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Unravelling Evidence for Global Climate Change in Mississippian Carbonate Strata from the Derbyshire and North Wales Platforms, UK

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Dear Editor,

Please find enclosed the revised manuscript for the Journal of the Geological Society manuscript titled:

"Unravelling Evidence for Global Climate Change in Mississippian Carbonate Strata from the Derbyshire and North Wales Platforms, UK".

The manuscript has been significantly updated and improved with thanks to the reviewers, and now takes on a more global perspective.

I confirm that the manuscript is not under review in another journal and that all the authors have agreed to the revised version.

Yours sincerely,

Lucy Manifold

Lucy Manifold

on behalf of myself, Cathy Hollis, Peter Del Strother, David Gold, and Peter Burgess.

Reviewer 2 Comments to Author: **If you want to reference facies descriptions from the southern margin of the Derbyshire carbonate platform,**
Gutteridge, P. 2003. A record of the Brigantian limestone succession in the partly infilled Dale Quarry, Wirksworth. Mercian Geologist v.15, 219-224 could be added

This paper is an excellent descripton of the Brigantian strata around the southern margin of the Derbyshire Platform. We are working on a paper that interprets the Brigantian strata of the Derbyshire and North Wales, which certainly references this paper, however the focus of this paper is the Asbian strata (lines 68 to 70).

Other explanations of the embayed northern margin of the Derbyshire carbonate platforms than just collapse are also possible.

The authors have added another sentence to explain how embayments may also have formed, but the authors believe that the texts sufficiently explains that the association with faults and embayments on the northern margin is interpreted because of the linear western margin, which is not associated with faults.

There is a change in stratigraphy along strike associated with embayed margin from Winnats Pass eastward towards Bradwell Dale with a distinct change in the platform margin and architecture.

This is true. But the outcrops at Bradwell Dale are Brigantian (Gawthorpe and Gutteridge 2003 on Bradwell Dale - "these shoals are equivalent to the Monsal Dale or lower part of the Eyam limestone". These outcrops are therefore not included as part of this Asbian description but are certainly de4scribed in our upcoming paper.

If you want a paper that debunks the idea of erosional features on the platform I suggest referring to Ford, T.D. 1987. The origin of the Winnats Pass, Castleton, Derbyshire. Mercian Geologist 10, 241-249.

Unfortunately the authors are unclear on the meaning of this comment and what part of the paper it is referring to.

I accept that the Asbian may not have been totally cyclic from a statistical point of view and stacking patterns may not be the best way to understand cyclicity in this context. But this doesn't mean that things are random, I think if we have a glacio-eustatic forcing mechansim that is higher frequency than the response time of the carbonate system, then we would see glimpsees of a sedimentary 'cyclicity' with superimposed random forcing events (exposure) which might explain the succession we see.

This may be something that we have to agree to disagree on. The paper does not state that the depositional environments are randomly distributed, rather indistinguishable-from-random. The interpretation is not suggesting that there were no cyclic sea level patterns occurring, but they were not preserved, or well preserved, at all in the Asbian strata. The paper outlining this interpretation is already published (Manifold et al., 2020)

A final comment, that needs to be discussed, is that some process, whether it is onset of glacio-eustasty of changing subsidence regime clearly starts at the Holkerian/Asbian boundary as Holkerian carbonates are generally very uniform compared with the complexity of the Asbian.

This is true about the Holkerian carbonates being extremely homogenous and agree that this is worth commenting on. The authors are limited on their comment here because the Holkerian strata is not well studied and was not examined in detail as part of this research. The Holkerian Woo Dale limestone on the whole is understudied in comparison the Asbian strata. Some minor comments have been added to acknowledge the characteristics and tectonic context of the Woo Dale limestone (lines 592-593, 619-622).

Unravelling Evidence for Global Climate Change in Mississippian Carbonate Strata from the Derbyshire and North Wales Platforms, UK

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ABSTRACT

The Mississippian Derbyshire and North Wales carbonate platforms were formed in similar tectonic settings within the Pennine and East Irish Sea Basin, respectively. The Derbyshire Platform was surrounded by sub-basins to the north, west, and south whilst the North Wales Platform, 130 km west, had a simpler land-attached geometry. Comparison of these age-equivalent platforms allows the controls on sedimentation, at an important juncture in Earth history, to be evaluated. Both platforms are dominated by moderate-to-high-energy, laterally discontinuous facies, with weak evidence for facies cyclicity, suggesting multiple controls on deposition. Influx of siliciclastic mud on the North Wales Platform led to perturbations in carbonate accumulation; along with abundant palaeosols and coal beds this implies a more humid climate, or shallower water depths compared to the Derbyshire Platform. On both platforms, exposure surfaces can rarely be correlated over >500 metres except for a regionally correlative palaeokarstic surface at the Asbian-Brigantian boundary. This exposure event appears to coincide with a significant regional facies change. Given the lack of evidence for ordering and cyclicity within the strata, the Asbian-Brigantian boundary may mark a significant event that could reflect onset of a transitional climate, prior to the second glaciation event in the Late Palaeozoic Ice Age.

INTRODUCTION

The Mississippian was an important period of Earth history, when climatic changes were underway as a result of the onset of the Gondwanan glaciation and continental reorganisation associated with the closure of the Rheic Ocean, prior to the Laurentian and Gondwanan collision (Sandberg, 1983; Wright and Vanstone, 2001; Haq and Schutter 2008; Cocks and Torsvik, 2011). Although there was reduced taphonomic diversity in the earliest Carboniferous, following the Frasnian-Fammenian mass extinction, rebound was rapid with the evolution of land plants and insects and a diverse submarine biosphere that dominantly comprised rugose corals, bryozoa, crinoids, brachiopods, and foraminifera (Heckel, 1974; James, 1983; Copper, 1988). The diversification of land plants, increased chemical weathering and mountain building have all been touted as triggers for the onset of the Late Palaeozoic Ice Age (LPIA) (Godderis et al, 2017), but the timing of the formation of ice sheets and the impact of glaciation on sedimentary architecture is still very much debated. There is widespread general acceptance that two periods of ice formation pre-dated the main glaciation in the Pennsylvanian. These ice pulses have been estimated to have occurred during the Tournasian and ~~Visean~~Viséan (Lakin et al., 2016; Liu et al., 2019), with the timing of the onset of the second period of ice-sheet formation estimated to range from ~ 335 Ma (mid-~~Visean~~Viséan; Wright and Vanstone, 2001; Poty, 2016) to ~ 322 Ma (Serphukhovian; Buggish et al., 2008). Evidence for changes in sedimentation on sub-equatorial Mississippian carbonate platforms as a result of glacio-eustacy have focused upon a change from low frequency to high frequency sedimentary cyclicity (Wright and Vanstone, 2000), deep incision of carbonate platforms at unconformities (Smith and Read, 2000) and isotopic perturbations associated with changes in organic carbon burial and denitrification, driven by ocean cooling (e.g. Buggisch et al., 2008; Liu et al., 2019).

~~Visean~~Viséan carbonate platforms in northern Europe are well-studied (e.g. van Hulten and Poty, 2008; Somerville, 2008; Poty et al., 2014; Poty, 2016; Herbig, 2016), and the tectono-stratigraphic evolution of the Pennine – Irish Sea Basin and southern Euramerican continent during the Mississippian is also well established (Cocks and Torvisk, 2011; Fraser and Gawthorpe, 2003). This study is focused upon the Derbyshire and North Wales Platforms, which are situated in the northern UK within the Pennine Basin (Figure 1). During the lower Carboniferous, both platforms were located on the northern margin of the Wales-Brabant Massif and the southern margin of the Pennine – Irish Sea Basin, which was an equatorial, intra-cratonic seaway north of the Rheic Ocean. The Derbyshire Platform is a Viséan (lower Carboniferous) platform with a long history of study (e.g. Wolverson Cope 1936, 1938; Shirley and Horsfield 1940; Stevenson and Gaunt, 1971; Aitkenhead et al., 1985; Harwood, 2005). Most publications, however, are local case-studies, and do not describe the depositional architecture of the whole platform. Moreover, much of the literature pre-dates modern sedimentological paradigms, such as sequence stratigraphy. The North Wales Platform, situated 130 km westwards, is relatively understudied in comparison (Ramsay, 1886; Neaverson, 1930, 1937; Somerville, 1979; Walkden and Davies, 1983; Davies et al., 1989; Davies et al., 2004; Juerges et al., 2015). These two closely situated, coeval platforms provide an excellent opportunity to assess the importance of localised, basinal and global controls on sedimentation, such as proximity to a landmass and volcanism, on carbonate depositional processes in comparison to significant changes in global climate and eustatic sea level resulting from the onset of the LPIA.

GEOLOGICAL SETTING

During the Viséan, ~~,~~ northern England was undergoing pulsed extension (Fraser and Gawthorpe 2003) with carbonate platform growth established ~245 Ma on the footwalls of rotated fault blocks (Ebdon et al., 1990; Fraser et al., 1990). During the Holkerian, the margins of these platforms began to steepen as the result of topographic differentiation between shallow water carbonate platforms and hanging wall basins, with high rates of extension along basement-involved faults (Schofield and Adams, 1985; Fraser and Gawthorpe, 2003). In the seismo-stratigraphic framework developed for the Carboniferous of the Pennine Basin (Ebdon et al., 1990; Fraser et al., 1990; Coward, 1993; Fraser and Gawthorpe, 2003; Figure 2), the Late Holkerian to mid-Asbian are equivalent to Stage EC4. The mid to late Asbian is equivalent to Stage EC5 (Ebdon et al., 1990; Fraser et al., 1990; Fraser and Gawthorpe, 2003) and is the focus of this paper. The North Wales Platform was a land-attached carbonate platform (approximately 1200 km^2) located in the East Irish Sea Basin. The Derbyshire Platform was a distally land attached extension of the East Midlands Platform approximately 100 km east. The platform extends from Castleton (Locality A) in the north to Matlock (Locality C) in the south (approximately 400 km^2) and the whole East Midlands Platform is approximately 5000 km^2. On the Derbyshire

Platform, Stage EC5 is equivalent to the Bee Low Limestone whilst the lithostratigraphic name for EC5 on the North Wales Platform is the Loggerheads Limestone (locally the Great Orme Limestone; Figure 2). During the Asbian (337.5 to 333 Ma; Rohde, 2005) the study area was located in the Tropical Zone at approximately 336°E 14°S (Piper, 1991; Cocks and Torsvik, 2011). The outcrops used in this study are situated on the margin of the Derbyshire Platform around Locality A, near to Castleton, East Midlands, and in proximity to the northern margin of the North Wales Platform, which outcrops as the Great Orme (Locality D) and Little Orme (Locality E) headlands near Llandudno, Conwy (Table 1a; Figure 1; Figure 3). Parallel to the northern margin of the North Wales Platform on the Isle of Anglesey, near Penmon Point (Locality F), facies were also mapped and sampled. Outcrops of the western margin of the Derbyshire Platform are near to Buxton and Hartington (Localities B, I and K). The North Wales platform interior was studied around Cefn Mawr and Llangollen (Localities H and G), 20 and 40 km south of the margin.

METHODS

Facies were mapped at a kilometre scale and logged at a scale of 1 cm : 50 cm across the Derbyshire and North Wales Platforms using natural outcrops, disused quarries, and core (25 sections) (Table 1a). 21 published stratigraphic sections were also used to support observations made from core and outcrop (from Stevenson and Gaunt, 1971; Aitkenhead et al., 1985; Table 1a). No core has been acquired around Localities D, E and F, so all observations of the North Wales Platform were made from outcrop and petrography. Additional localities, which were not logged but are described herein, are also noted (Table 1b). 125 polished and covered sections were prepared and half stained with Alizarin Red S and potassium ferricyanide to distinguish ferroan- and non-ferroan calcite and dolomite (after Dickson, 1965), and porosity. Samples were analysed using transmitted light microscopy and microfacies were classified using the Dunham classification scheme (Dunham, 1962). Quantification of components (matrix, cements, and allochems) was achieved by point counting 300 points of 30 samples using Petrog™. Micropalaeontological analyses of benthic, predominantly fusulinid, foraminifera and calcareous algae were conducted on 29 of the thin sections. A FEI QUANTA 650 scanning electron microscope was used to investigate features potentially below the resolution of transmitted light microscopy. A Bruker D8 Advance X-Ray Diffractometer was used to identify the mineral assemblage of 37 samples of platform exposure-related facies, and of 16 samples of limestone and siliciclastic-influenced bedrock.

RESULTS

~~Facies Association~~Depositional Environments

~~Eight~~ Six ~~facies association~~depositional environments, plus igneous rock formations and exposure-related facies, were identified from outcrop, core, and petrographic analysis of the exposed Asbian succession (Bee Low Limestone on the Derbyshire Platform and Loggerheads Limestone on the North Wales Platform). These are summarised in Table 2, briefly described below and in Figure 4.

Slope/foreslope ~~Facies Association~~Depositional Environment

The foreslope/slope ~~facies association~~depositional environment does not crop out on the North Wales Platform. On the Derbyshire Platform, it comprises two principle facies. On the northern and western margins, a poorly sorted conglomerate, comprising sub-rounded intraclasts of skeletal wack/packstone (0.5 – 10 cm diameter), peloids and fragments of crinoids, bryozoa and brachiopods, forms beds that dip at approximately 30^{o} northwards, towards the Edale Basin (Figure 5A). The fragments and clasts are micritised and coated by 1 – 10 mm thick radiaxial fibrous calcite (Figure 5B; Figure 6A; Table 2; e.g. Bathurst, 1959). Brachiopod moulds are partly-infilled by calcite cement, with sediment at the base of the moulds inclined at approximately 30^{o}. On the northern and western margins, limestone blocks that are several metres in diameter are found. Clean, skeletal grainstones are particularly abundant on the western margin of the Derbyshire Platform (Figure 6B). On the southern margin, beds of skeletal wacke/packstone are locally contorted and dip basinwards at approximately 20° (e.g. Locality 17) (Figure 5C and 5D).

On the northern platform margin, geopetal textures suggest that the steep bedding angle is a true representation of paleo-sedimentary dip. The thick radiaxial fibrous cements that bind clasts and grains typically form syn-depositionally as a result of high energy (wave and storm-driven) flux of seawater (Kendall, 1985; van der Kooij et al., 2010) and can bind non-cohesive material to maintain a steep slope angle (e.g. Kirkby, 1987; Kenter 1990; Della Porta et al., 2003; Bahamonde et al., 2004). The coarse grain size of clasts and skeletal grains, high skeletal diversity and poor sorting is suggestive of short-lived, episodic sediment transport, from a shallow water setting, in response slope failure by gravity or fault movement. The northern margin of the Derbyshire Platform is <1km north of an array of E-W trending faults, thought to be associated with the Edale Fault (Fraser et al., 1990; Fraser and Gawthorpe, 2003; Figure 3), and seismic activity along this fault might have triggered mass transport of sediment on the platform margin. Contorted, more shallow-dipping beds and an absence of large clasts on the southern margin of the Derbyshire Platform are suggestive of soft sediment deformation but a much shallower slope angle than on the northern margin.
The slope/foreslope of the~~This facies association~~ ~~on the~~ North Wales Platform has either been eroded or is not exposed, with the palaeo-platform margin interpreted from seismic data to be offshore of the present coastline (Figure 1; Floodpage, 2001; Pharoah et al., 2018).

Platform Margin ~~Facies Association~~Depositional Environment

The Platform Margin ~~Facies Association~~depositional environment comprises two principle facies which are observed on the margins of the Derbyshire and North Wales Platforms:

1) Carbonate mounds, which occur as massive, dome-shaped structures, ~~that~~ have a distinct core, intramound, and flank facies~~,~~ that ~~which~~ dip at approximately 30 – 40° (Figure 7). They are typically up to 50 m wide and 9 m high and are spaced a few hundred meters to kilometres apart. The core is cemented and dominated by crinoids, brachiopods and bryozoa. Vugs, which are <10 cm wide, are common and can be lined by radiaxial fibrous calcite cement. The intramound facies are bioclastic peloidal wackestone and packstone with a diverse skeletal assemblage (fragmented bryozoa, brachiopods, corals, foraminifera, dasycladacean algae including *Koninckopora*) and a high volume of micrite (Figure 6C - D). No microbial binding was observed in outcrop, thin section, or under SEM. Flank facies include brachiopods floatstones and crinoidal grainstones (Figure 7B, 7C).
2) Skeletal grainstones typically comprise light- or reddish-grey stacked beds and form discontinuous bodies that pinch out in one or more directions. They are either isolated, sheet-like or cross-bedded bodies (<100 m wide, 5 m thick) within thick (>2 m), tabular limestone beds. They dip and pinch in numerous directions (Type A), or downlap onto carbonate mounds (<10 m wide, <10 m thick) and dip obliquely to the mound interface (Type B or "intermound"). Both types of skeletal grainstone are coarse grained (>1 mm) and dominated by crinoid ossicles and large corals (20-30 cm). The skeletal assemblage is moderately sorted (0.2 - 2 mm), and includes disarticulated crinoids, and fragmented brachiopods, bryozoa, foraminifera, undifferentiated skeletal fragments, corals, and demosponge, dasycladacean algae, including *Koninckopora.*

Carbonate mounds are highly characteristic of the Viséan (Nichols, 1961, 1965; Bancroft et al., 1988; Horbury, 1992; Gutteridge, 1990; Gutteridge, 1995; Somerville, 2003). They most closely resemble the Type 2 mounds of Somerville (2003), interpreted to accrete from a crinoid – bryozoan - brachiopod core with abundant cemented micro-peloidal micrite such that structural support by organisms was short lived, and the mound was rapidly cemented. They are the most important constructive facies on the platform margin, but their spacing indicates that they did not form a continuous rim but rather formed isolated structures, or potentially~~-~~, in slightly deeper water (10 – 20 m) basinward of the margin (Harwood, 2005). Some allochems were dissolved and solution-enhanced to form irregular-shaped vugs; since marine cements line these vugs they are inferred to have formed soon after deposition. It is possible that algae stabilised soft sediment in localised, relatively shallow and restricted or protected areas, allowing mound colonisation but there is limited direct evidence for microbial activity ('cryptic evidence' of Pickard, 1996). Following initial colonisation, bryozoa built upwards, trapping transported, fragmented skeletal grains such as crinoids and brachiopods, which were then rapidly cemented to form the intramound facies ('bulk facies' of Bancroft et al., 1988). Opportunistic brachiopods and crinoids then colonised the flanks and top of the mound as it grew into areas of relatively shallow water, (e.g. Bancroft et al., 1988 and Somerville, 2003).

The clean texture with diverse, moderately sorted skeletal grains within the skeletal grainstone facies are indicative of a higher energy depositional setting in clear, shallow water. The preservation of cross-bedding is also indicative of high depositional energy and the pinching geometry of beds is typical of sediments influenced by wave-driven currents (Rankey and Reeder, 2012). These grainstones are interpreted to be platform margin sand-bars deposited on seaward facing platform margin, where the most agitated environments occurred, forming pinching beds shaped by multidirectional wave-energy (*see:* Rankey et al, 2006; Rankey and Reeder, 2012).

Platform Interior ~~Facies Association~~Depositional Environment

The platform interior ~~facies association~~depositional environment~~s~~ mostly comprises thick (0.5 - >3 m) tabular, beds that are laterally continuous for hundreds of metres (Figure 8A). The platform interior comprises a diverse, moderately sorted fine-grained skeletal assemblage of varying abundance (Figure 6E; Table 2) (brachiopods, crinoids, bryozoa, dasycladacean algae, demosponge, gastropods and a diverse range of benthic foraminifera (e.g. Figure 9) with several sub-facies:

1) Mounds which are internally uniform (i.e. lacking a core, intramound, and flank facies) with a low height-to-width ratio (20 m wide and 15 m high) and some weak bedding. They often overly a grainstone body and comprise tightly-stacked, thin-branched (branches approximately 1-2 cm in diameter) *Siphonodendron* corals (colonial rugose coral), some of which are fragmented, within a micrite matrix (Figure 8B).
2) Skeletal grainstones, which are sporadically interbedded and laterally discontinuous, with beds <0.3 m thick and 3-10 m wide. On the Derbyshire Platform, these skeletal grainstones are only observed in drill core from boreholes (e.g. Localities 2, 4 and 8; Table 1a).
3) Fine-grained skeletal wacke/packstone with a diverse, highly fragmented skeletal assemblage and diffuse mottling. This includes the Tollhouse Mudstone Bed, a distinct lithostratigraphic unit on the North Wales Platform which is up to 3.5 m thick, that comprises tabular, parallel beds of skeletal wackestone and mudstone, interbedded with skeletal packstone. Tubular and nodular structures (cm-scale diameter and length) occur at the base of some beds. The matrix is dark-grey/brown containing white skeletal fragments and cm-scale brachiopods. The microfossil assemblage comprises sub-mm diameter benthic foraminifera, brachiopods, crinoids, bryozoa, dasycladacean algae, and corals, with trace serpulidae.

Overall, parallel bedding, high skeletal diversity, and the high degree of grain fragmentation is suggestive of moderate to locally high energy deposition in an unrestricted subtidal environment within the platform interior. Mottling is interpreted to be bioturbation, although there is no preservation of the trace-making organism; it is most likely to be *Phycosiphon* or a similar feeding trace which selectively ingests clay-grade material, and occurs in a range of bathymetric conditions, possibly polychaetes (Gingras et al., 2002). The diffuse edges of the traces suggest that the sediment remained soft and unlithified for a long period. On sedimentary evidence alone, it is difficult to confidently estimate water depth within skeletal packstone facies, but could reflect sedimentation at or around fair weather wavebase. Tubular and nodular structures are burrows, indicating soft sediment reworking of submarine sediment, and suggesting low to moderate energy conditions and gentle winnowing of sediment. The small grain-size and abundance of micrite within skeletal wackestone facies, however, including the Tollhouse Mudstone Bed is indicative of deposition under moderate to low energy conditions by gentle winnowing with abundant dasycladacean algae indicative of water depths of less than 10 m (Jones, 2006).

Platform interior, coral-dominated mounds are rarely described from UK Mississippian platforms (e.g. Aretz and Herbig, 2003) and their low abundance is suggestive of niche environmental conditions. Rugose corals have been described from Carboniferous mounds (e.g. Shen and Webb, 2005; Gong et al, 2012). However they only rarely form the main frame-building organism within similar coral biostromes that have been recognised within the upper ~~Visean~~Viséan of the Dinant Platform (e.g. Aretz and Chevalier, 2007). A high abundance of tightly packed colonial corals is suggestive of localised, higher energy conditions compared to marginal mounds since the skeletal framework indicates an adaptation to high-energy waves or currents. This is consistent with the association of the build-ups with underlying grainstones and fragmentation of corals within the main structure. Corals may have attached to a microbially-stabilised substrate, similar to marginal mounds, on an area of relatively high topography, and thus an environment with shallower, more turbulent waters.

Peritidal ~~Facies Association~~Depositional Environment

The peritidal ~~facies association~~depositional environment is extremely rare and presents as stratiform, but slightly crinkled, and locally pinnacle-shaped microbial boundstone. It is observed at only two localities on the North Wales Platform (Locations G and H). The facies is typically no more than 0.25 m thick (Figure 8D) and includes laminae of alternating yellow-coloured cemented mudstone and white unconsolidated carbonate mud. XRD indicates that the facies comprises 82.8% calcite, 12.9% muscovite, 1.8% quartz, 1.2% halite, 0.7% barite, and 0.5% haematite. The fine lamination of this facies implies an area of very shallow water and the presence of minor halite suggests that at some point the environment was evaporitic. The crinkled nature of the beds and carbonate mud composition is suggestive of a microbial origin. The presence of terrigenous grains indicates the presence of siliciclastic material, accumulated and trapped because the laminite grew in very shallow water.

Exposure ~~Facies Associat~~-related Facies~~ion~~

Exposure-related facies can be categorised into four types, all of which are usually observed associated with each other (Figure 10a): i) pitted/mamillated surfaces (Type A), (ii) tubular and nodular/brecciated horizons (Type B), (iii-v) unconsolidated muds and clays (Type C), and coals (Type D~~;~~). These surfaces punctuate strata 18 to 49 times per 100 m of strata on the North Wales Platform and 8-18 times per 100 m on the Derbyshire Platform, and increase in frequency vertically (Manifold et al. 2020).

Type A surfaces consist of smooth, mamillated bedding surfaces with a wavelength of 0.2-1 m, and up to 10 cm deep, sometimes cross-cutting sedimentary features or infilled by Type C exposure facies. These surfaces can be traced laterally for tens of metres but are discontinuous over hundreds of metres. They are frequent, occurring on average every 10-15 m, but increasing in frequency towards the top Asbian, particularly on the North Wales Platform. In thin section, the platform interior limestones which directly underlie these surfaces are sometimes partly dissolved and replaced by coarse, sparry cements (Figure 6F).

Type B surfaces principally outcrop on the North Wales Platform, are <1.5 m thick and extend laterally for a few hundred metres; occurrences on the Derbyshire Platform are much less common, extensive for less than 100 m, and usually <1 m thick. They comprise nodules of skeletal packstone, 2-5 cm in diameter and are clast-supported, with inter-clastic sparite cement or unconsolidated sediment. This facies is underlain by beds of a similar appearance but with sub-vertical tubular structures, typically 3 cm wide and 25 cm long.

Type C surfaces are 0.05 – 0.8 m thick, often with a lenticular geometry, and can be red, brown, or yellow in colour. They are laterally extensive for tens to a few hundred meters, occurring between beds of platform top strata, Excluding calcite, the average composition of this facies is 32.1% kaolinite, 30.2% muscovite, 30.2% quartz, 7.5% other minerals, principally haematite and feldspars, with minor barite and pyrite. This facies is particularly abundant on the North Wales Platform around Locality D, and is also documented westwards around Anglesey (Howells, 2007). On the Derbyshire Platform, it is not seen in outcrop, but a few examples are well-preserved in core, one sample of which contains plant material and quartz nodules (<2 cm) (Figure 10a(iv)). Type D, coals, form around Localities G and H (Figure 4d) as three bands <1 m thick.

The smooth, mamillated Type A surfaces have been interpreted to form beneath a layer of soil (Walkden, 1974), although soil is rarely preserved on the Derbyshire Platform, or by dissolution by stem-flow around trees (Vanstone, 1996). Where soil is not present, these surfaces may be confused with compactional bedding surfaces and they are most confidently identified when they cross-cut sedimentary features or are associated with another platform exposure-related facies. The cements directly below the surface of Type A facies are mostly formed during meteoric diagenesis, within the meteoric phreatic realm (Walkden and Williams, 1991; Juerges et al. 2016).

Type B cemented nodular limestone is characteristic of calcrete, which forms as limestone precipitates around soil particles and roots to give a brecciated appearance (Durand et al., 2010). The tubular structures which underlie Type B surfaces are interpreted as burrows, rather than rootlets, because they are long, subvertical, lack a consistent structure and contain a coarser grained sediment than the surrounding matrix, which suggests reworking and sediment mixing by living organisms. Their consistent diameter and relatively short length is also inconsistent with rootlets, which often have varying diameters and can be metres in length (Klappa, 1980). Unlike the diffuse, mottled bioturbation within the platform top limestones the excellent preservation of these open burrows suggests the sediment was firm, probably partly cemented, suggesting a relatively shallow-water depth compared to the majority of the platform interior. These traces are most likely formed by shallow deposit-feeding and dwelling crustaceans which colonised the substrate in shallow seas prior to platform exposure.

The abundance of clay and the soft texture of Type C beds, along with their association in outcrop with Type B facies (calcretes) and the presence of plant material and terrestrially-derived minerals (quartz and muscovite), is consistent with them being palaeosols. Their colour is likely linked to the varying extent of iron oxidation of haematite. Type D facies, coal, forms in a narrow area in the southernmost part of the study area on the North Wales platform, and reflects a terrestrially-influenced, swampy environment close to the palaeo-shoreline on the Wales-Brabant Massif.

Extrusive Igneous Rocks ~~Facies Association~~

There were two main volcanic centres on the Derbyshire Platform during the ~~Visean~~Viséan, near Localities B and C (Figure 12; Arnold-Bemrose, 1907; Walkden, 1972), with two types of extrusive igneous rocks identified from outcrop and core. Type A is dark-coloured, mafic (pyroxene-dominated) and fine grained, sometimes contains calcite-filled vesicles (<7 mm). In outcrop, near Locality 13, they have a columnar habit but ordinarily they are massive, bed-parallel and vesicle-rich and have an irregular contact with underling limestone (Figure 10a(vi)). Type B comprises multicoloured, friable clays in core (Figure 10a(vii), and dark coloured clays in outcrop. Published core descriptions indicate that this facies occurs throughout the Asbian at bedding contacts (Walkden, 1972; Cox and Bridge, 1977; Cox and Harrison, 1980; Bridge and Gozzard, 1981; Harrison, 1981). When their occurrence is mapped, the facies shows a NW-SE distribution over the Derbyshire Platform (Figure 12). Beyond the perimeter of this mapped distribution, volcanic ash is not recorded, including on the North Wales Platform.

The fine, pyroxene-rich composition of the Type A lithology, as well as the abundance of calcite-filled vesicles, suggests that they are amygdaloidal basalts. Their occasional columnar habit indicates that the rock locally contracted upon cooling to form vertical joints (e.g. Haldar and Tišljar, 2014). Over forty igneous bodies of this type are preserved in Viséan strata, described as 'scutulum-type' shields (i.e. they formed during a singular eruption; Waters, 1981; de Silva and Lindsey, 2015). The irregular, interfingering contact between the basalts and the limestone suggests magma eruption was syndepositional, or at least pre-lithification (Figure 10b(i)). Although most igneous extrusive beds are interpreted to be deposited subaerially (Waters, 1981), the interaction of lava and unlithified sediment suggests that some were submarine. Type B volcanic facies have clay-sized grains which are suggestive of volcanic ash (consolidated as tuffs). Dark bands observed in outcrop comprise K-bentonite clays ("clay wayboards"; Trewin, 1968; Walkden, 1972; 1974) which are an alteration product of volcanic ash, suggesting that coloured and dark clays are of the same origin.

Siliciclastic ~~Facies Association~~Depositional Environment

No siliciclastic facies were observed on the Derbyshire Platform. On the North Wales Platform, dark grey mudrock forms beds, ~1-metre in thickness, between 1 to 5 metre thick limestone beds (Locality G; Figure 10c) and contain interbedded coal at Locality H. Mudrocks contain no marine bioclasts and often, but not always, overly mammilated (Type A) exposure surfaces. They have sharp lower and upper boundaries with interbedded limestone that are not cross-cut by burrows.

The absence of marine bioclasts within the mudrock suggests it is terrestrial, and its limited distribution, within the Loggerheads Limestone on the southern margin of the North Wales Platform (Location H), is suggestive of riverine influx of mud on the shoreline with the Wales – Brabant Massif. In particular, the association with coal, lack of macro- or microfauna and siliciclastic composition is suggestive of deposition in a low energy, swampy, marginal marine setting and a humid climate. Where mudrocks sharply overly limestone, and there is no intervening emergent surface, it is possible that the mudrock is marine; where it overlies an emergent surface then it could be terrestrial. Sharp upper boundaries indicate that once the clastic incursion event was over, the carbonate factory restarted, implying that changes in relative sea level were minor and certainly insufficient to shut down the carbonate factory by drowning.

Although the Derbyshire Platform was situated a similar distance from the shoreline of the Wales-Brabant Massif as the North Wales Platform (approximately 25 km, Figure 1), siliciclastic sediments did not reach the Derbyshire

Platform. This is likely because the intervening basin, the Widmerpool Gulf (Figure 3), would have trapped northerly-prograding siliciclastic sediment (Trewin and Holdsworth, 1972).

Biostratigraphy

The Tollhouse Mudstone crops out at the base of the Great Orme / Loggerheads Limestone (Figure 2) and is middle to Late Asbian age (EC5) (Biozones Cf6γ1-2; after Conil et al., 1991 and Somerville et al., 2008). The Loggerheads Limestone contain a typical Asbian microfaunal assemblage comprising dasycladacean green and coralline red algae (e.g. *Coelosporella* spp., *Koninckopora inflata* and *Ungdarella* spp.), palaeoberesellids (e.g. *Kamaenella* spp.), calcispheres (e.g. *Calcisphaera laevis* and *Calcisphaera pachysphaerica*) and benthic foraminifera including *Archaediscus angulatus*, *Bibradya* spp., *Cribrospira panderi*, *Cribrostomum* spp., *Endothyra phrissa*, *Eostaffella prisca*, *Forschia* spp., *Lituotubella glomospiroides*, *L. magna* and *Omphalotis omphalota.* On macrofaunal evidence, the Loggerheads Limestone is interpreted to have been deposited within a shallow, platform interior setting. The abundance of *Koninckopora*, *Ungdarella* and palaeoberesellids, as well as endothyroid foraminifera with multi-layered tests, specialised chamber partitions and cribrate apertures (i.e. *Bibradya* spp., *Cribrospira panderi*, *Cribrostomum* spp. and *Nevillea* spp.) and large thick-walled forschiids (*Forschia* spp.) within this unit suggest deposition in high-energy pseudo-algal meadows marginally below to above fair-weather wave base, in water depths of approximately 5 to 15 m (e.g. Gallagher, 1998; Gallagher and Somerville, 2003).

On the Derbyshire Platform, both the Bee Low Limestone and basal section of the overlying Monsal Dale Limestone (Brigantian) contain a typical Asbian microfaunal assemblage comprising dasycladacean green algae, palaeoberesellids, calcispheres and benthic foraminifera similar to that described the North Wales Platform. The texture and fabric of the Bee Low Limestone has been interpreted to reflect winnowing and bioturbation in a moderate energy setting, at or around, fair-weather wave base. The abundance of the foraminifera *Howchinia* spp., *Palaeotextularia* spp., *Pseudoendothyra* spp. (including *P. struvii*), *Tetrataxis conica* and *Vissariotaxis* spp. in samples from both the northern and north-western platform margin (Localities 11, 18, I) and platform interior (Locality J) of the Derbyshire Platform are consistent withrelatively low hydrodynamic energy (e.g. Gallagher, 1998; Gallagher and Somerville, 2003) and may suggest deposition below fair-weather wave base (between 15 m and 25 m). The western margin of the Derbyshire Platform is interpreted to be shallower, higher energy (e.g. Locality K) than the northern or southern margin on the basis of the abundance of dasycladacean green algae.

Asbian – Brigantian boundary

The boundary between the top of the Asbian and the base of the Brigantian is recognised across the Derbyshire and North Wales Platform, in both outcrop and core (Figure 11). It usually manifests as an irregular, pitted surface that resembles Type A facies (of the Exposure ~~Facies Associatio~~-related facies~~n~~), but pits are often deep (up to 1 metre), with a greater depth / width ratio than other mamillated surfaces. The surface can usually be walked out over the length of an outcrop, and on the North Wales Platform is also associated with Type C (usually reddened) palaeosols). On both platforms, there is a marked change of facies across the Asbian – Brigantian boundary, from clean, light coloured packstones with frequent emergent surfaces to darker, more chert rich packestones with abundant *Gigantoproductids*, and fewer emergent horizons (Manifold, 2019). On the Derbyshire Platform, the Asbian – Brigantian boundary is commonly also picked lithostratigraphically at the top of the Lower Matlock lava, whilst the top Asbian in the Eyam and Duffield boreholes is defined at the top of an agglomerate and dolerite sill, respectively (Chisholm et al., 1983; Waters, 2009).

DISCUSSION

Controls on Platform Architecture

An E - W oriented correlation using outcrop data from across the Derbyshire and North Wales Platforms was constructed using the biostratigraphic data (Figure 13). Biostratigraphic correlations have been published previously (Vaughan, 1905; Garwood, 1913; Conil et al., 1979; Strank et al., 1981; Waters et al., 2009) and the new data from this study supplements that interpretation. In particular, it differentiates a significant period of platform exposure and absence of carbonate deposition at the Asbian – Brigantian boundary, which was used as a datum for correlation because it can be confidently correlated across both the platforms.

Palaeo-wind direction

The dip angle of beds and the geopetal textures within slope facies from the northern margin of the Derbyshire Platform indicate a palaeo-dip on the platform slope of 30°. This is consistent with previous interpretations (Broadhurst and Simpson, 1967; Simpson and Broadhurst, 1969; Broadhurst and Simpson, 1973; Fraser et al. 1990; Gutteridge, 1991; Harwood, 2005), but is shown here to have resulted from stabilisation of the remobilised debris, as well as microbial boundstones (Harwood, 2005), by syn-depositional radiaxial fibrous calcite cementation. These cements precipitate as a result of wave and storm- facilitated seawater flux (Kirkby, 1987; Kenter 1990; Della Porta et al., 2003; Bahamonde et al., 2004; van der Kooij et al., 2010). Miller and Grayson (1982), Smith et al., (1985) and Gutteridge (1987) all interpreted the Derbyshire Platform to be a southward-dipping fault block, but Schofield (1982) and Gawthorpe and Gutteridge (1990) infer the northern margin to be leeward. On the north and west of the Derbyshire Platform, platform margin build-ups might have developed in response to footwall rotation, basinal currents or other environmental controls, and this combined with preferential cementation would have contributed to steepening of the platform margin. However, these features are also consistent with a windward-facing margin; a feedback mechanism can be interpreted between the moderately high energy setting, optimal carbonate productivity and platform margin steepening by ~~platform margin~~ cementation. In contrast, the southern margin of the Derbyshire Platform shows no evidence of extensive marine cementation, all measured sedimentary dips were less than 20°, and sediments were dominated by slumped skeletal grainstone facies, with no evidence of debrites. These features are all suggestive of a leeward margin. In particular, the absence of marine cements on the southern platform margin means that coarse sediment could have been transported southwards, with slumping of cohesive floatstone-rudstones down-slope.

The interpretation of a NW to SE directed wind direction seems counter-intuitive given the palaeogeographical setting; the study area was south of the equator during the late ~~Visean~~Viséan and global wind direction would therefore be expected to be from east to west (i.e. south – east trade winds). However, the Pennine Basin was a protected seaway, with a narrow eastward connection to the Rheic Ocean, with ~~and~~ a large landmass to the north (Cocks and Torsvik, 2011). Combined with Variscan mountain-building to the south of the study area, perturbations to the global wind patterns could have developed, and might have created a dominant NW to SE wind direction in the southern Pennine Basin. This is supported by mapped distribution of wind-dispersed volcanic ash (Figure 12).

Controls on platform margin morphology

Carbonate mounds crop out every few hundred metres to kilometres along the northern and western margin of the Derbyshire Platform and the northernmost outcrop of the North Wales Platform, with flanking and inter-fingering grainstone shoals. The western margin is dominated by extensive (<500m² wide, <5 m thick) clean *Koninckopora* grainstones. The northern margin of the Derbyshire Platform is embayed, with each embayment being approximately 1-2 km wide, separated by promontories that are a few hundred metres wide, in agreement with Ford (1987) and Harwood (2005). The western margin of the Derbyshire Platform is more linear, even though it is also windward-facing. The processes governing the morphology of the platform margin cannot be confidently determined, but it is tentatively suggested that embayments formed because of mass wasting or episodic collapse of the slope/margin as a result of movement along the Edale Fault. Embayments could also have formed as a result of syn-depositional, wave-driven, erosional processes, although the western margin may be expected to host embayments in this scenario. In contrast, the western margin is not underlain by a deep-seated crustal lineament, and it appears to retain a linear profile.

The Derbyshire Platform has previously been described as rimmed (e.g. Smith et al., 1985; Gutteridge, 1991) but the dispersed distribution of mounds and shoals suggests that build-ups were less laterally continuous than previously assumed. The depths at which mounds grew is also unclear; Harwood (2005) suggested water depths of 10 to 20 metres. Mound growth might have been assisted by wave-driven circulation of sea-water; displacement of corals from mounds on the northern margin on the Derbyshire Platform (e.g. Locality 15), and reworking into shoals implies episodic storm-related sedimentation. If so, this provides further support for this being a higher-energy, windward-facing margin than the southern platform margin. The basinward margin of the North Wales Platform is not present, because of erosion and the position of the present day shoreline.

Grainstone shoals on the northern margin of the Derbyshire Platform are not laterally continuous, as described in many modern, open ocean-facing platforms (Rankey, 2006; Rankey and Reeder 2012). Instead, they form bedded units up to 10 m thick that extend laterally for up to 50 m, passing into parallel-bedded platform interior facies. This would suggest that grainstone bodies were spatially restricted, perhaps because mounds flourished first, limiting shoals to intermound areas. Mounds may have become well established because local environmental conditions favoured microbial stabilisation of the mound core, in localised, slightly protected shallow waters. Alternatively, mounds developed within protected, lower energy areas between shoals. Embayments along the platform margin may have also spatially restricted shoal development and affected margin bathymetry; Broadhurst (1973) suggested undulating bathymetry led to faunal variation across the margin, but this was not observed here and the macrofauna (brachiopods, bryozoa, crinoids, *Siphonodendron* corals) occur at a range of water depths and are consistent with low levels of environmental stress (Ryland, 1970; Brand et al., 1989; Billing, 1991; Fedorowski, 2008).

On the western margin of the Derbyshire Platform, the shoals are laterally extensive (>3 km^2; e.g. Locality K). They are interpreted to have been deposited in shallower, higher energy, water than the northern margin, because of their cleaner texture and the abundance of *Koninckopora,* which indicate water depths of less than 10 m (Jones, 2006). The linear morphology of the western margin suggests that there were fewer embayments and therefore the geometry and distribution of the shoals was more likely controlled by the geometrical architecture of the margin, and resultant bathymetric variations. This interpretation contrasts with Gawthorpe and Gutteridge (1990) who interpreted that shoals developed during marine transgressions, suggesting a temporal control on sedimentary architecture.

Controls on facies distribution on the platform top

The platform interior facies of the Derbyshire and North Wales Platforms are characterised by bedded limestones punctuated by exposure surfaces. Between these surfaces, sedimentary texture and macrofaunal assemblages indicate a moderate - energy, subtidal platform interior setting, with deposition at, or potentially below, fair-weather wave base~~,~~. These facies then pass up into ~~shallowing~~ shallower, ~~up into~~ higher energy, wave-influenced facies capped by mamillated surfaces and/or calcretes or palaeosols. Peritidal facies are rarely preserved in Asbian strata, with only one clear example (Figure 8D; North Wales Platform), either because they never formed, perhaps due to a rapid fall in relative sea-level (e.g. Wright, 1986; Heckel, 1990; Wright, 1992), or because they were deposited and then removed by erosion. In contrast, south of the Wales – Brabant Massif, peritidal facies were common at this time (e.g. Poty et al., 2014). This ~~is~~ marked constrast is facies between the platforms that north and south of the Wales-Brabant Massif is surprising if sediment-stacking is indicative of~~despite stacking patterns that have been interpreted to represent~~ glacio-eustatic cycles (Wright and Vanstone, 2001; Poty, 2016~~), as has similarly been interpreted for the Mississippian in the UK~~) (~~Wright and Vanstone, 2001~~). The very rare occurrence of peritidal sediments amongst all the localities in this study suggests, therefore, that they almost never formed, and the laminites identified on the North Wales Platform are likely to reflect areas of locally high topography, providing a shallow-water environment for microbial organisms to colonise.

Although there is microfaunal evidence that deposition was in slightly deeper water on the Derbyshire Platform, compared to the North Wales Platform, there is no significant difference in carbonate facies between the two platforms. This is despite extensive syn-depositional volcanism on the Derbyshire Platform, and the proximity of the Wales – Brabant Massif to the North Wales Platform. The exception to this is towards the shoreline of the North Wales Platform, where coal and mudrock becomes common above exposure surfaces and mudrock is interbedded with limestone, creating more complex vertical stacking than further offshore. Overall, the limitation of interbedded mudrock to the southern margin of the North Wales Platform suggests that the influx of clastic sediment from the Wales – Brabant Massif did not supress carbonate productivity substantially across most of the North Wales Platform during the Asbian. This might be because the platform interior experienced moderate to high energy conditions, as (demonstrated by the high abundance, high diversity foraminiferal and algal assemblage such as *Koninckopora*, *Ungdarella*, palaeoberesellids, endothyroid foraminifera, *Bibradya* spp., *Cribrospira panderi*, *Cribrostomum* spp. and *Nevillea* spp., *Forschia* spp.), facilitating distribution of mud. Alternatively~~, or because~~ clastic sediment supply to the shoreline was localised and of insufficient volume to impact carbonate productivity.

Logging and mapping of facies distribution shows that all platform interior facies can be positioned adjacent, parallel, and/or interbedded with one another (Figure 4; Manifold et al., 2020). Lithofacies and exposure surfaces/facies can rarely be walked out for more than a few hundred metres in outcrop across both platforms. Manifold et al. (2020), argued that the lack of ordering/cyclicity was not because of missing facies, but because of the differing arrangement of facies between exposure events across the study area. Based on stratigraphical and statistical forward modelling, ~~they~~ Manifold et al (2020) interpreted facies on the Derbyshire and North Wales Platforms to be a mosaic (after Burgess and Pollitt, 2011 and Burgess, 2016). This conclusion is supported by the laterally discontinuous nature of exposure surfaces and facies in outcrop and suggests that factors other than relative sea-level fluctuation, such as changes in productivity, water quality, and self-organisation of strata, controlled facies distribution (Wright and Burgess, 2005). For example, platform interior float-rudstone facies, with an abundant and diverse assemblage of bryozoa, brachiopods, crinoids, and *Siphonodendron* corals, could have been established in response to optimal environmental conditions (Ryland, 1970; Brand et al., 1989; Billing, 1991; Fedorowski et al., 2008). Fluctuations in intensity of wave- and storm-driven currents, could also have been important, given the small size of both the Derbyshire and North Wales Platforms (approximately 5000 km^2), compared to some modern platforms (e.g. the Great Bahama Bank, approximately 175,000 km^2; Schlager and Ginsburg, 1981). The absence of a continuous rim on the platform margin would mean that corridors for these currents may have formed between mound communities, which would otherwise have absorbed wave energy. Overall, this has important implications for correlation of facies and interpretations of cyclicity. Shirley and Horsfield (1940) recognised that faunal bands (e.g. "Girvanella band") are not independently appropriate for correlation, because the same biota occur numerous times within the vertical succession of strata. Other biostratigraphic indicators, such as foraminifera, are long-ranging and often bridge the Asbian and Brigantian (e.g. Sevastopulo and Barham, 2014). For this reason, stacking patterns have often been used to interpret cyclicity (e.g. Wright and Vanstone, 2001; Poty, 2016), but if facies are not systematically distributed in an ordered fashion, then ~~facies association~~depositional environments cannot be used to correlate age-equivalent strata in a predictive manner. In summary, it seems unlikely that facies distribution between reliably dated, age-equivalent surfaces on the Derbyshire and North Wales Platforms, and equivalent aged strata on other platforms, cannot be predicted from deterministic models that assume ordered, systematically stacked facies.

Processes controlling platform exposure

Exposure events on the North Wales Platform are preserved as palaeokarstic surfaces, palaeosols, calcretes, and coals, and punctuate strata more frequently (18 to 49 times per 100 m of strata) than on the Derbyshire Platform (8-18 times per 100 m; Manifold et al., 2020). On average, platform exposure occurred approximately every 0.04 – 0.2 My, based on a 4.5±1.5 My duration for the Asbian (Rohde, 2005) and a total stratal thickness averaging at 180 m on both platforms. On the Derbyshire Platform, exposure events are typically mamillated surfaces and volcanic ashfalls, with palaeosols only observed in core (Locality 7; Table 1a). These exposure events are well-described and interpreted (e.g. Walkden and Davies, 1983; Walkden, 1972; 1974; Vanstone, 1998), but there has previously been no holistic attempt to explain the heterogeneity in the distribution of exposure events between the two time-equivalent platforms.

The most obvious difference between the two platforms is that volcanic ashfalls were restricted to the Derbyshire Platform because this is where the active volcanic centres were located. Furthermore, since the wind direction is interpreted to have been towards the southeast, ash would not have been transported westwards, towards the North Wales Platform. There are, however, other differences in the composition and style of exposure surfaces between the two platforms that cannot just be related to differences in volcanic activity. The abundance of well-developed calcretes on the North Wales Platform suggest arid or semi-arid conditions (Durand et al., 2010), but palaeosols, palaeokarstic surfaces, and coals are more indicative of humid or semi-humid conditions (Wright, 1980; Arnold, 2013). The presence of interbedded mudrocks near the palaeo-shoreline on the North Wales Platform also indicates that there was sufficient rainfall for rivers to transport and deposit siliciclastic sediments. These events may have also caused the water table to rise to form swamps, leading to localised formation of coal. These interpretations together suggest that on the North Wales Platform the climate oscillated between humid and arid (Wright, 1980; Falcon-Lang, 1999a and b), or spatially, with wet and dry areas. Since calcretes are commonly interbedded with palaeosols, climatic oscillations are considered more likely than localised climatic variability controlling spatial variation in the type of emergent surface. On the Derbyshire Platform, calcretes are present locally, but are thin and much less common than on the North Wales

Platform, whilst palaeosols are very rare and mudrock and coals are absent. Whether mamillated surfaces formed beneath soils (e.g. Walkden, 1972), which were subsequently removed, or from stemflow around trees (e.g. Vanstone, 1996), the inference is that semi-arid conditions persisted on the Derbyshire Platform during the Asbian.

It is therefore possible that there was a different climate than on the North Wales Platform, with ~~more~~ less frequent periods of humidity than further ~~east~~west. Alternatively, the Derbyshire Platform was not exposed as frequently, and perhaps for shorter periods, as suggested by the lower frequency of exposure surfaces on the Derbyshire Platform compared to the North Wales Platform. This could have occurred if carbonate sedimentation took place in deeper water than the North Wales Platform. It has been noted that the benthic foraminiferal assemblage (*Howchinia* spp., *Palaeotextularia* spp., *Pseudoendothyra* spp. (including *P. struvii*), *Tetrataxis conica* and *Vissariotaxis* spp.) on the Derbyshire Platform implies slightly deeper water than the North Wales Platform, which is consistent with its more distal location within the Pennine Basin, relative to the Wales – Brabant Massif. A similar conclusion, which highlighted the importance of bathymetry on exposure surface development across seven carbonate platforms of Carboniferous of the UK, was reached by Vanstone (1996). Given the similarity of facies and fauna between the two platforms, and the comparable thickness of Asbian strata (approximately 200 m; e.g. Aitkenhead et al., 1985) variation in water depths may have been driven by the natural topography of the basement and/or differential subsidence, rather than differences in carbonate productivity. The underlying basement was mapped by a gravity survey on the Derbyshire Platform and has been interpreted to strongly control the thickness of the overlying limestones (Maroof, 1976). Discerning the definite control on differential bathymetry is beyond the scope of this project, but it is perhaps logical that the distally land-attached Derbyshire Platform would have grown in deeper water than the land-attached North Wales Platform.

Global climatic changes recorded in the Pennine Basin

The Mississippian marks a critical point in Earth's history, as the proliferation of land plants led to a decrease in pCO_2 and global tectonic reorganisation led to continental amalgamation, modification of ocean circulation patterns, global cooling and transition from a greenhouse to an icehouse climate (Mii et al., 1999; Smith and Read, 2000; Barham et al., 2012; Qiao and Shen, 2015; Oehlert et al., 2019). Ice advance and retreat was initiated in the Mississippian, with two principal perturbations, one in the Tournasian (approximately 355 - 350 Ma) and one in the late Viséan to early Serphukovian (Mii et al., 1999; Buggisch et al., 2008; Armendariz et al., 2008; Montanez and Poulsen, 2013; Godderis et al., 2017; Oehlert et al., 2019; Rosa et al., 2019). The frequency and amplitude of sea level fluctuation apparently increased after each of these events, with the transition to full icehouse conditions in the Pennsylvanian (Mii et al., 1999; Montanez and Poulsen, 2013).

In northern England and Belgium, the onset of the 2nd phase of Mississippian glaciation has been related to preservation of high frequency cyclothems in the upper Asbian (Wright and Vanstone, 2001; Barham et al., 2012; Poty, 2016). This in part has been interpreted because of the contrast in stacking pattern to less apparently cyclic strata in the underlying Holkerian (EC4) (~~REF~~Schofield and Adams, 1985). There is little consensus on the duration of sea-level changes during the Asbian (Barnett et al., 2002) with estimates ranging from 0.1 My to 0.4 My (Horbury, 1989; Vanstone, 1996; Wright and Vanstone, 2001; Smith and Read, 1999, 2000). The frequency of platform exposure determined for Asbian strata in this study (0.04 – 0.2 My) is broadly consistent with fifth-order glacioeustatic oscillations (after Van Wagoner et al., 1990; Barnett et al., 2002 and references therein). However, the lack of ordering of strata, lateral discontinuity of exposure surfaces (over <500 metres) and sharp contacts between mudrock and limestone on the North Wales Platform calls into question the evidence for cyclicity within the upper Asbian. All of these features can be interpreted as the result of autogenic processes rather than systematic changes in relative sea level. A common argument used to support rapid, glacial-drive sea level fall, is the near-absence of peritidal facies (Wright, 1992). However, the strong evidence for a semi-arid to humid climate on the North Wales Platform, and the more distal location of the Derbyshire Platform suggests that peritidal facies did not form because of the depositional setting, not as a result of rapid changes in relative sea level. In contrast, peritidal facies are well preserved within cyclothems to the south of the Wales-Brabant Massif (Poty et al., 2014; Poty, 2016), suggesting that where peritidal facies were deposited, they were preserved. The presence of short-lived exposure events truncating slightly deeper water platform interior facies on the Derbyshire Platform could be indicative of some allogenic forcing of relative sea level, but the discontinuity of the dominant Type A surfaces suggests emergence was short-lived and localised. It is also noteworthy that forward modelling of carbonate platform growth during icehouse periods indicates that the rapid rise in sea level during interglacials can lead to suppression of carbonate sedimentation and even platform drowning (Paterson et al., 2006; Masiero et al., 2020). There is no indication of such events in either of the platforms studied here or within age-equivalent strata south of the Wales-Brabant Massif (Poty et al., 2014) where facies above emergent surfaces are subtidal, and deposited in water depths around or above fair weather wave base. Furthermore, Paterson et al (2006) show that subsidence is a critical control on the morphology of carbonate platforms under the influence of glacio-eustacy, resulting in different sedimentary stacking patterns in areas of high subsidence – where there is more complete preservation of stratigraphy. In contrast, areas of lower subsidence can exhibit 'missed beats', formed by continued emergence of a platform top, even during sea level rise. The Holkerian was a tectonically quiescent period, between rift events, and movement along bounding faults that would have facilitiated footwall uplift and rotation (Fraser and Gawthorpe, 2003). It is possible, therefore, that the stacking patterns observed within the upper Asbian are in part driven by fault-controlled uplift . Furthermore, it can~~This could~~ – tentatively – be ~~imply~~ implied that there are fewer emergent surfaces and greater preservation of strata on the Derbyshire Platform as a result of greater differential subsidence there compared to the North Wales Platform.

In summary, the data from this study and Manifold et al. (2020), suggests that evidence for systematic stacking and ordered parasequence development in the Asbian is less strong than has been previously invoked, calling into question the interpretation that the mid-Asbian marks the onset of fourth-order glacio-eustatically controlled cyclicity. Nevertheless, the increase in frequency of exposure surfaces, and decrease in bed thickness, up-section towards the Asbian - Brigantian boundary implies a decrease in accommodation space, consistent with a reduced rate of relative sea level rise across the basin. The Asbian – Brigantian boundary is a regionally correlatable karstic surface on both the Derbyshire and the North Wales Platforms, as well as in north Lancashire (Horbury, 1992) indicating that both platforms were exposed for some considerable time (Figure 11). It coincides with a number of important changes within the Pennine Basin, including a period of rifting and volcanism on the Derbyshire Platform (Fraser and Gawthorpe, 2003; Waters, 2009) and the influx of siliciclastic sediment in the northern Pennine Basin (so-called Yoredale Cycles; Tucker et al., 2009). It is also coincident with the diversification of *Gigantoproductid* brachiopods (Nolan et al., 2017). On the Namur-Dinant Platform carbonate sedimentation stopped during the Brigantian (Poty, 2016) whilst in the Rhenish Kulm Basin a sea level fall at the Asbian – Brigantian boundary is interpreted (Herbig, 2016). Therefore, although the hiatus could be indicative of significant, but still tectonically-controlled, basinal events, its recognition elsewhere in Europe, Russia as well as north America means that it could also be interpreted as a third – order sequence boundary associated with global cooling, as proposed by a number of previous studies (e.g. Smith and Read, 2000; Armendariz et al., Barnett et al., 2002; Giles, 2009; Qiao and Shen, 2015). Recent work suggests full icehouse conditions were not established until the very latest Mississippian (Serphukovian) or early Pennsylvanian (Montañez and Poulsen, 2013 and references therein), but the Asbian – Brigantian boundary perhaps provides the first indication of a critical change in global climate, associated with earliest stages of cooling, prior to the formation of peripolar ice formation in southern Gondwana (Montanez and Poulsen, 2013).

CONCLUSIONS

1) During the Asbian, healthy carbonate platform growth took place on the Derbyshire and North Wales platforms, with moderate- to high-energy conditions on the platform top sustained by a dominant north-westerly wind and currents driven through embayments and discontinuous facies belts on the platform margin.
2) Slope and platform margin stabilisation took place on windward (northern and western) margins by precipitation of radiaxial fibrous calcite cements, forming slope angles of 20 to 30^{o}. These margins were subject to periodic, tectonically-induced margin and slope collapse, forming embayments. Margins which did not parallel active faults are more likely to be linear. Leeward margins dipped less steeply, with basinward transport of cohesive sediment by slumping and gravity flow.
3) Carbonate productivity was strongly controlled by a range of environmental factors, not just water depth, such that facies form a mosaic with laterally discontinuous exposure surfaces that cannot be correlated for more than a few hundred metres in outcrop. Micro- and macrofaunal ranges are long, such that in combination it is

not possible to identify regionally extensive faunal bands or sedimentary surfaces that can be correlated within the Asbian succession across the region of study.

4) On the Derbyshire Platform, syn-depositional volcanism produced extrusive lavas and volcanic ash deposits that are interbedded with Asbian limestone strata, but neither are seen on the North Wales Platform. On the North Wales Platform, periodic incursions of sandstone occur towards the top of the Asbian, sourced from landmasses to the south and west of the platform. Although fine grained siliciclastic mud incursions occurred on the palaeo-shoreline of the North Wales shoreline, it did not have a detrimental effect on carbonate productivity on the platform as whole.
5) Exposure events are less frequent, and surfaces less mature, on the Derbyshire Platform compared to the North Wales Platform, suggesting that sedimentation on the Derbyshire Platform occurred on deeper water and therefore had fewer, shorter exposure events. The succession of calcretes, palaeosols, mammilated surfaces, and rare coals, on the North Wales Platform indicate climate fluctuations between semi-arid and semi-humid conditions. These more frequent periods of platform exposure do not seem to have decreased the keep-up capacity of the platform because shallow-water platform top Asbian strata on both platforms are approximately 200 m thick.
6) In the latest Asbian, a sustained period of platform exposure created a regionally correlatable, relatively deep-cutting mamillated surface. A marked change in facies occurs above this surface, which is also present to the north of the study area, marked by the onset of the Yoredale depositional system. This suggests that it is the most reliable datum for correlation across the Pennine Basin
7) As well as having regional significance, the Asbian – Brigantian boundary could have greater global significance than has been acknowledged in recent years, potentially marking the onset of global cooling that had a marked environmental effect on subsequent carbonate platform growth. Given the lack of evidence for ordering and cyclicity within Asbian strata on the Derbyshire and North Wales Platform, it is proposed that the Asbian – Brigantian boundary is a stronger indicator the climatic transition associated with the second glacial advance of the Late Palaeozoic Ice Age, and potentially the onset of fourth-order glacio-eustacy.

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Unravelling Evidence for Global Climate Change in Mississippian Carbonate Strata from the Derbyshire and North Wales Platforms, UK

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ABSTRACT

The Mississippian Derbyshire and North Wales carbonate platforms were formed in similar tectonic settings within the Pennine and East Irish Sea Basin, respectively. The Derbyshire Platform was surrounded by sub-basins to the north, west, and south whilst the North Wales Platform, 130 km west, had a simpler land-attached geometry. Comparison of these age-equivalent platforms allows the controls on sedimentation, at an important juncture in Earth history, to be evaluated. Both platforms are dominated by moderate-to-high-energy, laterally discontinuous facies, with weak evidence for facies cyclicity, suggesting multiple controls on deposition. Influx of siliciclastic mud on the North Wales Platform led to perturbations in carbonate accumulation; along with abundant palaeosols and coal beds this implies a more humid climate, or shallower water depths compared to the Derbyshire Platform. On both platforms, exposure surfaces can rarely be correlated over >500 metres except for a regionally correlative palaeokarstic surface at the Asbian-Brigantian boundary. This exposure event appears to coincide with a significant regional facies change. Given the lack of evidence for ordering and cyclicity within the strata, the Asbian-Brigantian boundary may mark a significant event that could reflect onset of a transitional climate, prior to the second glaciation event in the Late Palaeozoic Ice Age.

INTRODUCTION

The Mississippian was an important period of Earth history, when climatic changes were underway as a result of the onset of the Gondwanan glaciation and continental reorganisation associated with the closure of the Rheic Ocean, prior to the Laurentian and Gondwanan collision (Sandberg, 1983; Wright and Vanstone, 2001; Haq and Schutter 2008; Cocks and Torsvik, 2011). Although there was reduced taphonomic diversity in the earliest Carboniferous, following the Frasnian-Fammenian mass extinction, rebound was rapid with the evolution of land plants and insects and a diverse submarine biosphere that dominantly comprised rugose corals, bryozoa, crinoids, brachiopods, and foraminifera (Heckel, 1974; James, 1983; Copper, 1988). The diversification of land plants, increased chemical weathering and mountain building have all been touted as triggers for the onset of the Late Palaeozoic Ice Age (LPIA) (Godderis et al, 2017), but the timing of the formation of ice sheets and the impact of glaciation on sedimentary architecture is still very much debated. There is widespread general acceptance that two periods of ice formation pre-dated the main glaciation in the Pennsylvanian. These ice pulses have been estimated to have occurred during the Tournasian and Viséan (Lakin et al., 2016; Liu et al., 2019), with the timing of the onset of the second period of ice-sheet formation estimated to range from ~ 335 Ma (mid-Viséan; Wright and Vanstone, 2001; Poty, 2016) to ~ 322 Ma (Serphukhovian; Buggish et al., 2008). Evidence for changes in sedimentation on sub-equatorial Mississippian carbonate platforms as a result of glacio-eustacy have focused upon a change from low frequency to high frequency sedimentary cyclicity (Wright and Vanstone, 2000), deep incision of carbonate platforms at unconformities (Smith and Read, 2000) and isotopic perturbations associated with changes in organic carbon burial and denitrification, driven by ocean cooling (e.g. Buggisch et al., 2008; Liu et al., 2019).

Viséan carbonate platforms in northern Europe are well-studied (e.g. van Hulten and Poty, 2008; Somerville, 2008; Poty et al., 2014; Poty, 2016; Herbig, 2016), and the tectono-stratigraphic evolution of the Pennine – Irish Sea Basin and southern Euramerican continent during the Mississippian is also well established (Cocks and Torvisk, 2011; Fraser and Gawthorpe, 2003). This study is focused upon the Derbyshire and North Wales Platforms, which are situated in the northern UK within the Pennine Basin (Figure 1). During the lower Carboniferous, both platforms were located on the northern margin of the Wales-Brabant Massif and the southern margin of the Pennine – Irish Sea Basin, which was an equatorial, intra-cratonic seaway north of the Rheic Ocean. The Derbyshire Platform is a Viséan (lower Carboniferous) platform with a long history of study (e.g. Wolverson Cope 1936, 1938; Shirley and Horsfield 1940; Stevenson and Gaunt, 1971; Aitkenhead et al., 1985; Harwood, 2005). Most publications, however, are local case-studies, and do not describe the depositional architecture of the whole platform. Moreover, much of the literature pre-dates modern sedimentological paradigms, such as sequence stratigraphy. The North Wales Platform, situated 130 km westwards, is relatively understudied in comparison (Ramsay, 1886; Neaverson, 1930, 1937; Somerville, 1979; Walkden and Davies, 1983; Davies et al., 1989; Davies et al., 2004; Juerges et al., 2015). These two closely situated, coeval platforms provide an excellent opportunity to assess the importance of localised, basinal and global controls on sedimentation, such as proximity to a landmass and volcanism, on carbonate depositional processes in comparison to significant changes in global climate and eustatic sea level resulting from the onset of the LPIA.

GEOLOGICAL SETTING

During the Viséan, northern England was undergoing pulsed extension (Fraser and Gawthorpe 2003) with carbonate platform growth established ~245 Ma on the footwalls of rotated fault blocks (Ebdon et al., 1990; Fraser et al., 1990). During the Holkerian, the margins of these platforms began to steepen as the result of topographic differentiation between shallow water carbonate platforms and hanging wall basins, with high rates of extension along basement-involved faults (Schofield and Adams, 1985; Fraser and Gawthorpe, 2003). In the seismo-stratigraphic framework developed for the Carboniferous of the Pennine Basin (Ebdon et al., 1990; Fraser et al., 1990; Coward, 1993; Fraser and Gawthorpe, 2003; Figure 2), the Late Holkerian to mid-Asbian are equivalent to Stage EC4. The mid to late Asbian is equivalent to Stage EC5 (Ebdon et al., 1990; Fraser et al., 1990; Fraser and Gawthorpe, 2003) and is the focus of this paper. The North Wales Platform was a land-attached carbonate platform (approximately 1200 km^2) located in the East Irish Sea Basin. The Derbyshire Platform was a distally land attached extension of the East Midlands Platform approximately 100 km east. The platform extends from Castleton (Locality A) in the north to Matlock (Locality C) in the south (approximately 400 km^2) and the whole East Midlands Platform is approximately 5000 km^2. On the Derbyshire

Platform, Stage EC5 is equivalent to the Bee Low Limestone whilst the lithostratigraphic name for EC5 on the North Wales Platform is the Loggerheads Limestone (locally the Great Orme Limestone; Figure 2). During the Asbian (337.5 to 333 Ma; Rohde, 2005) the study area was located in the Tropical Zone at approximately 336°E 14°S (Piper, 1991; Cocks and Torsvik, 2011). The outcrops used in this study are situated on the margin of the Derbyshire Platform around Locality A, near to Castleton, East Midlands, and in proximity to the northern margin of the North Wales Platform, which outcrops as the Great Orme (Locality D) and Little Orme (Locality E) headlands near Llandudno, Conwy (Table 1a; Figure 1; Figure 3). Parallel to the northern margin of the North Wales Platform on the Isle of Anglesey, near Penmon Point (Locality F), facies were also mapped and sampled. Outcrops of the western margin of the Derbyshire Platform are near to Buxton and Hartington (Localities B, I and K). The North Wales platform interior was studied around Cefn Mawr and Llangollen (Localities H and G), 20 and 40 km south of the margin.

METHODS

Facies were mapped at a kilometre scale and logged at a scale of 1 cm : 50 cm across the Derbyshire and North Wales Platforms using natural outcrops, disused quarries, and core (25 sections) (Table 1a). 21 published stratigraphic sections were also used to support observations made from core and outcrop (from Stevenson and Gaunt, 1971; Aitkenhead et al., 1985; Table 1a). No core has been acquired around Localities D, E and F, so all observations of the North Wales Platform were made from outcrop and petrography. Additional localities, which were not logged but are described herein, are also noted (Table 1b). 125 polished and covered sections were prepared and half stained with Alizarin Red S and potassium ferricyanide to distinguish ferroan- and non-ferroan calcite and dolomite (after Dickson, 1965), and porosity. Samples were analysed using transmitted light microscopy and microfacies were classified using the Dunham classification scheme (Dunham, 1962). Quantification of components (matrix, cements, and allochems) was achieved by point counting 300 points of 30 samples using Petrog™. Micropalaeontological analyses of benthic, predominantly fusulinid, foraminifera and calcareous algae were conducted on 29 of the thin sections. A FEI QUANTA 650 scanning electron microscope was used to investigate features potentially below the resolution of transmitted light microscopy. A Bruker D8 Advance X-Ray Diffractometer was used to identify the mineral assemblage of 37 samples of platform exposure-related facies, and of 16 samples of limestone and siliciclastic-influenced bedrock.

RESULTS

Depositional Environments

Six depositional environments, plus igneous rock formations and exposure-related facies, were identified from outcrop, core, and petrographic analysis of the exposed Asbian succession (Bee Low Limestone on the Derbyshire Platform and Loggerheads Limestone on the North Wales Platform). These are summarised in Table 2, briefly described below and in Figure 4.

Slope/foreslope Depositional Environment

The foreslope/slope depositional environment does not crop out on the North Wales Platform. On the Derbyshire Platform, it comprises two principle facies. On the northern and western margins, a poorly sorted conglomerate, comprising sub-rounded intraclasts of skeletal wack/packstone (0.5 – 10 cm diameter), peloids and fragments of crinoids, bryozoa and brachiopods, forms beds that dip at approximately 30° northwards, towards the Edale Basin (Figure 5A). The fragments and clasts are micritised and coated by 1 – 10 mm thick radiaxial fibrous calcite (Figure 5B; Figure 6A; Table 2; e.g. Bathurst, 1959). Brachiopod moulds are partly-infilled by calcite cement, with sediment at the base of the moulds inclined at approximately 30°. On the northern and western margins, limestone blocks that are several metres in diameter are found. Clean, skeletal grainstones are particularly abundant on the western margin of the Derbyshire Platform (Figure 6B). On the southern margin, beds of skeletal wacke/packstone are locally contorted and dip basinwards at approximately 20° (e.g. Locality 17) (Figure 5C and 5D).

On the northern platform margin, geopetal textures suggest that the steep bedding angle is a true representation of paleo-sedimentary dip. The thick radiaxial fibrous cements that bind clasts and grains typically form syn-depositionally as a result of high energy (wave and storm-driven) flux of seawater (Kendall, 1985; van der Kooij et al., 2010) and can bind non-cohesive material to maintain a steep slope angle (e.g. Kirkby, 1987; Kenter 1990; Della Porta et al., 2003; Bahamonde et al., 2004). The coarse grain size of clasts and skeletal grains, high skeletal diversity and poor sorting is suggestive of short-lived, episodic sediment transport, from a shallow water setting, in response slope failure by gravity or fault movement. The northern margin of the Derbyshire Platform is <1km north of an array of E-W trending faults, thought to be associated with the Edale Fault (Fraser et al., 1990; Fraser and Gawthorpe, 2003; Figure 3), and seismic activity along this fault might have triggered mass transport of sediment on the platform margin. Contorted, more shallow-dipping beds and an absence of large clasts on the southern margin of the Derbyshire Platform are suggestive of soft sediment deformation but a much shallower slope angle than on the northern margin.
The slope/foreslope of the North Wales Platform has either been eroded or is not exposed, with the palaeo-platform margin interpreted from seismic data to be offshore of the present coastline (Figure 1; Floodpage, 2001; Pharoah et al., 2018).

Platform Margin Depositional Environment

The Platform Margin depositional environment comprises two principle facies which are observed on the margins of the Derbyshire and North Wales Platforms:

1) Carbonate mounds, which occur as massive, dome-shaped structures,have a distinct core, intramound, and flank facies that dip at approximately 30 – 40^{o} (Figure 7). They are typically up to 50 m wide and 9 m high and are spaced a few hundred meters to kilometres apart. The core is cemented and dominated by crinoids, brachiopods and bryozoa. Vugs, which are <10 cm wide, are common and can be lined by radiaxial fibrous calcite cement. The intramound facies are bioclastic peloidal wackestone and packstone with a diverse skeletal assemblage (fragmented bryozoa, brachiopods, corals, foraminifera, dasycladacean algae including *Koninckopora*) and a high volume of micrite (Figure 6C - D). No microbial binding was observed in outcrop, thin section, or under SEM. Flank facies include brachiopods floatstones and crinoidal grainstones (Figure 7B, 7C).
2) Skeletal grainstones typically comprise light- or reddish-grey stacked beds and form discontinuous bodies that pinch out in one or more directions. They are either isolated, sheet-like or cross-bedded bodies (<100 m wide, 5 m thick) within thick (>2 m), tabular limestone beds. They dip and pinch in numerous directions (Type A), or downlap onto carbonate mounds (<10 m wide, <10 m thick) and dip obliquely to the mound interface (Type B or "intermound"). Both types of skeletal grainstone are coarse grained (>1 mm) and dominated by crinoid ossicles and large corals (20-30 cm). The skeletal assemblage is moderately sorted (0.2 - 2 mm), and includes disarticulated crinoids, and fragmented brachiopods, bryozoa, foraminifera, undifferentiated skeletal fragments, corals, and demosponge, dasycladacean algae, including *Koninckopora.*

Carbonate mounds are highly characteristic of the Viséan (Nichols, 1961, 1965; Bancroft et al., 1988; Horbury, 1992; Gutteridge, 1990; Gutteridge, 1995; Somerville, 2003). They most closely resemble the Type 2 mounds of Somerville (2003), interpreted to accrete from a crinoid – bryozoan - brachiopod core with abundant cemented micro-peloidal micrite such that structural support by organisms was short lived, and the mound was rapidly cemented. They are the most important constructive facies on the platform margin, but their spacing indicates that they did not form a continuous rim but rather formed isolated structures, or potentially, in slightly deeper water (10 – 20 m) basinward of the margin (Harwood, 2005). Some allochems were dissolved and solution-enhanced to form irregular-shaped vugs; since marine cements line these vugs they are inferred to have formed soon after deposition. It is possible that algae stabilised soft sediment in localised, relatively shallow and restricted or protected areas, allowing mound colonisation but there is limited direct evidence for microbial activity ('cryptic evidence' of Pickard, 1996). Following initial colonisation, bryozoa built upwards, trapping transported, fragmented skeletal grains such as crinoids and brachiopods, which were then rapidly cemented to form the intramound facies ('bulk facies' of Bancroft et al., 1988). Opportunistic brachiopods and crinoids then colonised the flanks and top of the mound as it grew into areas of relatively shallow water, (e.g. Bancroft et al., 1988 and Somerville, 2003).

The clean texture with diverse, moderately sorted skeletal grains within the skeletal grainstone facies are indicative of a higher energy depositional setting in clear, shallow water. The preservation of cross-bedding is also indicative of high depositional energy and the pinching geometry of beds is typical of sediments influenced by wave-driven currents (Rankey and Reeder, 2012). These grainstones are interpreted to be platform margin sand-bars deposited on seaward facing platform margin, where the most agitated environments occurred, forming pinching beds shaped by multidirectional wave-energy (*see:* Rankey et al, 2006; Rankey and Reeder, 2012).

Platform Interior Depositional Environment

The platform interior depositional environment mostly comprises thick (0.5 - >3 m) tabular, beds that are laterally continuous for hundreds of metres (Figure 8A). The platform interior comprises a diverse, moderately sorted fine-grained skeletal assemblage of varying abundance (Figure 6E; Table 2) (brachiopods, crinoids, bryozoa, dasycladacean algae, demosponge, gastropods and a diverse range of benthic foraminifera (e.g. Figure 9) with several sub-facies:

1) Mounds which are internally uniform (i.e. lacking a core, intramound, and flank facies) with a low height-to-width ratio (20 m wide and 15 m high) and some weak bedding. They often overly a grainstone body and comprise tightly-stacked, thin-branched (branches approximately 1-2 cm in diameter) *Siphonodendron* corals (colonial rugose coral), some of which are fragmented, within a micrite matrix (Figure 8B).
2) Skeletal grainstones, which are sporadically interbedded and laterally discontinuous, with beds <0.3 m thick and 3-10 m wide. On the Derbyshire Platform, these skeletal grainstones are only observed in drill core from boreholes (e.g. Localities 2, 4 and 8; Table 1a).
3) Fine-grained skeletal wacke/packstone with a diverse, highly fragmented skeletal assemblage and diffuse mottling. This includes the Tollhouse Mudstone Bed, a distinct lithostratigraphic unit on the North Wales Platform which is up to 3.5 m thick, that comprises tabular, parallel beds of skeletal wackestone and mudstone, interbedded with skeletal packstone. Tubular and nodular structures (cm-scale diameter and length) occur at the base of some beds. The matrix is dark-grey/brown containing white skeletal fragments and cm-scale brachiopods. The microfossil assemblage comprises sub-mm diameter benthic foraminifera, brachiopods, crinoids, bryozoa, dasycladacean algae, and corals, with trace serpulidae.

Overall, parallel bedding, high skeletal diversity, and the high degree of grain fragmentation is suggestive of moderate to locally high energy deposition in an unrestricted subtidal environment within the platform interior. Mottling is interpreted to be bioturbation, although there is no preservation of the trace-making organism; it is most likely to be *Phycosiphon* or a similar feeding trace which selectively ingests clay-grade material, and occurs in a range of bathymetric conditions, possibly polychaetes (Gingras et al., 2002). The diffuse edges of the traces suggest that the sediment remained soft and unlithified for a long period. On sedimentary evidence alone, it is difficult to confidently estimate water depth within skeletal packstone facies, but could reflect sedimentation at or around fair weather wavebase. Tubular and nodular structures are burrows, indicating soft sediment reworking of submarine sediment, and suggesting low to moderate energy conditions and gentle winnowing of sediment. The small grain-size and abundance of micrite within skeletal wackestone facies, however, including the Tollhouse Mudstone Bed is indicative of deposition under moderate to low energy conditions by gentle winnowing with abundant dasycladacean algae indicative of water depths of less than 10 m (Jones, 2006).

Platform interior, coral-dominated mounds are rarely described from UK Mississippian platforms (e.g. Aretz and Herbig, 2003) and their low abundance is suggestive of niche environmental conditions. Rugose corals have been described from Carboniferous mounds (e.g. Shen and Webb, 2005; Gong et al, 2012). However they only rarely form the main frame-building organism within similar coral biostromes that have been recognised within the upper Viséan of the Dinant Platform (e.g. Aretz and Chevalier, 2007). A high abundance of tightly packed colonial corals is suggestive of localised, higher energy conditions compared to marginal mounds since the skeletal framework indicates an adaptation to high-energy waves or currents. This is consistent with the association of the build-ups with underlying grainstones and fragmentation of corals within the main structure. Corals may have attached to a microbially-stabilised substrate, similar to marginal mounds, on an area of relatively high topography, and thus an environment with shallower, more turbulent waters.

Peritidal Depositional Environment

The peritidal depositional environment is extremely rare and presents as stratiform, but slightly crinkled, and locally pinnacle-shaped microbial boundstone. It is observed at only two localities on the North Wales Platform (Locations G and H). The facies is typically no more than 0.25 m thick (Figure 8D) and includes laminae of alternating yellow-coloured cemented mudstone and white unconsolidated carbonate mud. XRD indicates that the facies comprises 82.8% calcite, 12.9% muscovite, 1.8% quartz, 1.2% halite, 0.7% barite, and 0.5% haematite. The fine lamination of this facies implies an area of very shallow water and the presence of minor halite suggests that at some point the environment was evaporitic. The crinkled nature of the beds and carbonate mud composition is suggestive of a microbial origin. The presence of terrigenous grains indicates the presence of siliciclastic material, accumulated and trapped because the laminite grew in very shallow water.

Exposure -related Facies

Exposure-related facies can be categorised into four types, all of which are usually observed associated with each other (Figure 10a): i) pitted/mamillated surfaces (Type A), (ii) tubular and nodular/brecciated horizons (Type B), (iii-v) unconsolidated muds and clays (Type C), and coals (Type D). These surfaces punctuate strata 18 to 49 times per 100 m of strata on the North Wales Platform and 8-18 times per 100 m on the Derbyshire Platform, and increase in frequency vertically (Manifold et al. 2020).

Type A surfaces consist of smooth, mamillated bedding surfaces with a wavelength of 0.2-1 m, and up to 10 cm deep, sometimes cross-cutting sedimentary features or infilled by Type C exposure facies. These surfaces can be traced laterally for tens of metres but are discontinuous over hundreds of metres. They are frequent, occurring on average every 10-15 m, but increasing in frequency towards the top Asbian, particularly on the North Wales Platform. In thin section, the platform interior limestones which directly underlie these surfaces are sometimes partly dissolved and replaced by coarse, sparry cements (Figure 6F).

Type B surfaces principally outcrop on the North Wales Platform, are <1.5 m thick and extend laterally for a few hundred metres; occurrences on the Derbyshire Platform are much less common, extensive for less than 100 m, and usually <1 m thick. They comprise nodules of skeletal packstone, 2-5 cm in diameter and are clast-supported, with inter-clastic sparite cement or unconsolidated sediment. This facies is underlain by beds of a similar appearance but with sub-vertical tubular structures, typically 3 cm wide and 25 cm long.

Type C surfaces are 0.05 – 0.8 m thick, often with a lenticular geometry, and can be red, brown, or yellow in colour. They are laterally extensive for tens to a few hundred meters, occurring between beds of platform top strata, Excluding calcite, the average composition of this facies is 32.1% kaolinite, 30.2% muscovite, 30.2% quartz, 7.5% other minerals, principally haematite and feldspars, with minor barite and pyrite. This facies is particularly abundant on the North Wales Platform around Locality D, and is also documented westwards around Anglesey (Howells, 2007). On the Derbyshire Platform, it is not seen in outcrop, but a few examples are well-preserved in core, one sample of which contains plant material and quartz nodules (<2 cm) (Figure 10a(iv)). Type D, coals, form around Localities G and H (Figure 4d) as three bands <1 m thick.

The smooth, mamillated Type A surfaces have been interpreted to form beneath a layer of soil (Walkden, 1974), although soil is rarely preserved on the Derbyshire Platform, or by dissolution by stem-flow around trees (Vanstone, 1996). Where soil is not present, these surfaces may be confused with compactional bedding surfaces and they are most confidently identified when they cross-cut sedimentary features or are associated with another platform exposure-related facies. The cements directly below the surface of Type A facies are mostly formed during meteoric diagenesis, within the meteoric phreatic realm (Walkden and Williams, 1991; Juerges et al. 2016).

Type B cemented nodular limestone is characteristic of calcrete, which forms as limestone precipitates around soil particles and roots to give a brecciated appearance (Durand et al., 2010). The tubular structures which underlie Type B surfaces are interpreted as burrows, rather than rootlets, because they are long, subvertical, lack a consistent structure and contain a coarser grained sediment than the surrounding matrix, which suggests reworking and sediment mixing by living organisms. Their consistent diameter and relatively short length is also inconsistent with rootlets, which often have varying diameters and can be metres in length (Klappa, 1980). Unlike the diffuse, mottled bioturbation within the platform top limestones the excellent preservation of these open burrows suggests the sediment was firm, probably partly cemented, suggesting a relatively shallow-water depth compared to the majority of the platform interior. These traces are most likely formed by shallow deposit-feeding and dwelling crustaceans which colonised the substrate in shallow seas prior to platform exposure.

The abundance of clay and the soft texture of Type C beds, along with their association in outcrop with Type B facies (calcretes) and the presence of plant material and terrestrially-derived minerals (quartz and muscovite), is consistent with them being palaeosols. Their colour is likely linked to the varying extent of iron oxidation of haematite. Type D facies, coal, forms in a narrow area in the southernmost part of the study area on the North Wales platform, and reflects a terrestrially-influenced, swampy environment close to the palaeo-shoreline on the Wales-Brabant Massif.

Extrusive Igneous Rocks

There were two main volcanic centres on the Derbyshire Platform during the Viséan, near Localities B and C (Figure 12; Arnold-Bemrose, 1907; Walkden, 1972), with two types of extrusive igneous rocks identified from outcrop and core. Type A is dark-coloured, mafic (pyroxene-dominated) and fine grained, sometimes contains calcite-filled vesicles (<7 mm). In outcrop, near Locality 13, they have a columnar habit but ordinarily they are massive, bed-parallel and vesicle-rich and have an irregular contact with underling limestone (Figure 10a(vi)). Type B comprises multicoloured, friable clays in core (Figure 10a(vii), and dark coloured clays in outcrop. Published core descriptions indicate that this facies occurs throughout the Asbian at bedding contacts (Walkden, 1972; Cox and Bridge, 1977; Cox and Harrison, 1980; Bridge and Gozzard, 1981; Harrison, 1981). When their occurrence is mapped, the facies shows a NW-SE distribution over the Derbyshire Platform (Figure 12). Beyond the perimeter of this mapped distribution, volcanic ash is not recorded, including on the North Wales Platform.

The fine, pyroxene-rich composition of the Type A lithology, as well as the abundance of calcite-filled vesicles, suggests that they are amygdaloidal basalts. Their occasional columnar habit indicates that the rock locally contracted upon cooling to form vertical joints (e.g. Haldar and Tišljar, 2014). Over forty igneous bodies of this type are preserved in Viséan strata, described as 'scutulum-type' shields (i.e. they formed during a singular eruption; Waters, 1981; de Silva and Lindsey, 2015). The irregular, interfingering contact between the basalts and the limestone suggests magma eruption was syndepositional, or at least pre-lithification (Figure 10b(i)). Although most igneous extrusive beds are interpreted to be deposited subaerially (Waters, 1981), the interaction of lava and unlithified sediment suggests that some were submarine. Type B volcanic facies have clay-sized grains which are suggestive of volcanic ash (consolidated as tuffs). Dark bands observed in outcrop comprise K-bentonite clays ("clay wayboards"; Trewin, 1968; Walkden, 1972; 1974) which are an alteration product of volcanic ash, suggesting that coloured and dark clays are of the same origin.

Siliciclastic Depositional Environment

No siliciclastic facies were observed on the Derbyshire Platform. On the North Wales Platform, dark grey mudrock forms beds, ~1-metre in thickness, between 1 to 5 metre thick limestone beds (Locality G; Figure 10c) and contain interbedded coal at Locality H. Mudrocks contain no marine bioclasts and often, but not always, overly mammilated (Type A) exposure surfaces. They have sharp lower and upper boundaries with interbedded limestone that are not cross-cut by burrows.

The absence of marine bioclasts within the mudrock suggests it is terrestrial, and its limited distribution, within the Loggerheads Limestone on the southern margin of the North Wales Platform (Location H), is suggestive of riverine influx of mud on the shoreline with the Wales – Brabant Massif. In particular, the association with coal, lack of macro- or microfauna and siliciclastic composition is suggestive of deposition in a low energy, swampy, marginal marine setting and a humid climate. Where mudrocks sharply overly limestone, and there is no intervening emergent surface, it is possible that the mudrock is marine; where it overlies an emergent surface then it could be terrestrial. Sharp upper boundaries indicate that once the clastic incursion event was over, the carbonate factory restarted, implying that changes in relative sea level were minor and certainly insufficient to shut down the carbonate factory by drowning.

Although the Derbyshire Platform was situated a similar distance from the shoreline of the Wales-Brabant Massif as the North Wales Platform (approximately 25 km, Figure 1), siliciclastic sediments did not reach the Derbyshire

Platform. This is likely because the intervening basin, the Widmerpool Gulf (Figure 3), would have trapped northerly-prograding siliciclastic sediment (Trewin and Holdsworth, 1972).

Biostratigraphy

The Tollhouse Mudstone crops out at the base of the Great Orme / Loggerheads Limestone (Figure 2) and is middle to Late Asbian age (EC5) (Biozones Cf6γ1-2; after Conil et al., 1991 and Somerville et al., 2008). The Loggerheads Limestone contain a typical Asbian microfaunal assemblage comprising dasycladacean green and coralline red algae (e.g. *Coelosporella* spp., *Koninckopora inflata* and *Ungdarella* spp.), palaeoberesellids (e.g. *Kamaenella* spp.), calcispheres (e.g. *Calcisphaera laevis* and *Calcisphaera pachysphaerica*) and benthic foraminifera including *Archaediscus angulatus*, *Bibradya* spp., *Cribrospira panderi*, *Cribrostomum* spp., *Endothyra phrissa*, *Eostaffella prisca*, *Forschia* spp., *Lituotubella glomospiroides*, *L. magna* and *Omphalotis omphalota.* On macrofaunal evidence, the Loggerheads Limestone is interpreted to have been deposited within a shallow, platform interior setting. The abundance of *Koninckopora*, *Ungdarella* and palaeoberesellids, as well as endothyroid foraminifera with multi-layered tests, specialised chamber partitions and cribrate apertures (i.e. *Bibradya* spp., *Cribrospira panderi*, *Cribrostomum* spp. and *Nevillea* spp.) and large thick-walled forschiids (*Forschia* spp.) within this unit suggest deposition in high-energy pseudo-algal meadows marginally below to above fair-weather wave base, in water depths of approximately 5 to 15 m (e.g. Gallagher, 1998; Gallagher and Somerville, 2003).

On the Derbyshire Platform, both the Bee Low Limestone and basal section of the overlying Monsal Dale Limestone (Brigantian) contain a typical Asbian microfaunal assemblage comprising dasycladacean green algae, palaeoberesellids, calcispheres and benthic foraminifera similar to that described the North Wales Platform. The texture and fabric of the Bee Low Limestone has been interpreted to reflect winnowing and bioturbation in a moderate energy setting, at or around, fair-weather wave base. The abundance of the foraminifera *Howchinia* spp., *Palaeotextularia* spp., *Pseudoendothyra* spp. (including *P. struvii*), *Tetrataxis conica* and *Vissariotaxis* spp. in samples from both the northern and north-western platform margin (Localities 11, 18, I) and platform interior (Locality J) of the Derbyshire Platform are consistent withrelatively low hydrodynamic energy (e.g. Gallagher, 1998; Gallagher and Somerville, 2003) and may suggest deposition below fair-weather wave base (between 15 m and 25 m). The western margin of the Derbyshire Platform is interpreted to be shallower, higher energy (e.g. Locality K) than the northern or southern margin on the basis of the abundance of dasycladacean green algae.

Asbian – Brigantian boundary

The boundary between the top of the Asbian and the base of the Brigantian is recognised across the Derbyshire and North Wales Platform, in both outcrop and core (Figure 11). It usually manifests as an irregular, pitted surface that resembles Type A facies (of the Exposure-related facies), but pits are often deep (up to 1 metre), with a greater depth / width ratio than other mamillated surfaces. The surface can usually be walked out over the length of an outcrop, and on the North Wales Platform is also associated with Type C (usually reddened) palaeosols). On both platforms, there is a marked change of facies across the Asbian – Brigantian boundary, from clean, light coloured packstones with frequent emergent surfaces to darker, more chert rich packestones with abundant *Gigantoproductids*, and fewer emergent horizons (Manifold, 2019). On the Derbyshire Platform, the Asbian – Brigantian boundary is commonly also picked lithostratigraphically at the top of the Lower Matlock lava, whilst the top Asbian in the Eyam and Duffield boreholes is defined at the top of an agglomerate and dolerite sill, respectively (Chisholm et al., 1983; Waters, 2009).

DISCUSSION

Controls on Platform Architecture

An E - W oriented correlation using outcrop data from across the Derbyshire and North Wales Platforms was constructed using the biostratigraphic data (Figure 13). Biostratigraphic correlations have been published previously (Vaughan, 1905; Garwood, 1913; Conil et al., 1979; Strank et al., 1981; Waters et al., 2009) and the new data from this study supplements that interpretation. In particular, it differentiates a significant period of platform exposure and absence of carbonate deposition at the Asbian – Brigantian boundary, which was used as a datum for correlation because it can be confidently correlated across both the platforms.

Palaeo-wind direction

The dip angle of beds and the geopetal textures within slope facies from the northern margin of the Derbyshire Platform indicate a palaeo-dip on the platform slope of 30°. This is consistent with previous interpretations (Broadhurst and Simpson, 1967; Simpson and Broadhurst, 1969; Broadhurst and Simpson, 1973; Fraser et al. 1990; Gutteridge, 1991; Harwood, 2005), but is shown here to have resulted from stabilisation of the remobilised debris, as well as microbial boundstones (Harwood, 2005), by syn-depositional radiaxial fibrous calcite cementation. These cements precipitate as a result of wave and storm- facilitated seawater flux (Kirkby, 1987; Kenter 1990; Della Porta et al., 2003; Bahamonde et al., 2004; van der Kooij et al., 2010). Miller and Grayson (1982), Smith et al., (1985) and Gutteridge (1987) all interpreted the Derbyshire Platform to be a southward-dipping fault block, but Schofield (1982) and Gawthorpe and Gutteridge (1990) infer the northern margin to be leeward. On the north and west of the Derbyshire Platform, platform margin build-ups might have developed in response to footwall rotation, basinal currents or other environmental controls, and this combined with preferential cementation would have contributed to steepening of the platform margin. However, these features are also consistent with a windward-facing margin; a feedback mechanism can be interpreted between the moderately high energy setting, optimal carbonate productivity and platform margin steepening by cementation. In contrast, the southern margin of the Derbyshire Platform shows no evidence of extensive marine cementation, all measured sedimentary dips were less than 20°, and sediments were dominated by slumped skeletal grainstone facies, with no evidence of debrites. These features are all suggestive of a leeward margin. In particular, the absence of marine cements on the southern platform margin means that coarse sediment could have been transported southwards, with slumping of cohesive floatstone-rudstones down-slope.

The interpretation of a NW to SE directed wind direction seems counter-intuitive given the palaeogeographical setting; the study area was south of the equator during the late Viséan and global wind direction would therefore be expected to be from east to west (i.e. south – east trade winds). However, the Pennine Basin was a protected seaway, with a narrow eastward connection to the Rheic Ocean, witha large landmass to the north (Cocks and Torsvik, 2011). Combined with Variscan mountain-building to the south of the study area, perturbations to the global wind patterns could have developed, and might have created a dominant NW to SE wind direction in the southern Pennine Basin. This is supported by mapped distribution of wind-dispersed volcanic ash (Figure 12).

Controls on platform margin morphology

Carbonate mounds crop out every few hundred metres to kilometres along the northern and western margin of the Derbyshire Platform and the northernmost outcrop of the North Wales Platform, with flanking and inter-fingering grainstone shoals. The western margin is dominated by extensive (<500m^2 wide, <5 m thick) clean *Koninckopora* grainstones. The northern margin of the Derbyshire Platform is embayed, with each embayment being approximately 1-2 km wide, separated by promontories that are a few hundred metres wide, in agreement with Ford (1987) and Harwood (2005). The western margin of the Derbyshire Platform is more linear, even though it is also windward-facing. The processes governing the morphology of the platform margin cannot be confidently determined, but it is tentatively suggested that embayments formed because of mass wasting or episodic collapse of the slope/margin as a result of movement along the Edale Fault. Embayments could also have formed as a result of syn-depositional, wave-driven, erosional processes, although the western margin may be expected to host embayments in this scenario. In contrast, the western margin is not underlain by a deep-seated crustal lineament, and it appears to retain a linear profile.

The Derbyshire Platform has previously been described as rimmed (e.g. Smith et al., 1985; Gutteridge, 1991) but the dispersed distribution of mounds and shoals suggests that build-ups were less laterally continuous than previously assumed. The depths at which mounds grew is also unclear; Harwood (2005) suggested water depths of 10 to 20 metres. Mound growth might have been assisted by wave-driven circulation of sea-water; displacement of corals from mounds on the northern margin on the Derbyshire Platform (e.g. Locality 15), and reworking into shoals implies episodic storm-related sedimentation. If so, this provides further support for this being a higher-energy, windward-facing margin than the southern platform margin. The basinward margin of the North Wales Platform is not present, because of erosion and the position of the present day shoreline.

Grainstone shoals on the northern margin of the Derbyshire Platform are not laterally continuous, as described in many modern, open ocean-facing platforms (Rankey, 2006; Rankey and Reeder 2012). Instead, they form bedded units up to 10 m thick that extend laterally for up to 50 m, passing into parallel-bedded platform interior facies. This would suggest that grainstone bodies were spatially restricted, perhaps because mounds flourished first, limiting shoals to intermound areas. Mounds may have become well established because local environmental conditions favoured microbial stabilisation of the mound core, in localised, slightly protected shallow waters. Alternatively, mounds developed within protected, lower energy areas between shoals. Embayments along the platform margin may have also spatially restricted shoal development and affected margin bathymetry; Broadhurst (1973) suggested undulating bathymetry led to faunal variation across the margin, but this was not observed here and the macrofauna (brachiopods, bryozoa, crinoids, *Siphonodendron* corals) occur at a range of water depths and are consistent with low levels of environmental stress (Ryland, 1970; Brand et al., 1989; Billing, 1991; Fedorowski, 2008).

On the western margin of the Derbyshire Platform, the shoals are laterally extensive (>3 km^2; e.g. Locality K). They are interpreted to have been deposited in shallower, higher energy, water than the northern margin, because of their cleaner texture and the abundance of *Koninckopora,* which indicate water depths of less than 10 m (Jones, 2006). The linear morphology of the western margin suggests that there were fewer embayments and therefore the geometry and distribution of the shoals was more likely controlled by the geometrical architecture of the margin, and resultant bathymetric variations. This interpretation contrasts with Gawthorpe and Gutteridge (1990) who interpreted that shoals developed during marine transgressions, suggesting a temporal control on sedimentary architecture.

Controls on facies distribution on the platform top

The platform interior facies of the Derbyshire and North Wales Platforms are characterised by bedded limestones punctuated by exposure surfaces. Between these surfaces, sedimentary texture and macrofaunal assemblages indicate a moderate - energy, subtidal platform interior setting, with deposition at, or potentially below, fair-weather wave base. These facies then pass up into shallower, higher energy, wave-influenced facies capped by mamillated surfaces and/or calcretes or palaeosols. Peritidal facies are rarely preserved in Asbian strata, with only one clear example (Figure 8D; North Wales Platform), either because they never formed, perhaps due to a rapid fall in relative sea-level (e.g. Wright, 1986; Heckel, 1990; Wright, 1992), or because they were deposited and then removed by erosion. In contrast, south of the Wales – Brabant Massif, peritidal facies were common at this time (e.g. Poty et al., 2014). This marked constrast is facies between the platforms that north and south of the Wales-Brabant Massif is surprising if sediment-stacking is indicative of glacio-eustatic cycles (Wright and Vanstone, 2001; Poty, 2016) (). The very rare occurrence of peritidal sediments amongst all the localities in this study suggests, therefore, that they almost never formed, and the laminites identified on the North Wales Platform are likely to reflect areas of locally high topography, providing a shallow-water environment for microbial organisms to colonise.

Although there is microfaunal evidence that deposition was in slightly deeper water on the Derbyshire Platform, compared to the North Wales Platform, there is no significant difference in carbonate facies between the two platforms. This is despite extensive syn-depositional volcanism on the Derbyshire Platform, and the proximity of the Wales – Brabant Massif to the North Wales Platform. The exception to this is towards the shoreline of the North Wales Platform, where coal and mudrock becomes common above exposure surfaces and mudrock is interbedded with limestone, creating more complex vertical stacking than further offshore. Overall, the limitation of interbedded mudrock to the southern margin of the North Wales Platform suggests that the influx of clastic sediment from the Wales – Brabant Massif did not supress carbonate productivity substantially across most of the North Wales Platform during the Asbian. This might be because the platform interior experienced moderate to high energy conditions, as (demonstrated by the high abundance, high diversity foraminiferal and algal assemblage such as *Koninckopora*, *Ungdarella*, palaeoberesellids, endothyroid foraminifera, *Bibradya* spp., *Cribrospira panderi*, *Cribrostomum* spp. and *Nevillea* spp., *Forschia* spp.), facilitating distribution of mud. Alternativelyclastic sediment supply to the shoreline was localised and of insufficient volume to impact carbonate productivity.

Logging and mapping of facies distribution shows that all platform interior facies can be positioned adjacent, parallel, and/or interbedded with one another (Figure 4; Manifold et al., 2020). Lithofacies and exposure surfaces/facies can rarely be walked out for more than a few hundred metres in outcrop across both platforms. Manifold et al. (2020), argued that the lack of ordering/cyclicity was not because of missing facies, but because of the differing arrangement of facies between exposure events across the study area. Based on stratigraphical and statistical forward modelling, Manifold et al (2020) interpreted facies on the Derbyshire and North Wales Platforms to be a mosaic (after Burgess and Pollitt, 2011 and Burgess, 2016). This conclusion is supported by the laterally discontinuous nature of exposure surfaces and facies in outcrop and suggests that factors other than relative sea-level fluctuation, such as changes in productivity, water quality, and self-organisation of strata, controlled facies distribution (Wright and Burgess, 2005). For example, platform interior float-rudstone facies, with an abundant and diverse assemblage of bryozoa, brachiopods, crinoids, and *Siphonodendron* corals, could have been established in response to optimal environmental conditions (Ryland, 1970; Brand et al., 1989; Billing, 1991; Fedorowski et al., 2008). Fluctuations in intensity of wave- and storm-driven currents, could also have been important, given the small size of both the Derbyshire and North Wales Platforms (approximately 5000 km^2), compared to some modern platforms (e.g. the Great Bahama Bank, approximately 175,000 km^2; Schlager and Ginsburg, 1981). The absence of a continuous rim on the platform margin would mean that corridors for these currents may have formed between mound communities, which would otherwise have absorbed wave energy. Overall, this has important implications for correlation of facies and interpretations of cyclicity. Shirley and Horsfield (1940) recognised that faunal bands (e.g. "Girvanella band") are not independently appropriate for correlation, because the same biota occur numerous times within the vertical succession of strata. Other biostratigraphic indicators, such as foraminifera, are long-ranging and often bridge the Asbian and Brigantian (e.g. Sevastopulo and Barham, 2014). For this reason, stacking patterns have often been used to interpret cyclicity (e.g. Wright and Vanstone, 2001; Poty, 2016), but if facies are not systematically distributed in an ordered fashion, then depositional environments cannot be used to correlate age-equivalent strata in a predictive manner. In summary, it seems unlikely that facies distribution between reliably dated, age-equivalent surfaces on the Derbyshire and North Wales Platforms, and equivalent aged strata on other platforms, cannot be predicted from deterministic models that assume ordered, systematically stacked facies.

Processes controlling platform exposure

Exposure events on the North Wales Platform are preserved as palaeokarstic surfaces, palaeosols, calcretes, and coals, and punctuate strata more frequently (18 to 49 times per 100 m of strata) than on the Derbyshire Platform (8-18 times per 100 m; Manifold et al., 2020). On average, platform exposure occurred approximately every 0.04 – 0.2 My, based on a 4.5±1.5 My duration for the Asbian (Rohde, 2005) and a total stratal thickness averaging at 180 m on both platforms. On the Derbyshire Platform, exposure events are typically mamillated surfaces and volcanic ashfalls, with palaeosols only observed in core (Locality 7; Table 1a). These exposure events are well-described and interpreted (e.g. Walkden and Davies, 1983; Walkden, 1972; 1974; Vanstone, 1998), but there has previously been no holistic attempt to explain the heterogeneity in the distribution of exposure events between the two time-equivalent platforms.

The most obvious difference between the two platforms is that volcanic ashfalls were restricted to the Derbyshire Platform because this is where the active volcanic centres were located. Furthermore, since the wind direction is interpreted to have been towards the southeast, ash would not have been transported westwards, towards the North Wales Platform. There are, however, other differences in the composition and style of exposure surfaces between the two platforms that cannot just be related to differences in volcanic activity. The abundance of well-developed calcretes on the North Wales Platform suggest arid or semi-arid conditions (Durand et al., 2010), but palaeosols, palaeokarstic surfaces, and coals are more indicative of humid or semi-humid conditions (Wright, 1980; Arnold, 2013). The presence of interbedded mudrocks near the palaeo-shoreline on the North Wales Platform also indicates that there was sufficient rainfall for rivers to transport and deposit siliciclastic sediments. These events may have also caused the water table to rise to form swamps, leading to localised formation of coal. These interpretations together suggest that on the North Wales Platform the climate oscillated between humid and arid (Wright, 1980; Falcon-Lang, 1999a and b), or spatially, with wet and dry areas. Since calcretes are commonly interbedded with palaeosols, climatic oscillations are considered more likely than localised climatic variability controlling spatial variation in the type of emergent surface. On the Derbyshire Platform, calcretes are present locally, but are thin and much less common than on the North Wales Platform, whilst palaeosols are very rare and mudrock and coals are absent. Whether mamillated surfaces formed beneath soils (e.g. Walkden, 1972), which were subsequently removed, or from stemflow around trees (e.g. Vanstone, 1996), the inference is that semi-arid conditions persisted on the Derbyshire Platform during the Asbian.

It is therefore possible that there was a different climate than on the North Wales Platform, with less frequent periods of humidity than further west. Alternatively, the Derbyshire Platform was not exposed as frequently, and perhaps for shorter periods, as suggested by the lower frequency of exposure surfaces on the Derbyshire Platform compared to the North Wales Platform. This could have occurred if carbonate sedimentation took place in deeper water than the North Wales Platform. It has been noted that the benthic foraminiferal assemblage (*Howchinia* spp., *Palaeotextularia* spp., *Pseudoendothyra* spp. (including *P. struvii*), *Tetrataxis conica* and *Vissariotaxis* spp.) on the Derbyshire Platform implies slightly deeper water than the North Wales Platform, which is consistent with its more distal location within the Pennine Basin, relative to the Wales – Brabant Massif. A similar conclusion, which highlighted the importance of bathymetry on exposure surface development across seven carbonate platforms of Carboniferous of the UK, was reached by Vanstone (1996). Given the similarity of facies and fauna between the two platforms, and the comparable thickness of Asbian strata (approximately 200 m; e.g. Aitkenhead et al., 1985) variation in water depths may have been driven by the natural topography of the basement and/or differential subsidence, rather than differences in carbonate productivity. The underlying basement was mapped by a gravity survey on the Derbyshire Platform and has been interpreted to strongly control the thickness of the overlying limestones (Maroof, 1976). Discerning the definite control on differential bathymetry is beyond the scope of this project, but it is perhaps logical that the distally land-attached Derbyshire Platform would have grown in deeper water than the land-attached North Wales Platform.

Global climatic changes recorded in the Pennine Basin

The Mississippian marks a critical point in Earth's history, as the proliferation of land plants led to a decrease in pCO_2 and global tectonic reorganisation led to continental amalgamation, modification of ocean circulation patterns, global cooling and transition from a greenhouse to an icehouse climate (Mii et al., 1999; Smith and Read, 2000; Barham et al., 2012; Qiao and Shen, 2015; Oehlert et al., 2019). Ice advance and retreat was initiated in the Mississippian, with two principal perturbations, one in the Tournasian (approximately 355 - 350 Ma) and one in the late Viséan to early Serphukovian (Mii et al., 1999; Buggisch et al., 2008; Armendariz et al., 2008; Montanez and Poulsen, 2013; Godderis et al., 2017; Oehlert et al., 2019; Rosa et al., 2019). The frequency and amplitude of sea level fluctuation apparently increased after each of these events, with the transition to full icehouse conditions in the Pennsylvanian (Mii et al., 1999; Montanez and Poulsen, 2013).

In northern England and Belgium, the onset of the 2nd phase of Mississippian glaciation has been related to preservation of high frequency cyclothems in the upper Asbian (Wright and Vanstone, 2001; Barham et al., 2012; Poty, 2016). This in part has been interpreted because of the contrast in stacking pattern to less apparently cyclic strata in the underlying Holkerian (EC4) (Schofield and Adams, 1985). There is little consensus on the duration of sea-level changes during the Asbian (Barnett et al., 2002) with estimates ranging from 0.1 My to 0.4 My (Horbury, 1989; Vanstone, 1996; Wright and Vanstone, 2001; Smith and Read, 1999, 2000). The frequency of platform exposure determined for Asbian strata in this study (0.04 – 0.2 My) is broadly consistent with fifth-order glacioeustatic oscillations (after Van Wagoner et al., 1990; Barnett et al., 2002 and references therein). However, the lack of ordering of strata, lateral discontinuity of exposure surfaces (over <500 metres) and sharp contacts between mudrock and limestone on the North Wales Platform calls into question the evidence for cyclicity within the upper Asbian. All of these features can be interpreted as the result of autogenic processes rather than systematic changes in relative sea level. A common argument used to support rapid, glacial-drive sea level fall, is the near-absence of peritidal facies (Wright, 1992). However, the strong evidence for a semi-arid to humid climate on the North Wales Platform, and the more distal location of the Derbyshire Platform suggests that peritidal facies did not form because of the depositional setting, not as a result of rapid changes in relative sea level. In contrast, peritidal facies are well preserved within cyclothems to the south of the Wales-Brabant Massif (Poty et al., 2014; Poty, 2016), suggesting that where peritidal facies were deposited, they were preserved. The presence of short-lived exposure events truncating slightly deeper water platform interior facies on the Derbyshire Platform could be indicative of some allogenic forcing of relative sea level, but the discontinuity of the dominant Type A surfaces suggests emergence was short-lived and localised. It is also noteworthy that forward modelling of carbonate platform growth during icehouse periods indicates that the rapid rise in sea level during interglacials can lead to suppression of carbonate sedimentation and even platform drowning (Paterson et al., 2006; Masiero et al., 2020). There is no indication of such events in either of the platforms studied here or within age-equivalent strata south of the Wales-Brabant Massif (Poty et al., 2014) where facies above emergent surfaces are subtidal, and deposited in water depths around or above fair weather wave base. Furthermore, Paterson et al (2006) show that subsidence is a critical control on the morphology of carbonate platforms under the influence of glacio-eustacy, resulting in different sedimentary stacking patterns in areas of high subsidence – where there is more complete preservation of stratigraphy. In contrast, areas of lower subsidence can exhibit 'missed beats', formed by continued emergence of a platform top, even during sea level rise. The Holkerian was a tectonically quiescent period, between rift events, and movement along bounding faults that would have facilitiated footwall uplift and rotation (Fraser and Gawthorpe, 2003). It is possible, therefore, that the stacking patterns observed within the upper Asbian are in part driven by fault-controlled uplift . Furthermore, it can – tentatively – be implied that there are fewer emergent surfaces and greater preservation of strata on the Derbyshire Platform as a result of greater differential subsidence there compared to the North Wales Platform.

In summary, the data from this study and Manifold et al. (2020), suggests that evidence for systematic stacking and ordered parasequence development in the Asbian is less strong than has been previously invoked, calling into question the interpretation that the mid-Asbian marks the onset of fourth-order glacio-eustatically controlled cyclicity. Nevertheless, the increase in frequency of exposure surfaces, and decrease in bed thickness, up-section towards the Asbian - Brigantian boundary implies a decrease in accommodation space, consistent with a reduced rate of relative sea level rise across the basin. The Asbian – Brigantian boundary is a regionally correlatable karstic surface on both the Derbyshire and the North Wales Platforms, as well as in north Lancashire (Horbury, 1992) indicating that both platforms were exposed for some considerable time (Figure 11). It coincides with a number of important changes within the Pennine Basin, including a period of rifting and volcanism on the Derbyshire Platform (Fraser and Gawthorpe, 2003; Waters, 2009) and the influx of siliciclastic sediment in the northern Pennine Basin (so-called Yoredale Cycles; Tucker et al., 2009). It is also coincident with the diversification of *Gigantoproductid* brachiopods (Nolan et al., 2017). On the Namur-Dinant Platform carbonate sedimentation stopped during the Brigantian (Poty, 2016) whilst in the Rhenish Kulm Basin a sea level fall at the Asbian – Brigantian boundary is interpreted (Herbig, 2016). Therefore, although the hiatus could be indicative of significant, but still tectonically-controlled, basinal events, its recognition elsewhere in Europe, Russia as well as north America means that it could also be interpreted as a third – order sequence boundary associated with global cooling, as proposed by a number of previous studies (e.g. Smith and Read, 2000; Armendariz et al., Barnett et al., 2002; Giles, 2009; Qiao and Shen, 2015). Recent work suggests full icehouse conditions were not established until the very latest Mississippian (Serphukovian) or early Pennsylvanian (Montañez and Poulsen, 2013 and references therein), but the Asbian – Brigantian boundary perhaps provides the first indication of a critical change in global climate, associated with earliest stages of cooling, prior to the formation of peripolar ice formation in southern Gondwana (Montanez and Poulsen, 2013).

CONCLUSIONS

1) During the Asbian, healthy carbonate platform growth took place on the Derbyshire and North Wales platforms, with moderate- to high-energy conditions on the platform top sustained by a dominant north-westerly wind and currents driven through embayments and discontinuous facies belts on the platform margin.
2) Slope and platform margin stabilisation took place on windward (northern and western) margins by precipitation of radiaxial fibrous calcite cements, forming slope angles of 20 to 30^{o}. These margins were subject to periodic, tectonically-induced margin and slope collapse, forming embayments. Margins which did not parallel active faults are more likely to be linear. Leeward margins dipped less steeply, with basinward transport of cohesive sediment by slumping and gravity flow.
3) Carbonate productivity was strongly controlled by a range of environmental factors, not just water depth, such that facies form a mosaic with laterally discontinuous exposure surfaces that cannot be correlated for more than a few hundred metres in outcrop. Micro- and macrofaunal ranges are long, such that in combination it is not possible to identify regionally extensive faunal bands or sedimentary surfaces that can be correlated within the Asbian succession across the region of study.

4) On the Derbyshire Platform, syn-depositional volcanism produced extrusive lavas and volcanic ash deposits that are interbedded with Asbian limestone strata, but neither are seen on the North Wales Platform. On the North Wales Platform, periodic incursions of sandstone occur towards the top of the Asbian, sourced from landmasses to the south and west of the platform. Although fine grained siliciclastic mud incursions occurred on the palaeo-shoreline of the North Wales shoreline, it did not have a detrimental effect on carbonate productivity on the platform as whole.
5) Exposure events are less frequent, and surfaces less mature, on the Derbyshire Platform compared to the North Wales Platform, suggesting that sedimentation on the Derbyshire Platform occurred on deeper water and therefore had fewer, shorter exposure events. The succession of calcretes, palaeosols, mammilated surfaces, and rare coals, on the North Wales Platform indicate climate fluctuations between semi-arid and semi-humid conditions. These more frequent periods of platform exposure do not seem to have decreased the keep-up capacity of the platform because shallow-water platform top Asbian strata on both platforms are approximately 200 m thick.
6) In the latest Asbian, a sustained period of platform exposure created a regionally correlatable, relatively deep-cutting mamillated surface. A marked change in facies occurs above this surface, which is also present to the north of the study area, marked by the onset of the Yoredale depositional system. This suggests that it is the most reliable datum for correlation across the Pennine Basin
7) As well as having regional significance, the Asbian – Brigantian boundary could have greater global significance than has been acknowledged in recent years, potentially marking the onset of global cooling that had a marked environmental effect on subsequent carbonate platform growth. Given the lack of evidence for ordering and cyclicity within Asbian strata on the Derbyshire and North Wales Platform, it is proposed that the Asbian – Brigantian boundary is a stronger indicator the climatic transition associated with the second glacial advance of the Late Palaeozoic Ice Age, and potentially the onset of fourth-order glacio-eustacy.

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Figure Captions

Figure 1: Palaeogeography map of the mid-Asbian modified from Floodpage et al. (2001) and Fraser and Gawthorpe (2003) with outcrops and field areas highlighted.

Figure 2: Seismostratigraphic divisions of the Pennine Basin, after Ebdon et al. (1990), Fraser (1990), Fraser and Gawthorpe (2003), extrapolated to the North Wales Platform, 130 km westwards, with major tectonic and climatic events.

Figure 3: Map of the UK, with faults in Carboniferous strata highlighted, indicating two main field areas, A) The Great Orme, North Wales (BGS 1:10,000, 2016), B) Derbyshire (Fraser and Gawthorpe, 2003; Frazer et al. 2014).

Figure 4: A: Platform characteristics of the lower-mid Asbian northern margin of the North Wales Platform, showing a band of shallow-water skeletal mudstone-wackestone. The remainder of the platform is inferred to be emerged. B: Platform characteristics of the mid-upper Asbian southern margin of the Derbyshire Platform, showing a relatively shallow slope with slumping at the margin, and small mounds, minor grainstones and laterally discontinuous exposure events in the interior. C: Platform characteristics of the mid-upper Asbian northern margin of the Derbyshire Platform, showing a mound and shoal complex at the margin above a steep slope with boulder beds. Within the platform interior, minor grainstones, volcanics, and laterally discontinuous exposure events are characteristic. D: Platform characteristics of the mid-upper Asbian northern margin of the North Wales Platform. The margin is not exposed, but near the margin, shoals and mounds outcrop and there is one example of microbial mats. Landwards, siliciclastic mudstones and coals, occur in the interior around the Asbian – Brigantian boundary.

Figure 5: (A) Steeply dipping northern margin of the Derbyshire Platform cemented debrites. (B) The fabric of debrites is best observed on a polished surface. They comprise fragmented, centimetre-scale bioclasts which are cemented by white radiaxial-fibrous cements. The southern margin of the Derbyshire Platform comprises slumped, dolomitized floatstones (C and D), Harborough Rocks.

Figure 6: Summary of principal distinctive microfacies identified, referred to throughout text. PPL = Plane polarised light; XPL = cross polarised light. A: (PPL) Platform slope facies (Winnats Pass, Locality 18) comprising cloudy, radiaxially cemented brachiopods which are partly dissolved; B: (PPL) Diverse algal assemblage hosted by clear cements sampled from the western margin of the Derbyshire Platform (Locality K); C: (PPL) Sample of mound from the North Wales Platform (Little Orme, Locality 20) comprising fenestrate bryozoans hosted by sucrosic sparite. The right hand side of the section is dolomitised; D: (XPL) Second sample from mound from the North Wales Platform (Little Orme, Locality 20) comprising radiaxially cemented *Koninckopora* (dasycladacean algae); E: (PPL) Typical example of platform interior facies comprising micrite-hosted packstone with highly fragmented bioclasts (Great Orme, Locality D); F: (PPL) Carbonate mud-wackestone from an emergent surface (Great Orme, Locality D), partially dissolved and replaced by cement.

Figure 7: A: lateral log of the carbonate mound of the Little Orme, North Wales Platform; B: lateral log of the carbonate mound of Pin Dale Quarry, Derbyshire Platform; C: vertical log of the carbonate mound of Pin Dale Quarry, Derbyshire Platform. Note the different scales of each log.

Figure 8: A: thickly bedded platform interior bioclastic wackestones and packstones with bioturbated beds, North Wales Platform; B: location of coral-dominated mound, morphology of mound, and densely packed *Siphonodendron* corals, northern platform interior, North Wales Platform; C: form lines of skeletal and algal grainstones, parallel to the margin, North Wales Platform. D: stratiform and pinnacle laminites, northern margin, North Wales Platform.

Figure 9: Photogmicrographs of: A: *Koninckopora inflata* (Loggerheads Limestone), B: *Bibradya sp.* (Monsal Dale Limestone), C: *Omphalotis omphalota* (Loggerheads Limestone), D: *Forschia* sp. (Loggerheads Limestone), E: *Cribrospira panderi* (Bee Low Limestone), F: *Cribrostomum* sp. (Loggerheads Limestone), G: *Lituotubella glomospiroides* (Loggerheads Limestone), H: *Eostaffella*

Figure 10A: Exposure-related facies.
i: Type A, undulating limestone, North Wales Platform;
ii: Type B, nodular limestone, north wales Platform;
iii: red-coloured unconsolidated muds and clays, North Wales Platform;
iv: brown-coloured unconsolidated muds and clays with plant material and quartz clasts, Derbyshire Platform;
v: yellow-coloured unconsolidated muds and clays, North Wales Platform.

Figure 10B: Igneous facies in core.
i: contact between extrusive volcanics (weathered basalt) and Bee Low limestone, Derbyshire Platform;
ii: multicoloured volcanic ash from core, Derbyshire Platform.

Figure 10C:
i: Mudrock overling and draping a Type A mammilated surface, Trefor Rocks, North Wales Platform
ii: Mudrock bed between two limestone beds, with no evidence of emergence, suggesting marine deposition, Trefor Rocks, North Wales Platform
iii: Dark green palaeosol overlying karstic surface beneath Asbian – Brigantian boundary, Tarmac Hendre Quarry, near Mold. Green-brown weathered limestone is Asbian, grey-weathered limestone is Brigantian

Figure 11: Regional exposure surface cropping out on the North Wales Platform (top photo; Locality G) and Derbyshire Platform (bottom photo) where it is characterised by a 0.5 m thick package of rubbled limestone and unconsolidated mud/clay (Redhill Quarry, 4 km north of Locality 17).

Figure 12: Volcanic centres near Buxton (NW) and Matlock (SE) and the approximate distribution of volcanic ash based on core observations by Cox and Bridge (1977), Cox and Harrison (1980), Bridge and Gozzard, (1981) and Harrison (1981).

Figure 13: Biostratigraphic correlation across the Derbyshire and North Wales Platfroms (west to east), with Asbian – Brigantian boundary highlighted.

Figure 14: Regional Asbian palaeogeography, modified from Floodpage et al. (2001) andFraser and Gawthorpe (2003). A: ramp development on the Derbyshire Platform with initial stages of margin formation on both platforms. B: development of flat-topped platforms in Derbyshire and North Wales, C: Regional platform emergence and siliciclastic inundation on the North Wales Platform.

Tables

Locality number	Log name	DP/NWP	Source	Length (m)	Easting	Northing
1	Cardlemere Lane	DP	C	35.7	417627	358349
2	Gratton Moor	DP	C	41.9	420350	360340
3	Lees Bottom	DP	C	40.2	417050	370500
4	Bee Low Quarry	DP	C	100	408540	379040
5	Biggin	DP	C	100	415250	358200
6	Four Lane Ends	DP	C	42	427295	354327
7	Hurdlow Town	DP	C	120	411347	366736
8	Longcliffe	DP	C	21	422090	356440
9	Middle Peak Quarry (1)	DP	O	8.55	427882	355009
10	Middle Peak Quarry (2)	DP	O	4.26	428193	354894
11	Cave Dale (1)	DP	O	8	415059	382607
12	Cave Dale (2)	DP	O	7	415016	382609
13	Cave Dale (3)	DP	O	12	415016	382570
14	Pin Dale Quarry (1)	DP	O	6.5	415814	382279
15	Pin Dale Quarry (2)	DP	O	9	416083	382332
16	Pin Dale Quarry (3)	DP	O	26	416083	382332
17	Carsington	DP	O	4	427941	353868
18	Winnats Pass (1)	DP	O	15.8	413792	382719
19	Great Orme South West (1)	NWP	O	43.1	276633	382430
20	Little Orme Mound	NWP	O	40	281885	382664
21	Marine Drive (1)	NWP	O	3.6	278132	383263
22	Marine Drive (2)	NWP	O	9.5	275295	383827
23	Marine Drive (3)	NWP	O	10.5	278120	383763
24	Great Orme South West (2)	NWP	O	67	276646	382813
25	Great Orme South East (1)	NWP	O	52	277621	382903
26	BLBP33F147	DP	L	243	418857	369666
27	BLBP40F17A	DP	L	243.4	423334	361206
28	BLBP40F17B	DP	L	235.6	423769	361449
29	BLBP41F18B	DP	L	197	419075	361004
30	CELFMB9	DP	L	67.5	414693	381719
31	CELFMB13	DP	L	54.9	414681	381810
32	CELFP722	DP	L	19.5	408573	378387
33	CELFP723	DP	L	29.9	408208	377473
34	CELFP726	DP	L	84.5	418944	376568
35	CELFP727	DP	L	84.5	417279	375122
36	CELFMB14	DP	L	64.8	414604	381653
37	CELFMB15	DP	L	68.4	414511	381740
38	CELFMB16	DP	L	40.5	414617	381770

39	CELFAF3	DP	L	81	414851	381982
40	CELFAF4	DP	L	84.6	415112	382094
41	CELFAF1	DP	L	72.9	414963	382249
42	CELFAF2	DP	L	83.7	415160	382272
43	CELFAF5	DP	L	111.6	415587	382119
44	CELFP2	DP	L	36	415927	382199
45	CELFP721	DP	L	24.2	414218	380272
46	CELFP725	DP	L	43.4	415126	382533

Table 1a. Log names, platform which log was undertaken (DP = Derbyshire Platform, NWP = North Wales Platform), data source (O = outcrop, C = core, L = literature). Note logs starting BLBP: Aitkenhead et al (1985), P = page number; F = figure number. Logs starting CELF: Stevenson and Gaunt (1971), P = page number; F = figure number; MB = name used in literature.

		Easting (UK National Grid)	Northing (UK National Grid)
A	Castleton	415086	382935
B	Buxton	405757	373139
C	Matlock	429894	360294
D	Great Orme	276750	383335
E	Little Orme	281298	382384
F	Penmon Point	264076	381251
G	Llangollen	321495	342006
H	Cefn Mawr	310823	293820
I	Earl Sterndale	408014	366937
J	Monsal Trail	416761	372610
K	Hand Dale/Long Dale (near Hartington)	413770	361204

Table 1b: Additional Localities, not logged but mapped and mentioned in text and shown in Figure 1. Grid references are the central point to the general area which may be <5 km^2.

~~Facies Association~~ Depositional Environment	Facies	Distribution	Texture and geometry	Average grain volume	Average matrix and cement volume	Sedimentary structures	Biogenic structures	Diagenetic features	Interpretation
Slope / foreslope	Limestone boulders, several metres in diameter, forming a ~~M~~matrix-supported conglomerate Slumped wack/packstone and floatstone	Matrix supported conglomerate and boulders only occur on northern and western margin of Derbyshire Platform Slumped wack/packstone occurs on southern margin of Derbyshire Platform	Matrix-supported conglomerate has pooly sorted wack/packstone clasts (0.5-10cm diameter) and fragmented skeletal debris	Crinoids 5.3% (0.3 - 18.7%); Bryozoa 4.6% (0.7 - 14.7%) Foraminfera 2.4% (1.7 - 3.3%); Brachiopods 0.9% (0.0 - 2.7%) Dasycladaceoan algae 1.1% (0.0 - 2.7%); Other skeletal (<2%) Peloids 19.5% (3.7 - 34.4%); Intraclasts 1.4% (0.0 - 6.0%)	Micrite 15% (0 - 41%) Radiaxial fibrous calcite 48% (37 - 68%) Dolomite <1%; Bitumen <1%	Conglomerate dips at >30^{o} north, towards basin, with poorly defined cross beds Slumped beds dip at ~20^{o} south, towards basin	None	Geopetal cement in brachopod moulds within conglomerate dip at ~30^{o} Conglomeratic clasts coated by radiaxial fibrous calcite Slumped wack/packstone beds are differentially dolomitized	Coarse grain size (pebbles and boulders) indicate mass transport by gravity Localisation of facies on platform margins and palaeo-dips are consistent with slope sedimentation, with periodic mobilisation of sediment, e.g. due to faulting/mass wasting Radiaxial fibrous calcite cement formed on windward margin by seawater circulation, binding clasts and stabilising a high slope angle On the leeward margin, lower slope angles developed, with periodic slumping induced by tectonic activity
Platform margin	Mounded, skeletal wackestone Skeletal grainstone Laminated and stratiform bindstone Siphonodendron rudstone - framestone	Mounded facies are located on the northern and western margins of the North Wales and Derbyshire Platforms Skeletal wack/packstones occur between mounds Skeletal grainstones downlap onto carbonate mounds and form isolated sheets	Dome-shaped mounds up to 40 m wide and 9m high, with core of crinoids, brachiopds and bryozoa with peloidal cement and crinoidal pack-grainstone flanks Skeletal wack-packstone within intermound areas comprising fragmented bryozoa, brachopods, corals, foraminifera and micrite Grainstones dominated by crinoids with fragmented bryozoa, benthicformainifera, *Konickopora*	**Mound** Bryozoa 8.8% (0.7 - 23.7%); Crinoids 7.5% (0.0 - 28%);Brachiopods 2.9% (0.3 - 9.0%); other skeletal each <1% Dasycladacean algae 0.9% (0.0 - 4.7%) Peloids 15.6% (1.3 - 47.3%); Aggregate grains 3.3% (0.0 - 14.3%) **Grainstone** Crinoids 18.2% (1.0 - 44.7%); Brachiopods 8.8% (0.7 - 12.7%); Bryozoa 4.2% (0.0 - 12.0%); Foraminfera 3.0% (0.0 - 8.7%); Dasycladaceaen algae 3.5% (0.0 - 10.6%); all other skeletal allochems each < 1% Peloids 15.5% (0.3 - 24.7%); Aggregate grains 3.1% (0.0 - 10.7%)	**Mound** Micrite 19.7% (0.0 - 41.3%) Sparite cement 38.6% (23.3 - 53.5%) **Grainstone** Micrite 0.4% (0.0 - 2.3%) Sparite cement 34.4% (16.3 - 64.0%) Bitumen 0.1% (0.0 - 0.3%)	Sheet-like grainstones are cross-bedded, thickly bedded (<2 m), up to 5 m thick and pinch out laterally over < 100 metres Intermound grainstones downlap onto mounds and are < 10 m wide and < 10 m thick	None	Abundant peloidal and radiaxial fibrous calcite cement throughout mounds Skeletal grainstones cemented by clear, blocky and sparry calcite	Platform margin mounds formed by trapping and binding of skeletal grains by lime mud, potentially facilitated by microbial binding, although evidence for this is cryptic Intermound areas accumulated fine-grained, fragmented skeletal debris and lime mud Skeletal grainstones formed sheet-like bodies in high energy areas of the platform margin and onlapped mounds
Platform top	Mounded skeletal mudstone-wackestone Mottled mud/wackestone Skeletal wack/packstone Skeletal grainstone	Mounds are localised on the Derbyshire Platform, on the platform top, with low height - to - width ratio (20m wide and 15 m high) Mounds often occur on top of skeletal grainstones Skeletal grainstones are < 0.3 m thick and 3 -10 m wide	Mounds comprise *Siphonodendron* corals, brachiopds, bryozoa, demosponges and gastropods Skeletal grainstones comprise *Dasycladacean* algae, brachiopods, benthic foraminfera and peloids Skeletal wackestone comprises bethic foraminfera, brachiopods, crinoids, bryozoa and serpulids.	**Mound** Coral 18.2% (9.0 - 23.3%); Brachiopods 5.6% (3.0 - 7.7%); Bryozoa 2.1% (1.7 - 2.3%); other skeletal each < 1% Peloids 2.0% (0.0 - 6.0%) **Bedded facies** Brachiopods 10.6% (6.3 - 18.3%); Foraminifera 4.4% (3.0 - 7.0%); Crinoids 3.0% (1.7 - 5.3%); Bryozoa 1.5% (1.3 - 2.0%); Dasycladacean algae 1.8% (0.0 - 5.3%); other skeletal grains < 1% Peloids 16.1% (2.3 - 27.4%); Aggregate grains 2.3% (0.0 - 7.0%)	**Mound** Micrite 44.5% (40.7 - 48.0%) Sparite cement 24.3% (21.3 - 26.3%) Dolomite < 1% **Bedded facies** Micrite 40.3% (38.7 - 41.3%) Sparite cement 8.0% (1.7 - 11.7%)	With the exception of mounds, beds are laterally continuous and parallel bedded	Skeletal wackestone to mudstone has dark, cm-scale mottling with diffuse edges	Compacted (stylolitized) and cemented by sparry calcite	Skeletal wack/packstone and grainstone are typically flat bedded and laterally continuous on an outcrop scale. They occur extensively across the Derbyshire and North Wales Platform. High diversity, high abundance skeletal assemblage is consistent with moderate energy deposition in the photic zone Coral-dominated mounds are locally developed on topographic highs and interpreted to have been deposited under high energy conditions
Peritidal	Algal laminite	Very rare occurrence on North Wales Platform, beneath emergent surfaces	Crinkled, pinnacled bindstone	Minor quartz and muscovite	-		None	Minor halite	Microbial bindstone deposited in intertidal setting. Trapping of quartz and muscovite from terrestrial source. Halite consistent with evaporation

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Emergence - related facies	A - Mammilated surfaces B - Nodular / rubbled limestone C - Unconsolidated muds / clays D - Coal	Type A surfaces are ubiquitous on both platforms. Type B surfaces occur on both platforms but are thicker and more extensive on North Wales Platform Type C & D surfaces are mostly restricted to North Wales Platform. Type D are only found in the most proximal parts of the North Wales Platform	Type A surfaces have wavelength of 0.2 to 1 m, and downcut into underlying beds. They are often coated by clay rich in volcanic ash on the Derbyshire Platform Type B surfaces are <1.5 m thick and comprise clast-supported conglomerates of skeletal packstone (nodules ~ 2-5cm diameter) Type C surfaces comprise calcite, kaolinite, muscovite and quartz	-	-	-	Vertical and sub-vertical, structureless tubular structures with a consistent diameter underlie Type B surfaces and have a coarser grained sediment fill than the surrounding matrix are interpreted as open burrows formed in firm sediment, prior to emergence	Type B surfaces, nodules are cemented by sparry calcite Type C surfaces include haematite	Type A surfaces are interpreted to have formed by erosion beneath soil cover Type B surfaces are calcretes Type C surfaces are paleosols Type D surfaces are coals formed within swamps close to the palaoe-shoreline
Igneous rocks	A - Amygdoloidal basalt B - Clay-rich layers	This facies association only occurs on the Derbyshire Platform	Type A - Amygdoloidal basalt is interbedded with limestone and rarely forms localised, columnar basalt Type B - clays that lie on top of mammilated surfaces	-	-		None	Type A are massive, dark green to greenish-black, pyroxene-rich with calcite cemented vesicles Type B comprises multi-coloured, friable clays	Amydoloidal basalts interpreted as lava flows, with columnar structures indicative of cooling to form vertical joints Clays have been analysed previously (Walkden, 1972) to be potassium bentonites, an alteration of volcanic ash
Siliciclastic	~~A - Quartz pebble conglomerate~~ ~~B - Fine to coarse grained sandstone~~ C - mudrock ~~(clastic)~~	This facies association only occurs on the North Wales Platform	~~Sandstones and quartz pebble conglomerate are dominated by quartz with sub-rounded, well sorted grains~~ ~~Locally, sandstone contains Dasycladacean green algae~~ Silici~~Mudrock is~~ clastic and forms beds up to ~1 metre thick beneath and above emergent surfaces	-	-	~~Fine grained sandstone has upper-plane-bed lamination and unidirectional cross - bedding~~ ~~Fine to coarse grained sandstone with multi-directional cross-bedding~~ ~~Mudrock is P~~planar laminated and fissile	None	~~Sandstones are calcite and dolomite cemented~~.	~~The sub-rounded and well-sorted texture of quartz grains in sandstones and quartz conglomerate indicates moderate maturity~~ ~~The quartz-rich composition and unimodal cross beds suggest deposition in a fluvial channel, whilst herringbone cross stratification and dasycladecan algae are indicative ofa shallow marine, tidally influenced setting.~~ Mudrock is interpreted as marginal marine, since they are only found in the most proximal settings, in proximity to emergent surfaces

Table 2: Summary table of distribution, sedimentological characteristics and interpretation of facies associations and facies- observed in the strata of the Derbyshire and North Wales Platforms, quantified using point counting of 300 points per thin section.

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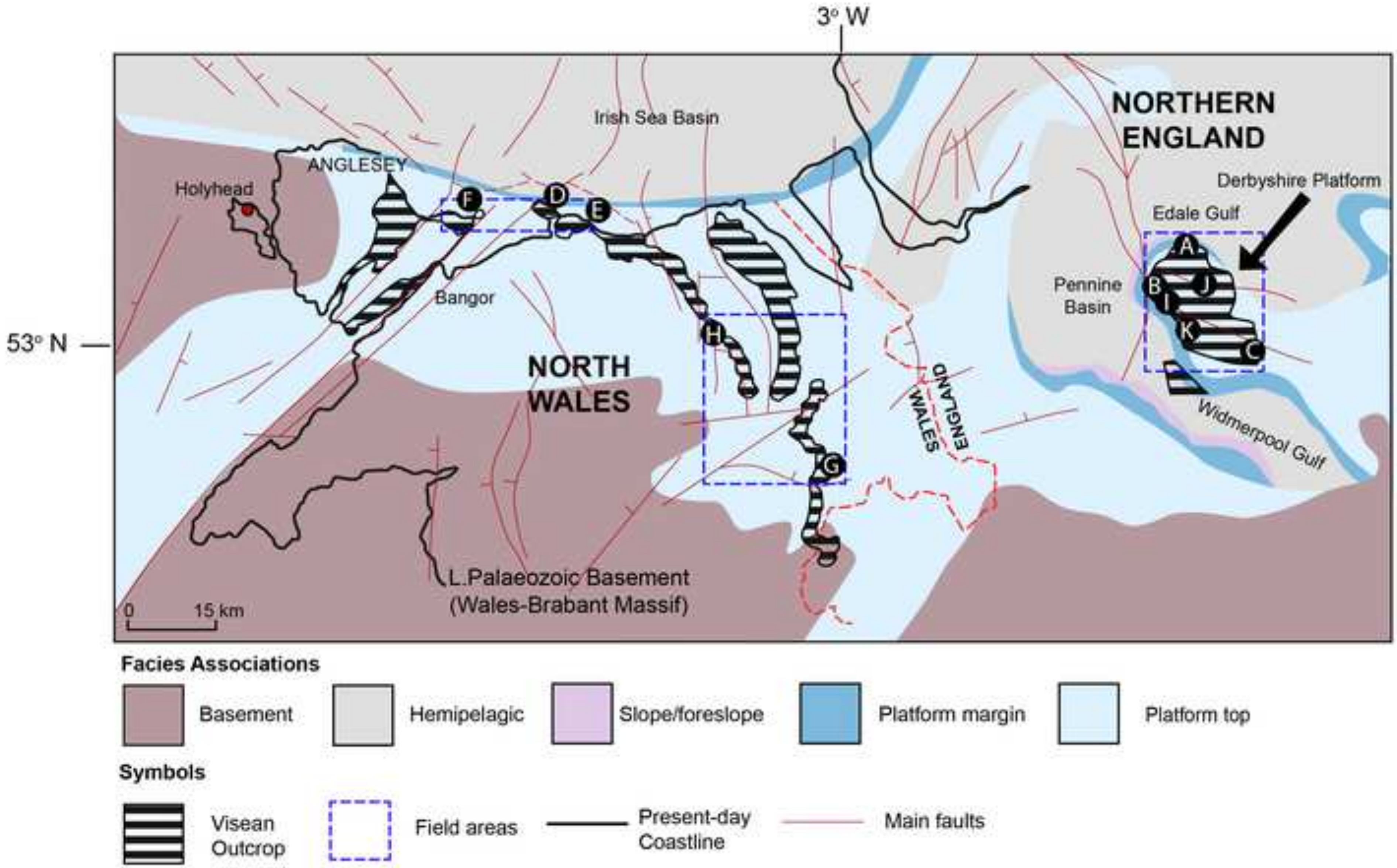
Sandstone Facies	Locality	Easting	Northing	Direction
1 – quartz arenite	Locality 19	277566	383190	124/05 NE
2 – calcite cemented sandstone	Locality 19	277481	383138	180/04 N, 179/04 N, 127/02 NE
2 – calcite cemented sandstone	Locality F	263925	380927	152/23 NE, 151/21 NE

Table 3: Palaeocurrent directions for two sandstone facies which contain crossbedding. Palaeocurrent trends are typically towards the NE.

figure 1 Click here to access/download;figure;Figure 1.jpg



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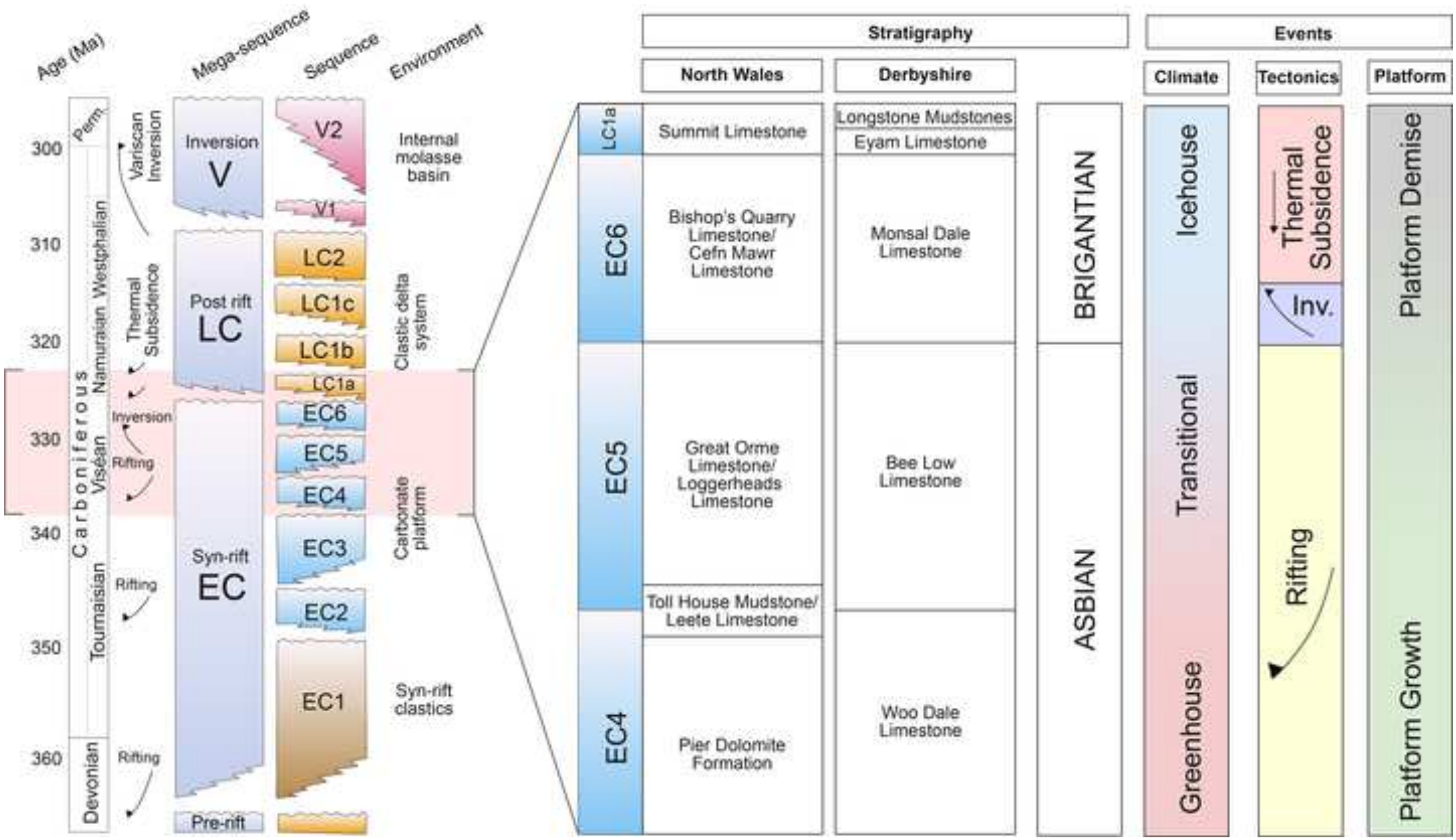

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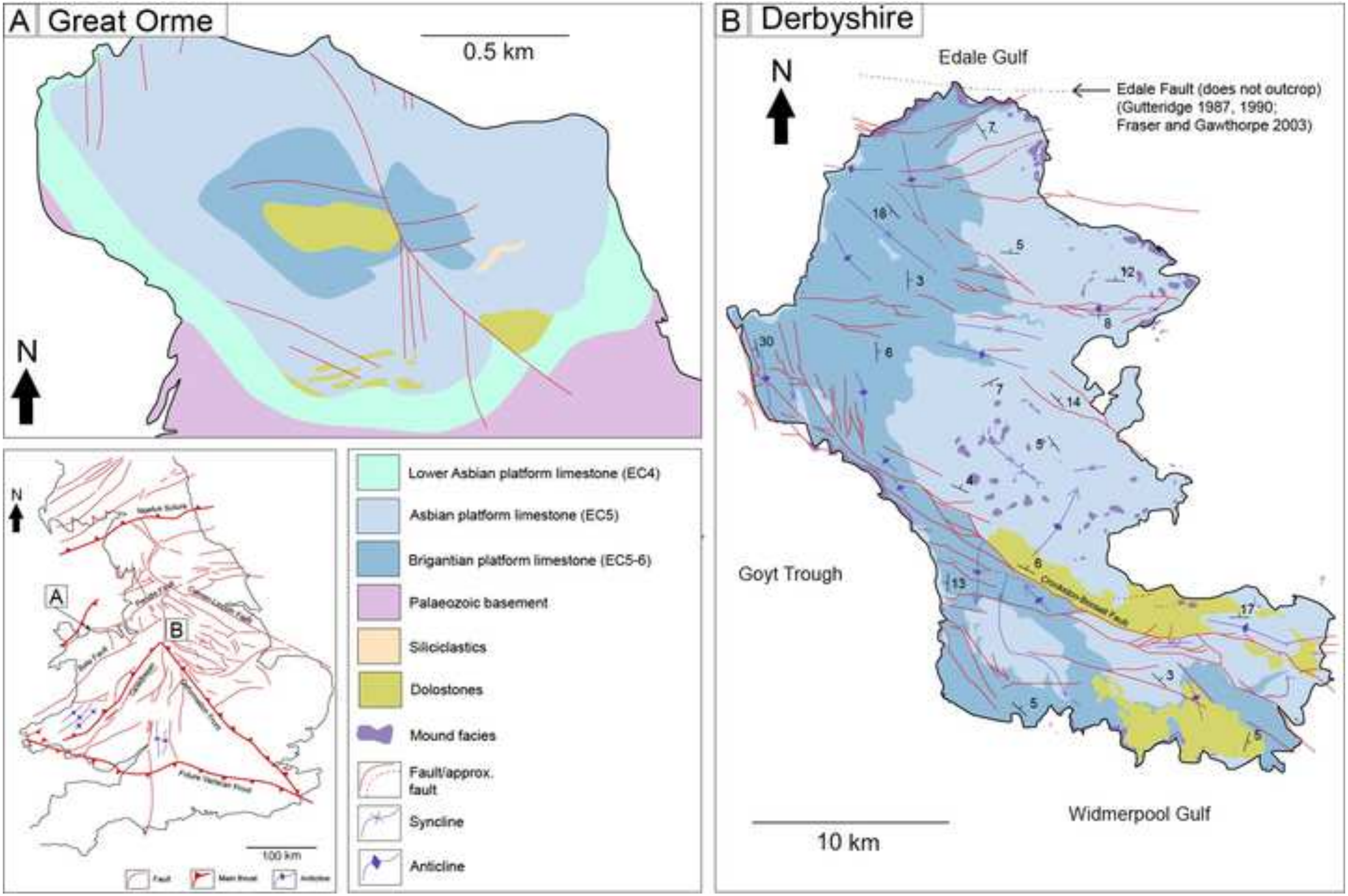

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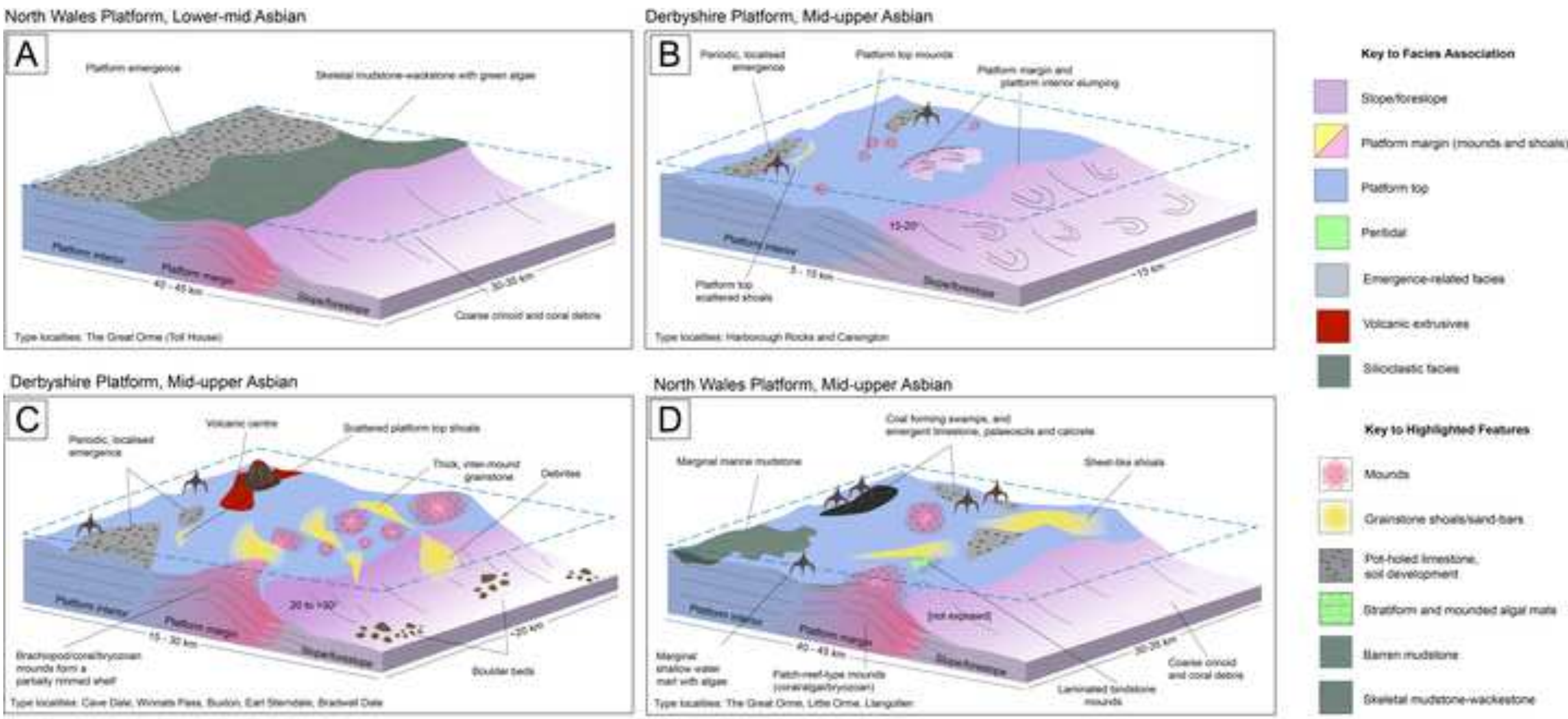

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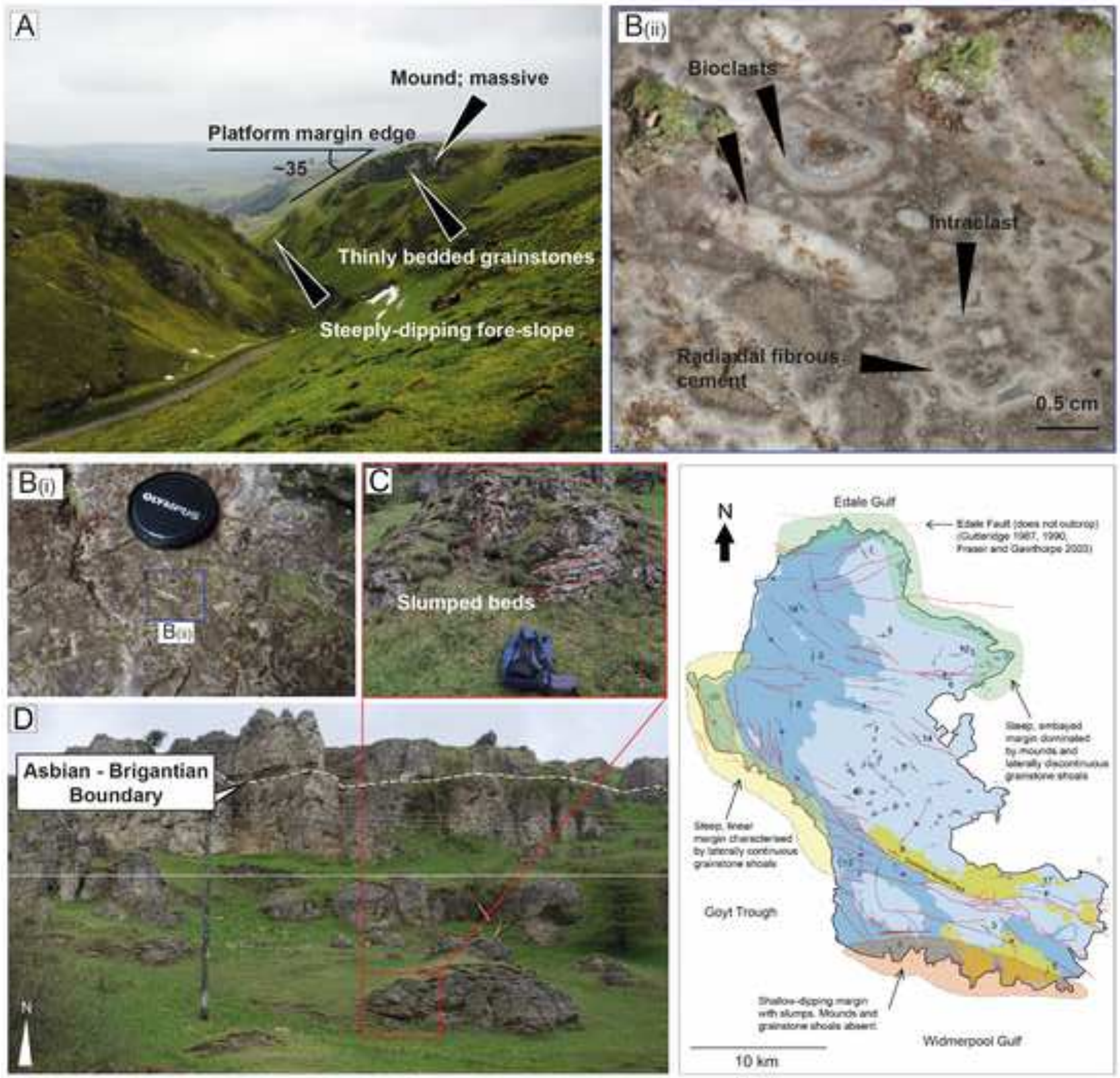
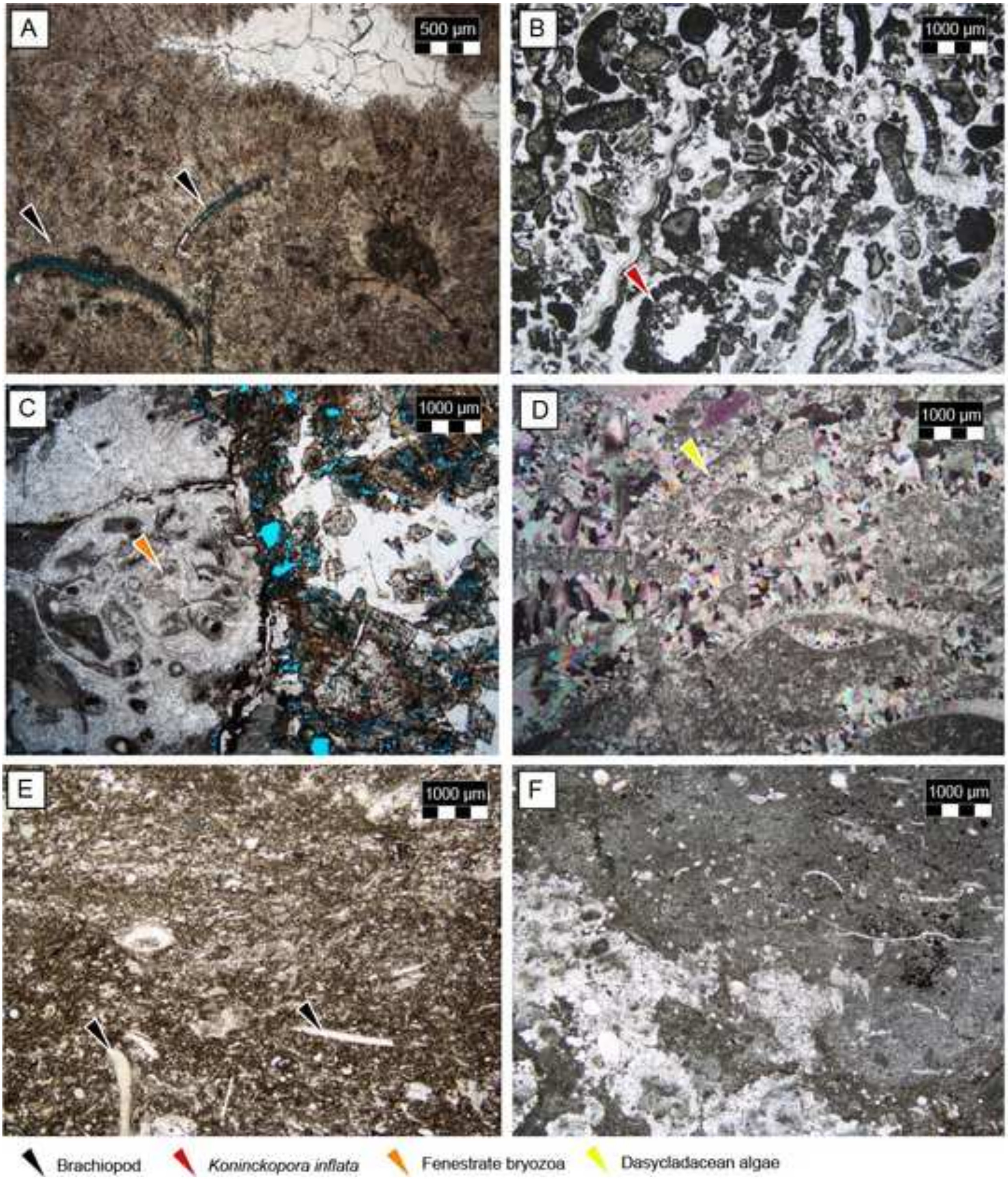

A
Mound; massive
Platform margin edge
~35°
Thinly bedded grainstones
Steeply-dipping fore-slope
B(ii)
Bioclasts
Intraclast
Radiaxial fibrous cement
0.5 cm
B(i)
B(ii)
C
Slumped beds
D
Asbian - Brigantian Boundary
N
N
Edale Gulf
Edale Fault (does not outcrop) (Gutteridge 1987, 1990, Fraser and Gawthorpe 2003)
Steep, embayed margin dominated by mounds and laterally discontinuous grainstone shoals
Steep, linear margin characterised by laterally continuous grainstone shoals
Goyt Trough
Shallow-dipping margin with slumps. Mounds and grainstone shoals absent.
Widmerpool Gulf
10 km


A
500 µm
B
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C
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Brachiopod
Koninckopora inflata
Fenestrate bryozoa
Dasycladacean algae

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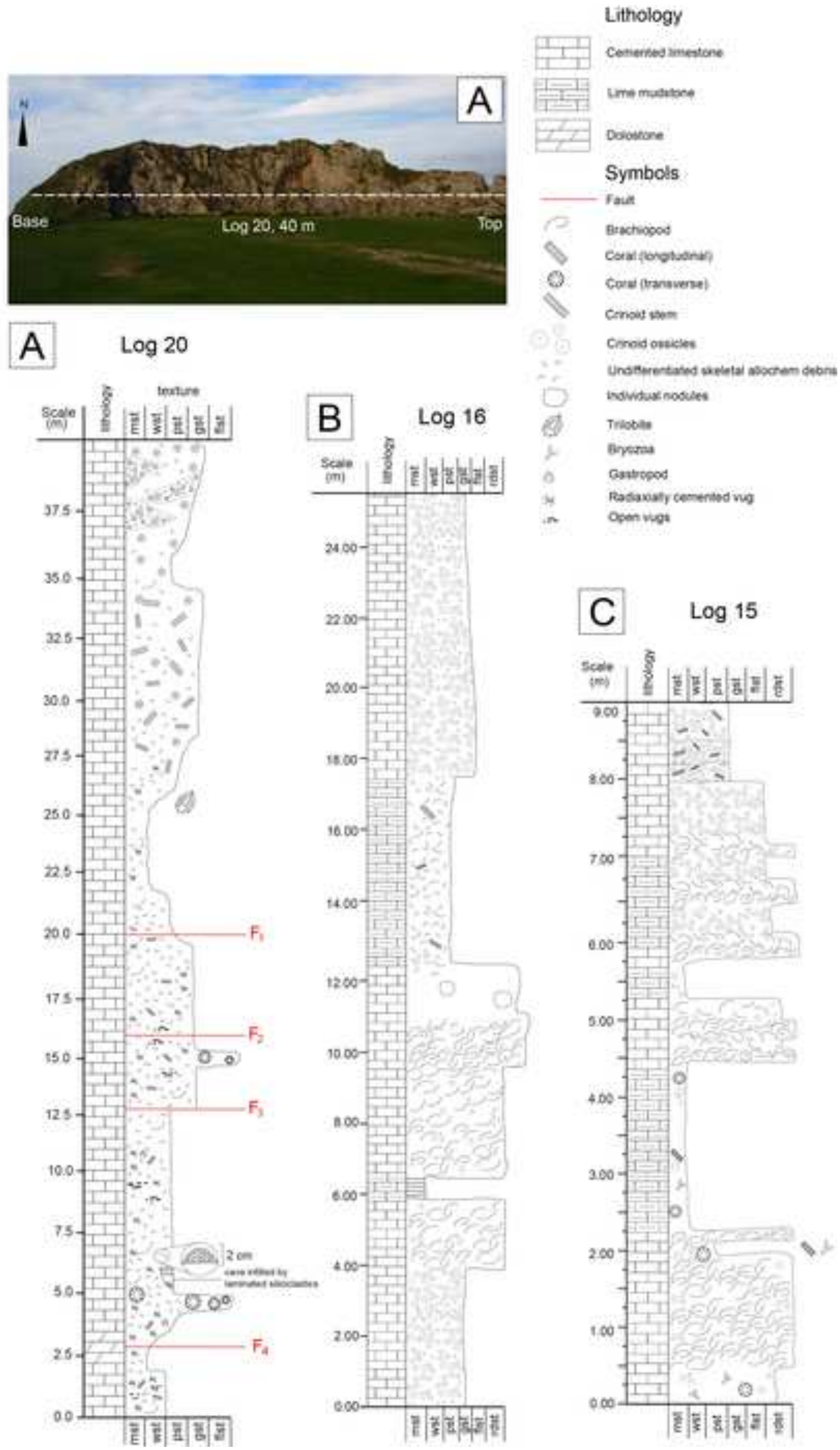

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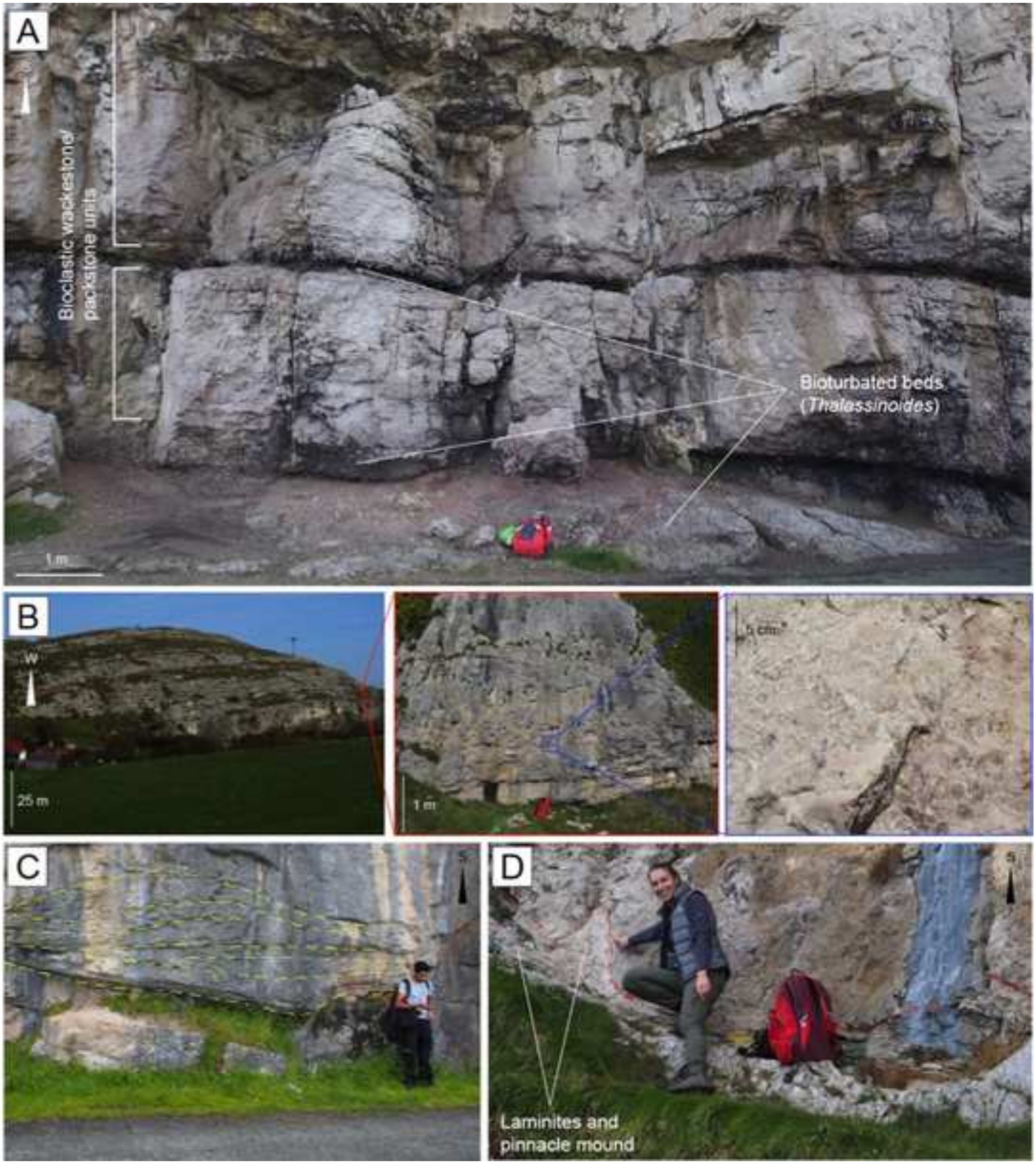

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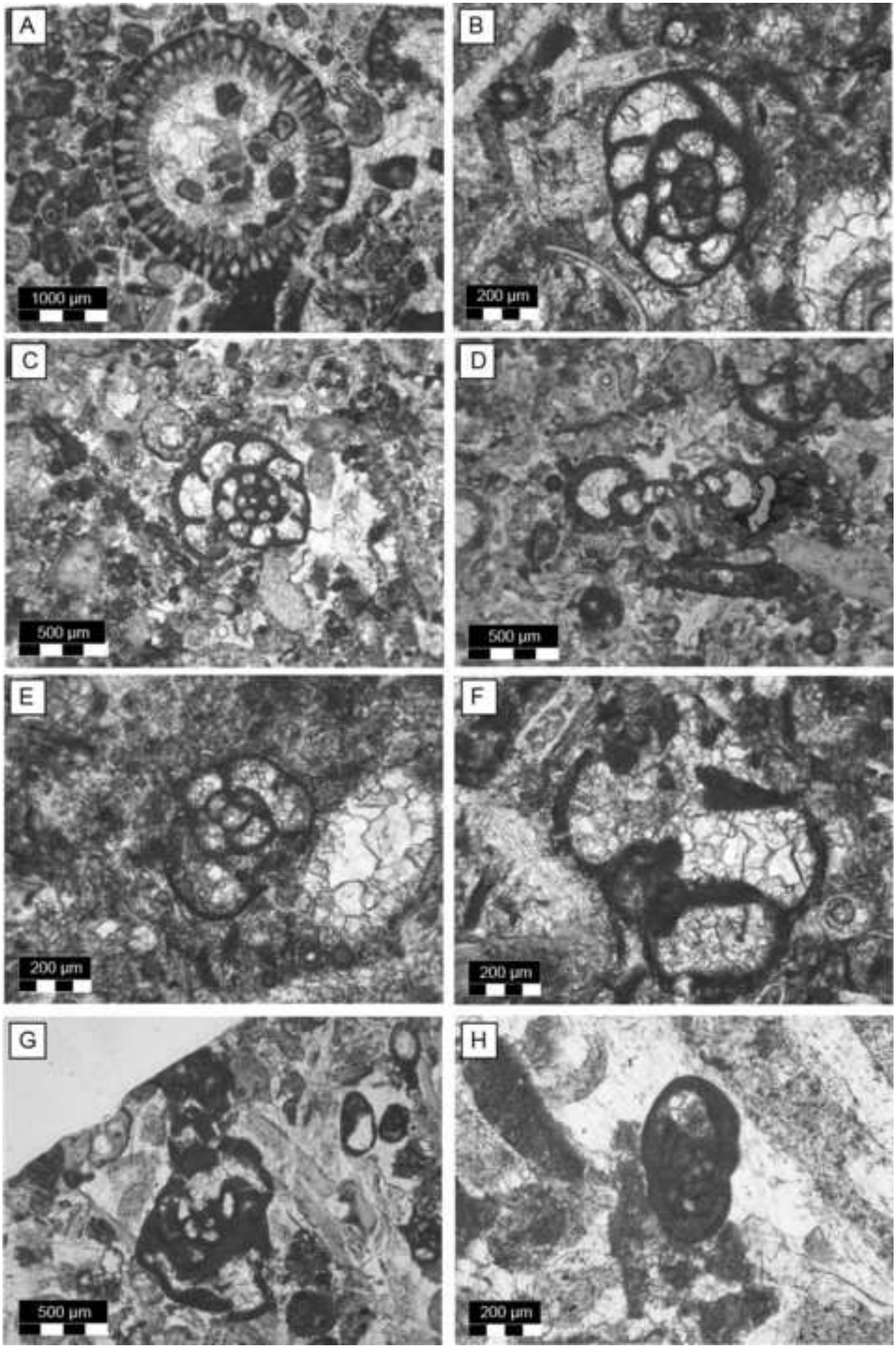

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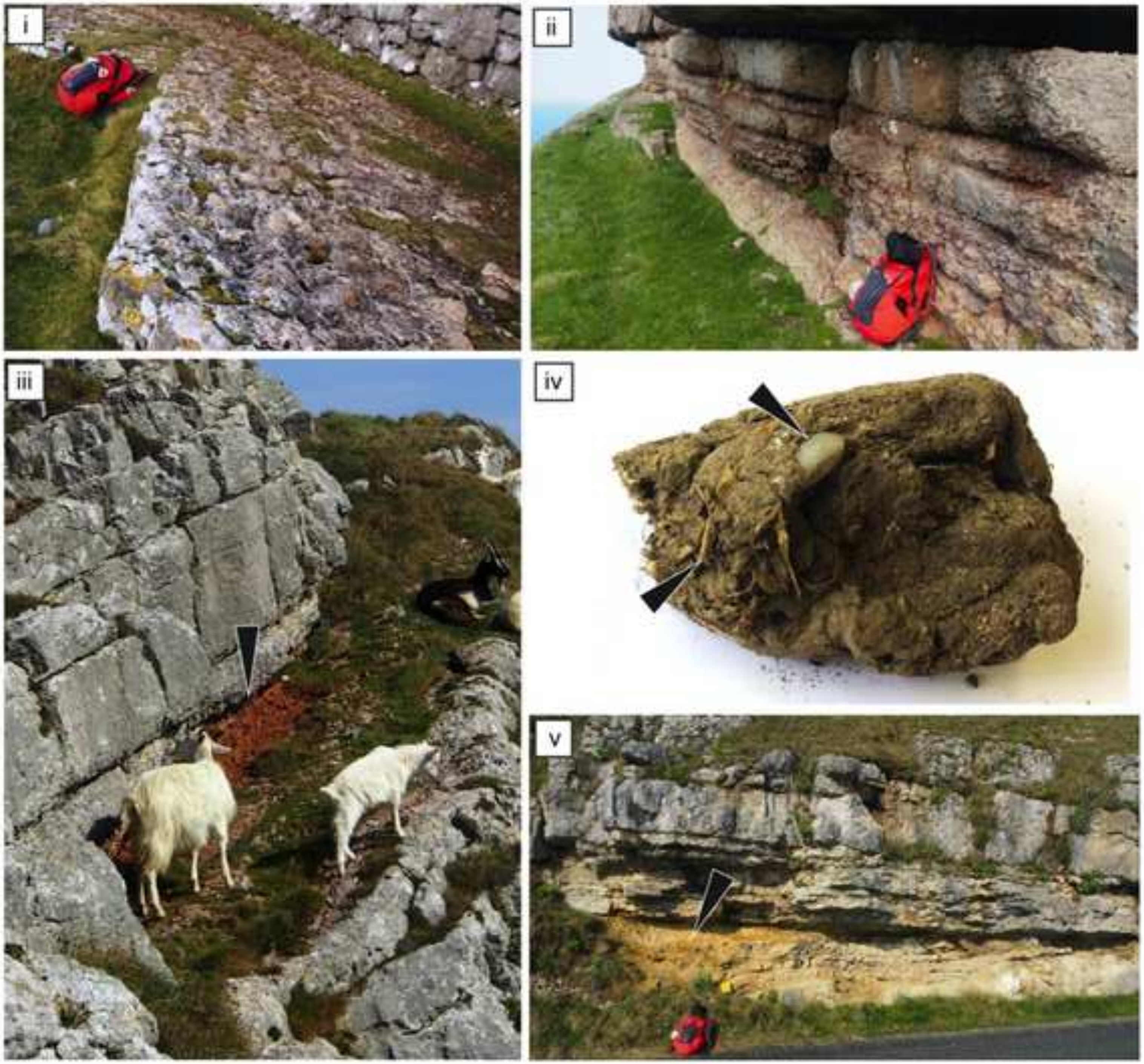

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figure 10c

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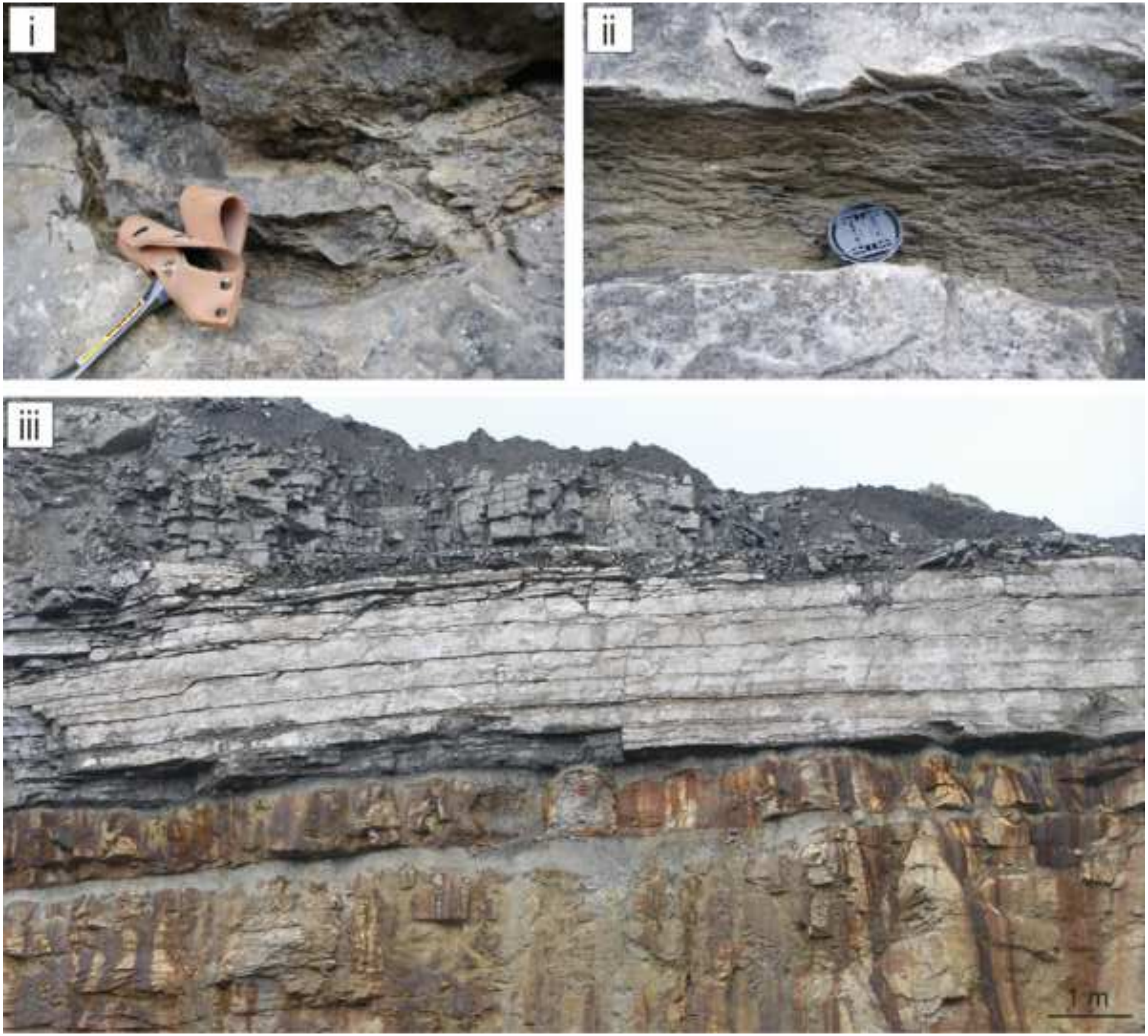

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figure 12

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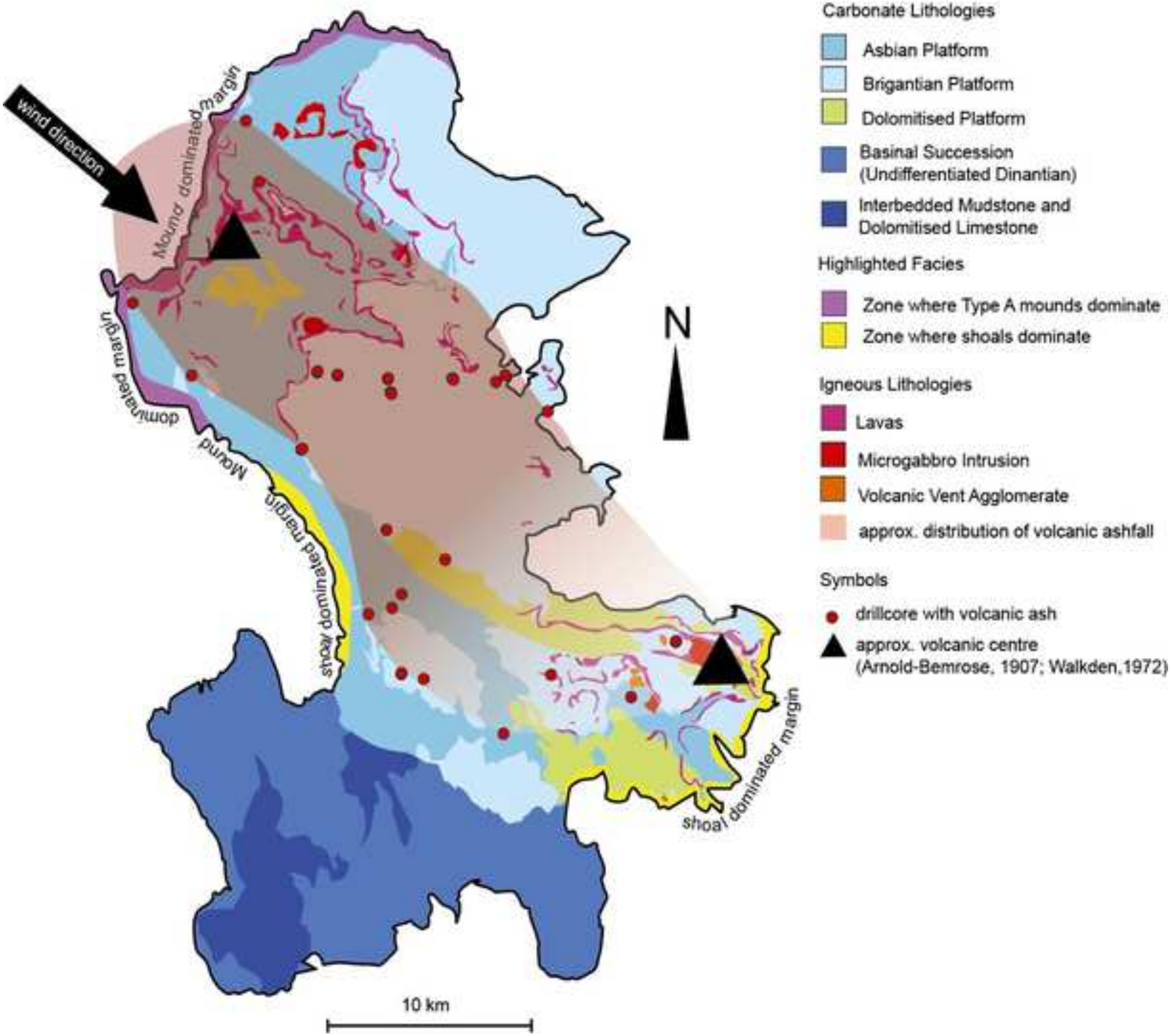

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