate that the carbonate platform of southern Pembrokeshire periodically rose above sea-level. This required evidence, for example omission surfaces or palaeokarstic solution features, is found on a number of other outcrops of Carboniferous Limestone in England and Wales (e.g. Walkden, 1974; Walkden & Davies, 1983).

It had been thought that long periods of emergence did not occur during the formation of the Pembroke Limestone Group

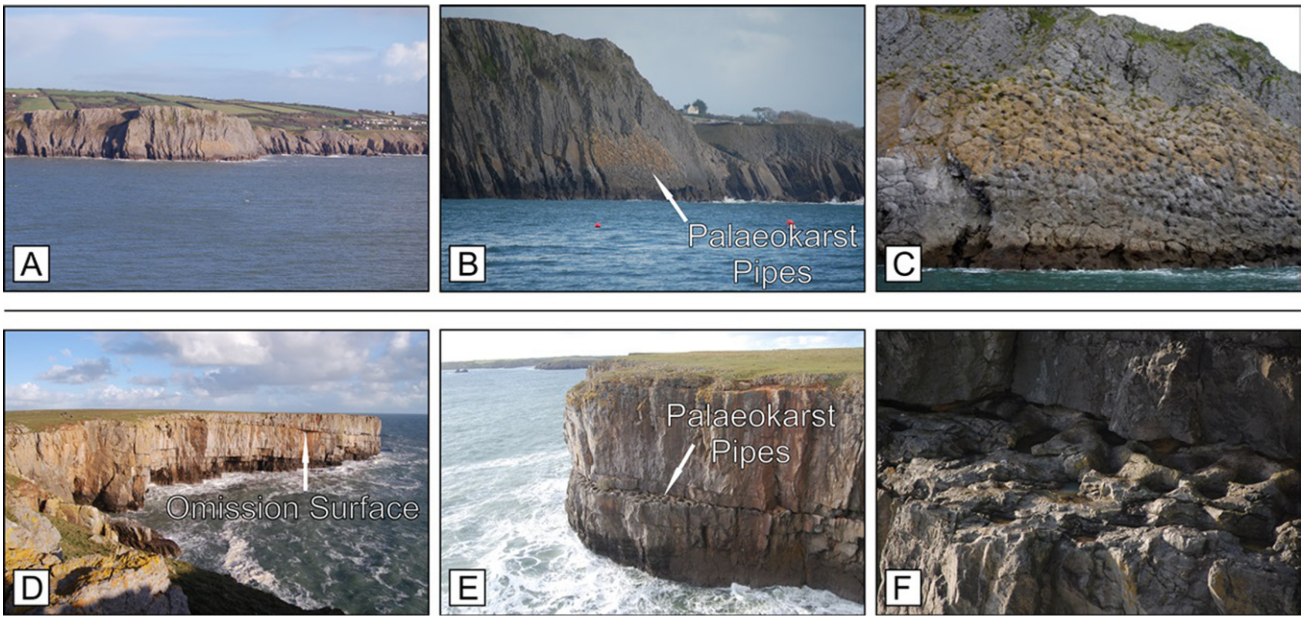

Figure 12. The Carboniferous Limestone in southern Pembrokeshire also hosts a number of intraformational palaeokarst features including the omission surfaces and palaeokarst solution pits at Proud Giltar (A-C) and Stackpole Head (D-F). The palaeokarst features are associated with both horizontal and now near vertical or overturned strata and they demonstrate that the limestone was subjected to subaerial erosion during periods of emergence in the early Asbian of the Carboniferous. The regularity of the stratification near Stackpole Head suggests that the periods of emergence were probably caused by sea level changes rather than flexure of the continental shelf.

and, therefore, no karst dissolution could be attributed to that time. However, it has recently been shown that there are a number of examples of omission surfaces and palaeokarstic solution features in the Pembroke Limestone Group (George, 2008). These are found on both horizontal and now near vertical or overturned strata. The palaeokarstic solution features are represented by shallow cylindrical pits a few decimetres across as seen clearly at, for example, Proud Giltar (Fig. 12A-C) and Stackpole Head (Fig. 12D-F). They illustrate that sedimentation was cyclothemic with repetitive emergence and submergence of the carbonate platform of southern Pembrokeshire emergence from the early Asbian. The regularity of the stratification near Stackpole Head suggests that the periods of emergence were probably caused by sea level changes rather than flexure of the continental shelf. The carbonate platforms were low-lying, vegetated, and subject to weathering during the marine regressions. It has been suggested that the roughly cylindrical hollow shapes of the piped and hummocky palaeokarst surfaces were created by the dissolution of limestone by rainwater channelled along plant stems or tree trunks (Vanstone, 1998). Moreover, each period of emergence may have lasted for tens of thousands to hundreds of thousands of years, during which the hydrodynamic conditions were conducive to limestone weathering at depth within the saturated phreatic zone (Vanstone, 1998). It is proposed, as a working hypothesis, that the ghost-rock may have formed in the phreatic zone during periods of emergence from the early Asbian, when the cyclothem tops were exposed to subaerial modification, as evidenced by the omission surfaces and palaeokarstic solution features.

6. Conclusions

The Carboniferous Limestone at Bullslaughter Bay hosts some of the most notable examples of deep weathering in the British Isles. It has been investigated in order to identify the process responsible for the weathering and to try to better understand the formation of breccias. The field observations have shown that the weathering was isovolumetric but the weathering profile is not characterised by a vertical gradient and its depth suggests that meteoric waters did not contribute significantly to the weathering process. The analytical work demonstrated that the weathered limestone has lost significant amounts of calcium and parts are virtually decalcified. The dominant primary minerals of illite and quartz have been preserved while secondary clay minerals are generally absent. Furthermore, the surface morphologies of individual grains do not show the deep corrosion pitting that have hitherto been seen on other saprolitised grains from Wales or elsewhere in the British Isles. The weathered limestone is therefore interpreted as a “ghost-rock”. It is proposed that the ghost-rock may have formed in the phreatic zone during periods of emergence from the early Asbian of the Carboniferous. This is the first time that ghost-rock in a limestone sedimentary complex has been reported from the British Isles and it may help to throw new light onto the possible formation of the Gash Breccias at Bullslaughter Bay.

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