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Late Silurian event stratigraphy and facies of South Wales and the Welsh Borderland, United Kingdom

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Abstract

Lithofacies and biostratigraphical analysis has enabled the establishment of a stratigraphic event framework for Ludfordian and Pridoli strata in south Wales and the Welsh Borderland. In SW Wales, the Golden Grove Axis acted as a structural hinge separating the shallow marine storm-influenced Cae'r mynach Seaway from a pediment surface above which Ludfordian colluvium (Abercyfor Formation) was deposited. The Axis seeded four NW-derived river-influenced delta progrades of Leintwardinian to early Pridoli age (Tilestones Formation). A NE-sourced early Pridoli wave-influenced delta deposited the Downton Castle Sandstone Formation (DCSF), coeval to the youngest Tilestones prograde, with a lateral interface existing between Mynydd Epynt and the Clun Forest area. Except for the Malverns area, the DCSF is no longer recognized south of the Neath Disturbance. Early Pridoli forced regression promoted widespread subaerial exposure north of the Neath Disturbance, with incision into tracts close to the Welsh Borderland Fault System. The basinward-shift in facies belts resulted in marine erosion and deposition of a phosphatic ravinement pebble lag. The wave-influenced Clifford's Mesne Sandstone Formation delta subsequently seeded on the Gorsley Axis with tidally influenced Rushall Formation accumulating in a back-barrier setting. The Pwll-Mawr Formation records the easterly advance of coeval coastal deposits on the western side of the remnant Cae'r mynach Seaway. Behind migrating delta coastlines, green muds accumulated on coastal plains (Temeside Mudstone Formation) with better drained red dryland alluvium (Moor Cliffs Formation) charting expansion of Old Red Sandstone lithofacies. Mid-Pridoli incision preserves the Pont ar Llechau Formation estuarine valley fill.

1. Introduction

The transition from marine late Ludlow facies into continental Old Red Sandstone (ORS) deposits widely seen in South Wales and the Welsh Borderland (Figures 1 and 2) is linked to fundamental changes in palaeogeography and sediment provenance. It records the abandonment of the Early Palaeozoic Welsh Basin as the site of sediment accumulation, the arrival of red beds sourced from a growing Caledonian Orogen to the north and its accommodation within the successor Anglo-Welsh Basin.

The stark changes in facies and faunas associated with this transition have long attracted the attention of geologists. In studying them in Shropshire, Murchison (1839) discovered the vertebrate-bearing Ludlow Bone Bed (LBB) which he used to define the boundary between his newly erected Silurian and ORS 'systems'. This was later adopted as the *de facto* Silurian–Devonian boundary for this region (see review by D.A. Bassett, 1991). The LBB continued in this defining role until the formal introduction of the Pridoli Series (Bassett, 1985), since when it has been widely assumed to mark the UK base of this newest and youngest Silurian division (e.g. Cocks *et al.* 1992; Miller, 1995; White & Lawson, 1989; Lane, 2000). With the recognition that a significant part of the ORS succession in the southern UK is Pridoli in age, the concept and use of a basal Devonian 'Downton Series' was abandoned (e.g. Cocks *et al.* 1992; Schofield *et al.* 2009).

The historical and stratigraphical importance of the LBB, and the facies changes associated with it, is reflected in numerous palaeontological studies of the associated strata (e.g. Elles & Slater, 1906; Holland *et al.* 1963; Bassett *et al.* 1982; Miller, 1995; Siveter *et al.* 1989; White & Lawson, 1989; Lane, 2000). However, sedimentological investigation of the transition has been limited both in terms of the stratigraphy and geographical area (e.g. Allen & Tarlo, 1963; Antia, 1979, 1980, 1981; Waters & Lawrence, 1987; Smith & Ainsworth, 1989; Veevers & Thomas, 2011; Bailey & Bailey, 2019). With the notable exceptions of J.S.C. Hobson, unpub. PhD thesis,

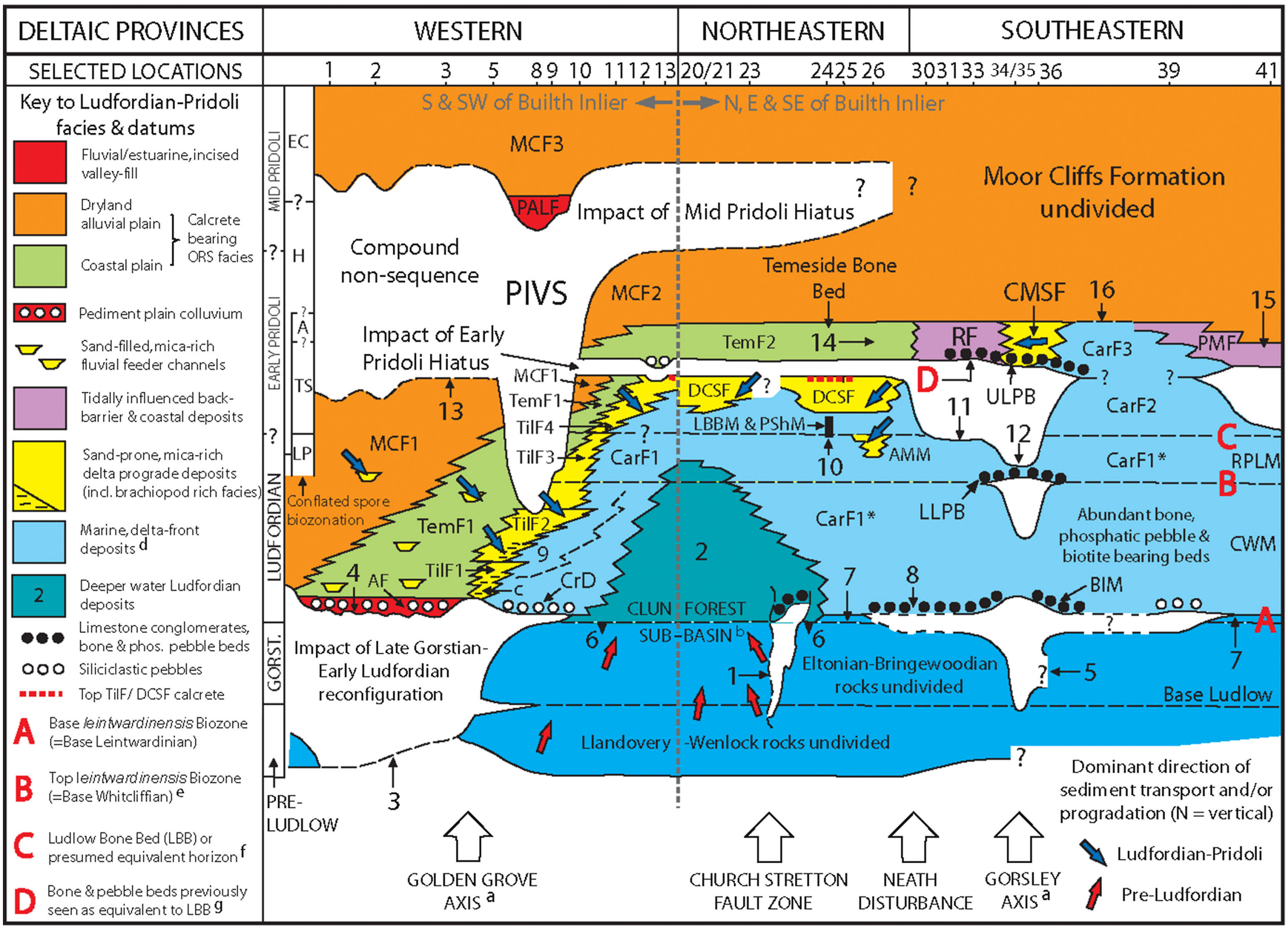

Figure 1. (Colour online) Chronostratigraphic architecture focusing principally on the lithostratigraphy and sedimentary facies of Ludfordian to mid-Pridoli successions of south and mid Wales and the Welsh Borderland (see Figure 2 for transect line). Overlaps and extends Figure 3 of Hillier *et al.* (2019). NB – seeks to show only chronostratigraphic relationships during, but not the relative or absolute duration of separate time intervals. See Tables 1 and 2 for explanation of lithostratigraphical symbols and notes. Other abbreviations: conglom., conglomerate; Gorst., Gorstian; phos., phosphatic.

University of Birmingham (Hobson, 1960) and Allen (1985), no regional synthesis of the sedimentary facies and events has been attempted. The current study, in seeking to do this, has been informed by the work of Barclay *et al.* (2015) who amended the usage of the term ORS in South Wales and the Welsh Borderland. As part of the current study, in the light of new sedimentological and biostratigraphical findings, the lithostratigraphical nomenclature used for late Ludlow to earliest Pridoli rocks in Wales and its borders has been further rationalized. A sedimentary architecture allied to detailed facies analysis permits a radical reinterpretetion of the palinspastic relationships of sedimentary environments and of sediment provenance during this interval as well as offering insight of the main events that fashioned its stratigraphy.

2. Geological context

2.a. Plate tectonic context

Prior to the late Ludlow, the Silurian palaeogeography of Wales and the Welsh Borderland was dominated by the Welsh Basin, an area of subsidence that was flanked to the south and east by the more stable Midland Platform and to the north by the Irish Sea Platform (or Monian Terrane). All were structural elements of a tectonic plate traditionally known as 'Avalonia', but which recent studies have shown to be more complex in its crustal composition and early history (e.g. Waldron *et al.* 2014). By the close of the Ordovician, this assemblage of crustal fragments – part of the Anglo-Acadian Belt of Cocks & Fortey (1982), or Avalonian Terrane Assemblage of Verniers *et al.* (2002) – had fused with the more easterly plate of Baltica to form a single, mid southern latitude, tectonic and faunal province.

The early Silurian closure of the Iapetus Ocean and the consequent collision between parts of Avalonia-Baltica and the northern supercontinent of Laurentia initiated the Scandian Orogeny in northern Europe. This event, viewed as a late stage of the protracted Caledonian orogenic cycle, strongly influenced Silurian deposition within the Welsh Basin and along its margins (e.g. Woodcock *et al.* 1996; Davies *et al.* 2016). The Middle Devonian deformation of the basin's marine Silurian fill, and of the Pridoli to Early Devonian red beds that succeeded it, has long been viewed as consequential to the terminal collision of Avalonia-Baltica with Laurentia and as the manifestation in the UK of the North American Acadian Orogeny (e.g. Soper *et al.* 1987; Woodcock *et al.* 1988). However, this Middle Devonian deformation is now believed to significantly postdate the closure of the Iapetus Ocean and thought more likely to mark events taking place within an evolving Variscan orogenic province to the south (e.g. Woodcock & Soper, 2006; Woodcock *et al.* 2007). Use of the

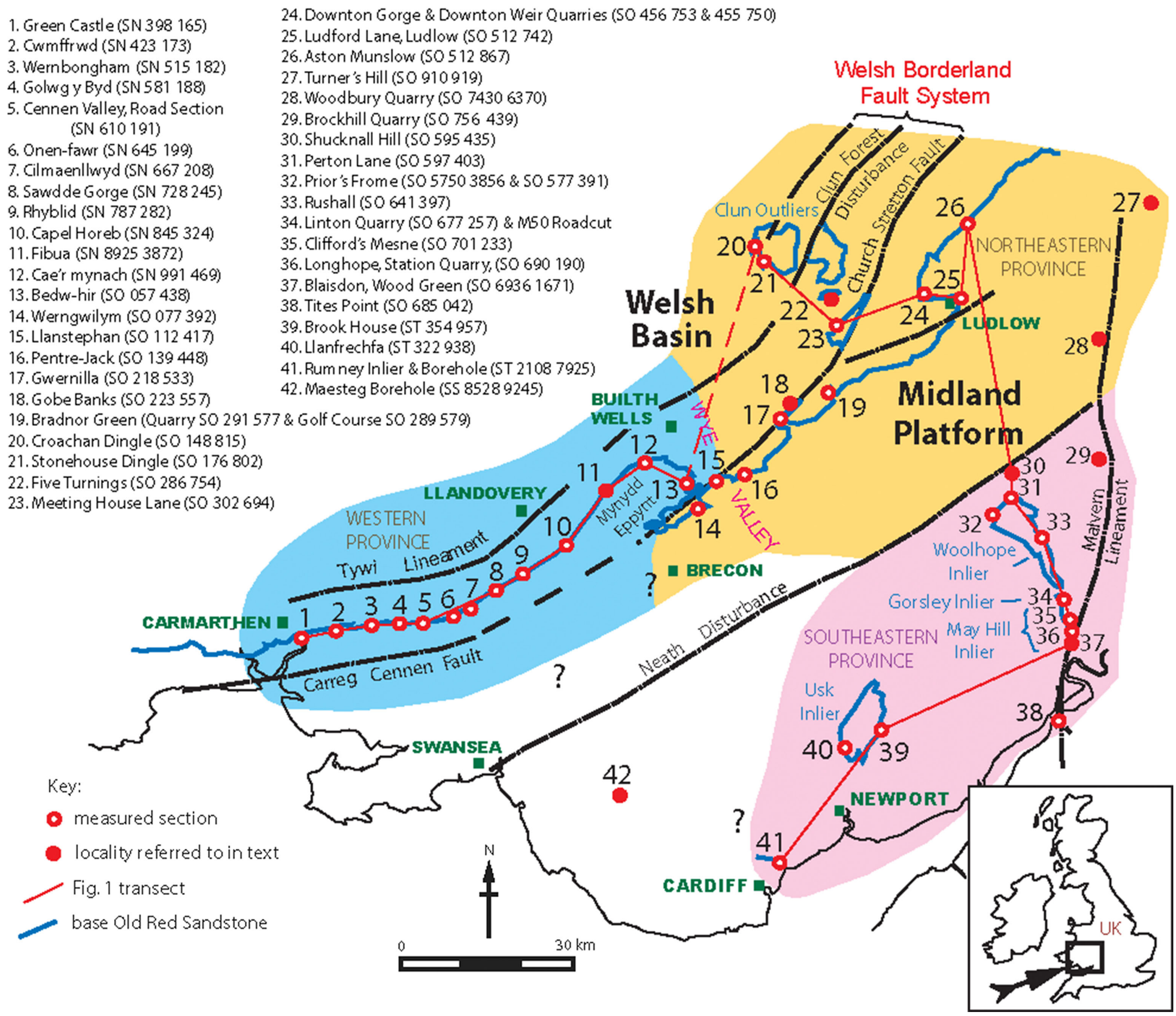

Figure 2. (Colour online) Location of study area with distribution of measured sections and key localities mentioned in text across south Wales and the Welsh Borderland, including national grid references and key tectonic elements. Transect line of Figure 1 is shown.

term 'Acadian Orogeny' as a label for this event is also questioned (Woodcock, 2012a).

2.b. Pre-late Ludlow palaeogeography

The Welsh Basin provides a record of continuous deposition of predominantly deep marine facies from Early Ordovician until at least early Ludlow times (Figures 1 and 3a; e.g. Davies *et al.* 1997; Cave & Hains, 2001). In contrast, sediment accumulation on the Midland Platform during this interval was discontinuous both temporally and spatially (Bassett *et al.* 1992; Cramer, 1964; Woodcock *et al.* 1996). Palaeocurrent and provenance studies for early to mid-Silurian rocks in Wales confirm that different sectors of the platform were the dominant sources of sediment supplied to the basin during this period. The basin and platform were separated by the active, NE-striking, Welsh Borderland Fault System (WBFS; Woodcock & Gibbons, 1988; Cherns *et al.* 2006). Movements on intra-basinal faults were significant at various times during the basin's evolution. The Midland Platform was also host to important fracture belts, including the Neath Disturbance and Malvern Lineament that influenced the deposition and preservation of Silurian sediments (e.g. Bassett *et al.* 1992; Butler *et al.* 1997).

Late diagenetic illite crystallinity data for late Llandovery deep water facies in west Wales (Merriman, 2006; Woodcock, 2012a) implies that the western part of the Welsh Basin was subject to less overburden than areas further east adjacent to the WBFS. This region of the basin may have experienced limited inversion as early as the latest Llandovery, the focus of deep water facies deposition then shifting eastwards as the basin and its attendant fractures responded to the plate convergence (e.g. Davies *et al.* 1997; Cave & Hains, 2001; Smith, 2004). Accompanying these physiographical changes, the dominant supply of detritus shifted from the east to that shed from tectonically uplifted Avalonian tracts that lay to the south and south-west, linked to the Midland Platform (e.g. Morton *et al.* 1992; Ball *et al.* 1992). By the mid Wenlock, as plate collision abolished the Iapetus Ocean, links to the southern Rheic Ocean had likely already been established and the latter was the dominant marine influence during the Ludlow and Pridoli.

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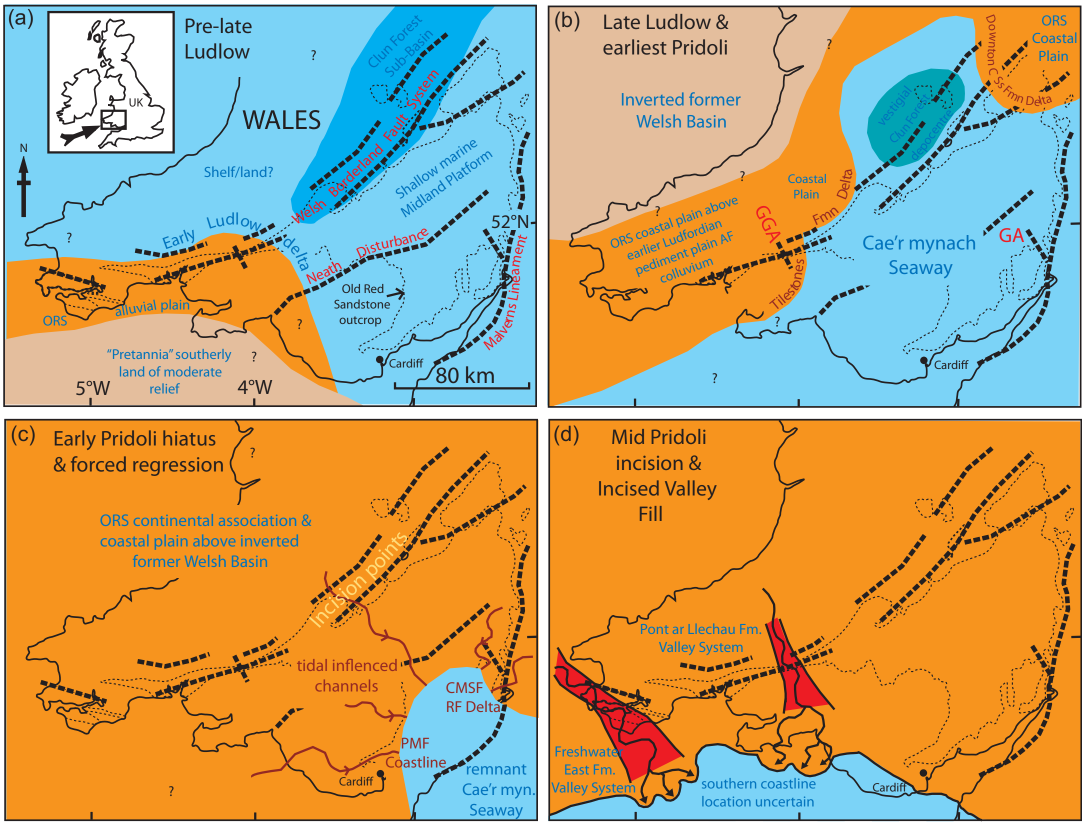

Figure 3. (Colour online) Palaeogeographic reconstructions of the study area. (a) Pre-late Ludlow. (b) Late Ludlow and earliest Pridoli. GGA, Golden Grove Axis; GA, Gorsley Axis; AF, Abercyfor Formation. (c) Early Pridoli hiatus and forced regression. CMSF-RF, Clifford's Mesne Sandstone Formation – Rushall Formation; PMF, Pwll-Mawr Formation. (d) Mid-Pridoli incision and incised valley fill.

By early Ludlow (Gorstian) time, active deep-water deposition was confined to a narrow belt of subsidence previously labelled the Montgomery Trough, or as preferred here, the Clun Forest Sub-Basin (Figures 1 and 3a; Holland & Lawson, 1963). At this point, much of the former Welsh Basin had likely evolved into a region of shallow marine deposition or was emergent (Hillier *et al.* 2019). The facies that accumulated in and adjacent to the Clun Forest Sub-Basin across its eastern and southern margins and the contiguous Midland Platform describe the northward and westward progradation of shallower over deeper facies in a pattern that confirms that the supply of sediment during this period remained predominantly from the south and east (e.g. Siveter, 2000; Barclay *et al.* 2005; Schofield *et al.* 2004, 2009). However, Hillier *et al.* (2011) link the late Gorstian input of tectonically generated alluvial fans shed off local fault scarps to the earliest onset of terrestrial red bed conditions in SW Wales (e.g. Hillier & Williams, 2004; Barclay *et al.* 2015). The first appearance within these red bed tracts of detritus sourced from the Caledonian Orogen (e.g. Sherlock *et al.* 2002; see Sections 2.c and 2.d below) shows that a fundamental reconfiguration of sediment supply routes and depocentres was ongoing during late Gorstian times. Wales, it appears, then lay within reach of the alluvium being shed from uplifting regions to the north. Hillier *et al.* (2019) recognize Late Gorstian tectonism as a factor in the semi-regional inversion of the area to the north and west of the WBFS. This, they contended, promoted the formation of an extensive, low-gradient pediment plain cut by migrating, southwards flowing streams emerging from Caledonian uplands.

2.c. Late Ludlow (Ludfordian) and Pridoli palaeogeography

By the close of the Gorstian, the range of active marine deposition had contracted to an area occupied by the WBFS and adjacent parts of the Midland Platform, centred on a vestigial Clun Forest depocentre. The latter continued to receive sediment from a southerly sector, and it was within its confines that the thickest Ludfordian successions, including facies of deepest aspect, accumulated (Figure 3b). An early Ludfordian deepening event led to an expansion of marine conditions and the establishment of an extensive shallow-water, storm-influenced setting here recognized as the Cae'r mynach Seaway. In South Wales, the Golden Grove Axis acted as a structural hinge that separated this expanded region of marine deposition from the still extant pediment surface to west, and it seems likely that similar structural features perhaps linked to the Central Wales and Tywi lineaments also influenced the early location of this interface.

A focus of this study is the sedimentology of the separate delta progrades that subsequently advanced into the remnant marine tract from northerly and easterly quadrants as the input of sediment from the south declined and the supply of Caledonian detritus came to dominate. In SW Wales, thin deposits of locally derived debritic colluvium (Abercyfor Formation, AF) that overstep strata deformed during earlier Ashgill, Telychian and Late Gorstian structural events were the first to accumulate on the pediment surface (Hillier *et al.* 2019). The onset and expansion of ORS deposition records the spread of alluvial conditions that characterized the Pridoli and Lower Devonian succession of South Wales and the Welsh Borderland (Allen, 1985; Bassett *et al.* 1982;

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Bassett *et al.* 1992; Woodcock, 2012b). The thick, northerly derived red bed succession (e.g. Allen, 1974a) records accommodation within the developing Anglo-Welsh Basin, which expanded to subsume the regions of the former pediment and marine seaway alike (Figures 1 and 3c; Hillier *et al.* 2019). This basin has been viewed as a Caledonian foreland basin formed in response to the collision between Avalonia and Laurentia and which migrated southwards to affect Wales during the Pridoli and Lower Devonian (e.g. King, 1994). However, Woodcock *et al.* (2007) suggest that the tectonic legacy of this collision was minimal in southern Britain. They link the accommodation and preservation of the Caledonian marine and non-marine succession in Wales to ongoing strike-slip displacement along the site of Iapetus suture zone and the development to the south of post-collision, transtensional basins. However, early Variscan tectonism, known to have been influential in Wales from as early as the Llandovery, continued to play a role by influencing links to the Rheic Ocean (see Section 6h) (Woodcock, 2012c).

This study builds on the findings of Hillier *et al.* (2019) in recognizing separate episodes of basin-wide denudation and local incision of the ORS alluvial plain during the early and mid-Pridoli (Figures 3c–d). Regions of maximum erosion and incision were likely structurally controlled, with local faulting influential. In SW Wales, the valley fills preserve the deposits of streamflow conglomerates, alluvial fan and estuarine heterolithics of the Freshwater East Formation (FEF). This study provides details of the contemporaneous Pont ar Llechau Formation (PALF) valley fill succession, but also of a putative earlier Pridoli hiatus (Figures 1 and 3c–d).

2.d. Sediment composition and source

Ludfordian and early Pridoli delta progradation resulted in widespread micaceous sandstone deposition. This is recorded in the north and south-east of the study area as the Downton Castle Sandstone Formation (DCSF) and its local correlatives, and in the west as the Tilestones Formation (TilF). In studying the DCSF, Hobson (J.S.C. Hobson, unpub. PhD thesis, University of Birmingham, Hobson, 1960) recognized the influence of two discrete delta systems: a 'Welsh Delta' that Allen (1974b) confirmed advanced into the Ludlow and Clun areas from the north-east; and a 'Woolhope Delta' that supplied the coeval sandstones of the Woolhope, Malvern and May Hill inliers from the east. Our study supports these earlier findings for the DCSF of its type area, but by uncovering greater complexity including sandstone facies of differing age and setting suggests that the concept of a Woolhope Delta is misleading. Our data also fail to endorse previous suggestions that the sediment source for the TilF lay either to the west (Allen, 1985) or south (e.g. Potter & Price, 1965; Owen, 1967; Cope & Bassett, 1987; J. Almond, unpub. PhD thesis, University of Bristol, Almond, 1983; Bassett *et al.* 1992). Behind these deltas, terrestrial ORS sediment accumulated, with coastal plain deposits of the Temeside Mudstone Formation (TemF) passing into terrestrial dryland deposits of the Moor Cliffs Formation (MCF; Hillier *et al.* 2019).

The abundance of large white mica flakes in Ludfordian and Pridoli sandstones in Wales and the Welsh Borderland testifies to the extensive unroofing of high-grade metamorphic rocks – probably mica schists – within sediment source areas. Outcrop location and size, and their detailed petrography, show that neither the Dutch Gin Schists of Pembrokeshire nor the Rushton Schists in Shropshire could have served as the principal source for this material (e.g. Baker *et al.* 1968; McIlroy & Horak, 2006), which must have lain further to the north. The schists and gneisses of the Mona Complex, forming part of a putative Irish Sea landmass, have been considered as a source for 'Downtonian' sandstones in the Welsh Borderlands that, in addition to quartz, mica and other heavy minerals, include abundant garnet (e.g. Heard & Davies, 1924; Wallis, 1928; Walder, 1941). Allen (1974b) rejected this possibility and anticipated Sherlock *et al.* (2002) in suggesting that unroofed metamorphic tracts within the Caledonian Orogen were the more likely source for these mica- and garnet-rich mineral assemblages.

Hillier & Williams (2004) suggest that the initial route via which this detritus was delivered to SW Wales, during the Gorstian, was a circuitous one that had to negotiate a still extant Welsh Basin to the north. However, the flood of mica supplied to Ludfordian–Pridoli sandbodies and the evidence provided by palaeocurrent vectors (Figure 3b) shows that the former basin had then ceased to exist as an intervening trap for sediment. This former site of deep marine sediment accumulation appears by this time to have formed part of a cryptic, but likely extensive Ludfordian land area (Hillier *et al.* 2019). Rivers that drained northerly source terrains were able to traverse this landscape as they delivered their mica-rich load to southerly facing Ludfordian shorelines in mid and south Wales. The long-distance terrestrial sediment transport models previously invoked for the ORS (e.g. Allen, 1974b; Simon & Bluck, 1982; Allen & Crowley, 1983), it appears, were already well established by late Ludlow times.

However, local mineral and clast assemblages reported from the Ludfordian–Pridoli rocks of the region point to a more complex regional palaeogeography. J.S.C. Hobson, unpub. PhD thesis, University of Birmingham (Hobson, 1960) matched clasts in the DCSF of the Kington area to nearby Precambrian tracts. In the Silurian inliers in the south-east of the study area, the Precambrian rocks of the Midland Platform as seen in the Malvern Hills have been viewed as the likely source of local mineral assemblages rich in detrital biotite, zircon and rutile (Walmsley, 1959; Tucker, 1960; J.S.C. Hobson, unpub, PhD thesis, University of Birmingham, Hobson, 1960; Phipps & Reeve, 1967). Palaeocurrent data in this study support Hobson's (J.S.C. Hobson, unpub. PhD thesis, University of Birmingham Hobson, 1960) assertion that some sediment in this region was supplied from the east. In the west, clast assemblages in the TilF and its contiguous facies, include plutonic igneous rocks, chlorite/muscovite schists and phyllitic and low-grade metamorphic lithologies (J. Almond, unpub. PhD thesis, University of Bristol, Almond, 1983), which are consistent with the unroofing and reworking of conglomerate bodies present within the older basinal succession to the north (e.g. Davies *et al.* 1997; Evans, 1992; Schofield *et al.* 2004, 2009; Wilby *et al.* 2007). The abundance of angular acid volcanic clasts in other units implies that exposed volcanic units present within a now eroded early-mid Ordovician succession were also a source of debris (Hillier *et al.* 2011). A picture emerges of locally active sources of sediment along the flanks of a Ludfordian–Pridoli depositional tract, possibly inselbergs that stood proud to the basal ORS pediment and its successor delta coastal plain, but with the latter principally in receipt of sediment delivered from distant orogenic uplands to the north.

3. Stratigraphy, events and nomenclature

3.a. Introduction

The regional and global forcing factors outlined above, linked to new and existing biostratigraphical findings, offer context for the

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Table 1. Alphabetical key to lithostratigraphical symbols used in Figure 1, including primary sources of nomenclature, significant synonyms and comments on specific usage in this text. Symbols with numbered suffixes refer to parts a division that display different geographical and/or stratigraphical ranges (e.g. TemF1, TemF2). Other abbreviations: Lr, Lower; Up, Upper; Mudst, Mudstone

Symbol	Name and rank	Source	Significant synonyms	Comment on usage
AMM	Aston Munslow Member	This study		Member of CarF1
AF	Abercyfor Formation	Barclay *et al.* (2015)	Basal Green Beds of Strahan *et al.* (1907)	
BlM	Blaisdon Member	This study; after Lawson (1955)	Lr Blaisdon Beds	Incorrectly shown as Aymestry Limestone on BGS digital maps
CarF	Cae'r mynach Formation	Schofield *et al.* (2004); adapted and extended by this study	NE and SE provinces; see Figures 1 and 2. W Province: Roman Camp & Up Cwm Clyd Beds; Holopella Grits & Shales; Up Orthodonta Mudstones (various authors); mud-prone parts of Lawson's (1955) Clifford's Mesne Beds	CarF1, pre-Early Pridoli parts of the formation; CarF2 and CarF3, separate Early Pridoli units (see text)
CMSF	Clifford's Mesne Sandstone Formation	Lawson (1954, 1955); adapted by this study	Sand-prone parts of Lawson's (1955) Clifford's Mesne Beds	
CrD	Cribyn Du Member	Schofield *et al.* (2009)		Member of CarF1
CWM	Chapel Wood Member	Waters & Lawrence (1987)		Reassigned to CarF1
DCSF	Downton Castle Sandstone Formation	Elles & Slater (1906); adapted by this study	See Figure 4	
LBB	Ludlow Bone Bed	Murchison (1839)	Included in DCSF by Bassett *et al.* (1982)	Reassigned to CarF2
LBBM	Ludlow Bone Bed Member	Bassett *et al.* (1982)	Previously inc. in DCSF	Reassigned to CarF2
LLPB	Lower Linton Pebble Bed	This study; after Lawson (1954, 1955)	Lower Phosphatised Pebble Bed	
MCF	Moor Cliffs Formation	Barclay *et al.* (2015); adapted by this study		
PALF	Pont ar Llechau Formation	Schofield *et al.* (2009)		Here recognized as mid-Pridoli in age
PMF	Pwll-Mawr Formation	This study	Included in Raglan Mudstone Formation (= MCF) by Waters & Lawrence (1987)	Newly recognized following a reassessment of the Rumney Borehole between 43.56 and 57.3 m and observations in the Usk area
PShM	Platyschisma Shale Member	Bassett *et al.* (1982)	Previously included in DCSF	Reassigned to CarF2
RF	Rushall Formation	Squirrel & Tucker (1960)	Shown as DCS on some BGS digital maps	
RPLM	Roath Park Lake Member	Waters & Lawrence (1987)	Previously included in Llanedeyrn Formation	Reassigned to CarF1
TemF	Temeside Mudstone Formation	Elles & Slater (1906) and later authors; adapted by this study	Green Downtonian; Green Beds of west Carmarthenshire and north Pembrokeshire	
TilF	Tilestones Formation	Strahan *et al.* (1907)	Long Quarry Beds	
ULPB	Upper Linton Pebble Bed	This study; after Lawson (1954, 1955)	Upper Phosphatised Pebble Bed	

sedimentological and palaeogeographical analysis presented herein. Figure 1 and Tables 1 and 2 summarize these findings and provide the architectural framework for the following account. Several key events emerge as influential in the development of the region's Ludfordian to early Pridoli successions and serve to inform revisions to regional lithostratigraphical nomenclature. Figure 4 shows how many of the older terms relate to the new scheme. Much of the new nomenclature follows that applied by the British Geological Survey (BGS) during its mapping of parts of central and southern Wales (e.g. Schofield *et al.* 2004, 2009; Barclay *et al.* 2005) and also the recommendations of Barclay *et al.* (2015) in their review of ORS terminology. Some further comment is required. Changes to the established terminology for the type Ludlow succession permit unfettered use of chronostratigraphical nomenclature first used Cherns & Bassett (1999), but which has previously failed to gain widespread acceptance (Figure 5). In their seminal study of the Ludlow Series type area, Holland *et al.* (1963) proposed four new chronostratigraphical stages, the Eltonian, Bringewoodian, Leintwardinian and Whitcliffian. The Subcommission on Silurian Stratigraphy (Holland, 1980) concluded subsequently that the Ludlow should be divided into two internationally recognizable units and, in response, Holland *et al.* (1980) proposed the stage terms that are in current use, the Gorstian and Ludfordian. However, Waters & Lawrence (1987)

Table 2. Explanation of numbered architectural elements and other notes in Figure 1

1	Complex interface associated with the CSFZ between region of net mass-wasting and stratigraphical omission, to the east, and of slump and undisturbed sediment accumulation, to the west. Mass-wasting involving retrogressive slumping was likely active throughout much of the Gorstian, with a late phase of slide scar incision and infill extending into the early Ludfordian (see Whitaker, 1962, 1994).
2	Thick succession of deeper water Ludfordian facies, not described in this paper, deposited in the CFS. Sediment input was complex, but the pattern of progradation from the south remained significant into Whitcliffian times. Includes units in the Leintwardine and Aymestry areas that Whitaker (1962) and Lawson (1973) assigned to Lr & Up Leintwardine Beds, but that differ from equivalent strata of the Ludlow area. The nomenclature of these units requires revision.
3	Putative base of the late-Aeronian to Gorstian succession prior to intra-Ludlow breaching.
4	Basal Old Red Sandstone unconformity of west Carmarthenshire and north Pembrokeshire.
5	Lawson (1955) records of a significant non-sequence in the May Hill Inlier between his Lr & Up Flaxley Beds.
6	CFS sites where earliest deposits of the 'Leintwardinan transgression' are latest Gorstian (*incipiens* Biozone) in age.
7	Leintwardinian facies in the Ludlow and Rumney areas, also present in the Malverns (Phipps & Reeve, 1967), that form part of predominantly Gorstian formations, including nodular limestones at the Ludfordian Stratotype. Some have correctly included these the Aymestry Limestone Formation (or facies) (e.g. Alexander, 1936; Watkins, 1979; Cherns, 1988; Cherns & Bassett, 1999). However, they have also been included in the Lower Leintwardine Beds (Holland *et al.* 1963; Whitaker, 1962; Shergold & Shirley, 1968); including by Cherns (2011) and Melchin *et al.* (2020). See text.
8	Units present on Wenlock Edge and in the Woolhope Inlier that, in contrast with those in Note 7, have previously included in the Aymestry Limestone, but that include beds of bored limestone clast conglomerate and overlie an extensive omission surface. Equivalent to the Blaisdon Member of the May Hill Inlier (BlM; see above).
9	Pro-deltaic CarF facies of Leintwardinian age, but which lack marine macofauna typical of the sub-stage. See text.
10	Location of major C isotope excursion discovered by Loydell & Frýda (2011) that they equate with the intra-Ludfordian LAU Excursion. Note, the onset of LAU C isotope excursion is c.423.86 Ma (Melchin *et al.* 2020), within error of the age of the LBB reported by Catlos *et al.* (2020) (see Note f and text).
11	Putative ravinement surface cut in response to the early Pridoli forced regression.
12	Gorsley Axis region of maximum early Pridoli omission. Likely compounds the impacts of multiple latest Ludfordian and early Pridoli erosional and/or non-depositional events.
13	Putative compound erosion surface conflating the impacts of the early and mid-Pridoli hiatuses in the Western Province.
14	First, and to date, only recorded occurrence of a Zone A miospore assemblage came from an unspecified location within the TemF2 (see text).
15	Highest sample point yielding TS Biozone floras in Rumney Borehole as reported by Burgess & Richardson (1995).
16	The MCF-CarF3 contact in the southern part of the May Hill Inlier is likely faulted and a significant part of the CarF3 succession excised from the surface outcrop.
Other notes	
a	Narrow, fault-influenced zones of uplift overlain by condensed Ludlow successions in which non-sequences testify to multiple and/or prolonged periods of erosion and/or omission. Both subaerial and submarine erosional processes appear to have been significant (e.g. Holland & Lawson, 1963; Cherns, 1980, 1988). See text.
b	Sense of Holland & Lawson (1963, p.275).
c	TilF1 facies with diverse brachiopod assemblages, including *Hyattidina canalis*, seen in the Cennen area. See text.
d	Equivalent to the 'coquinoid siltstone facies' of Watkins (1979) in which he included both the 'calcareous shelly siltstone' and 'flaggy limestone' facies of Holland & Lawson (1963).
e	Based on both shelly and graptolitic assemblages. Corresponds to the widely recognized disappearance of Watkins' (1979) *Shaleria ornatella* Association (= top Upper Leintwardine Beds and equivalent levels of various authors).
f	Catlos *et al.* (2020) report detrital zircon dates for the LBB of 424.91 ± 0.34/0.42/063 Ma (see text for discussion).
g	Includes locally conglomeratic, bone-bearing beds of the Woolhope area (e.g. Stamp, 1923; Squirrel & Tucker, 1960) and ULPB of the Gorsley and May Hill inliers. See text.

and Cherns & Bassett (1999) have since recognized that the four-fold divisions of Holland *et al.* (1963) can be employed as regional sub-stages, or chronozones of the Gorstian and Ludfordian stages. Such usage is followed here. The definitions of each chronozone including their type sections are as detailed in Holland *et al.* (1963). Lawson & White (1989) further document their benthic fossil content including critical faunal incomings and outgoings. The findings of subsequent studies, including work on miospores and acritarchs, are alluded to in the text. Figure 5 shows how these regional Ludlow chronozones relate to selected international and regional biozonal schemes. We follow Higgs (2022) in his usage of informal chronostratigraphic subdivisions of the Pridoli.

Note that the southerly sourced Ludlow facies of the Clun Forest Sub-Basin are not a focus of this study and are alluded to only briefly below. A more detailed lithostratigraphical summary of this succession is in preparation. Reference below to 'BGS digital maps' relates to maps that are publicly available via the BGS Map Portal and BGS Map Viewer.

The derivation and distribution of prograde sandstones allows three depositional provinces to be distinguished: a Western (or

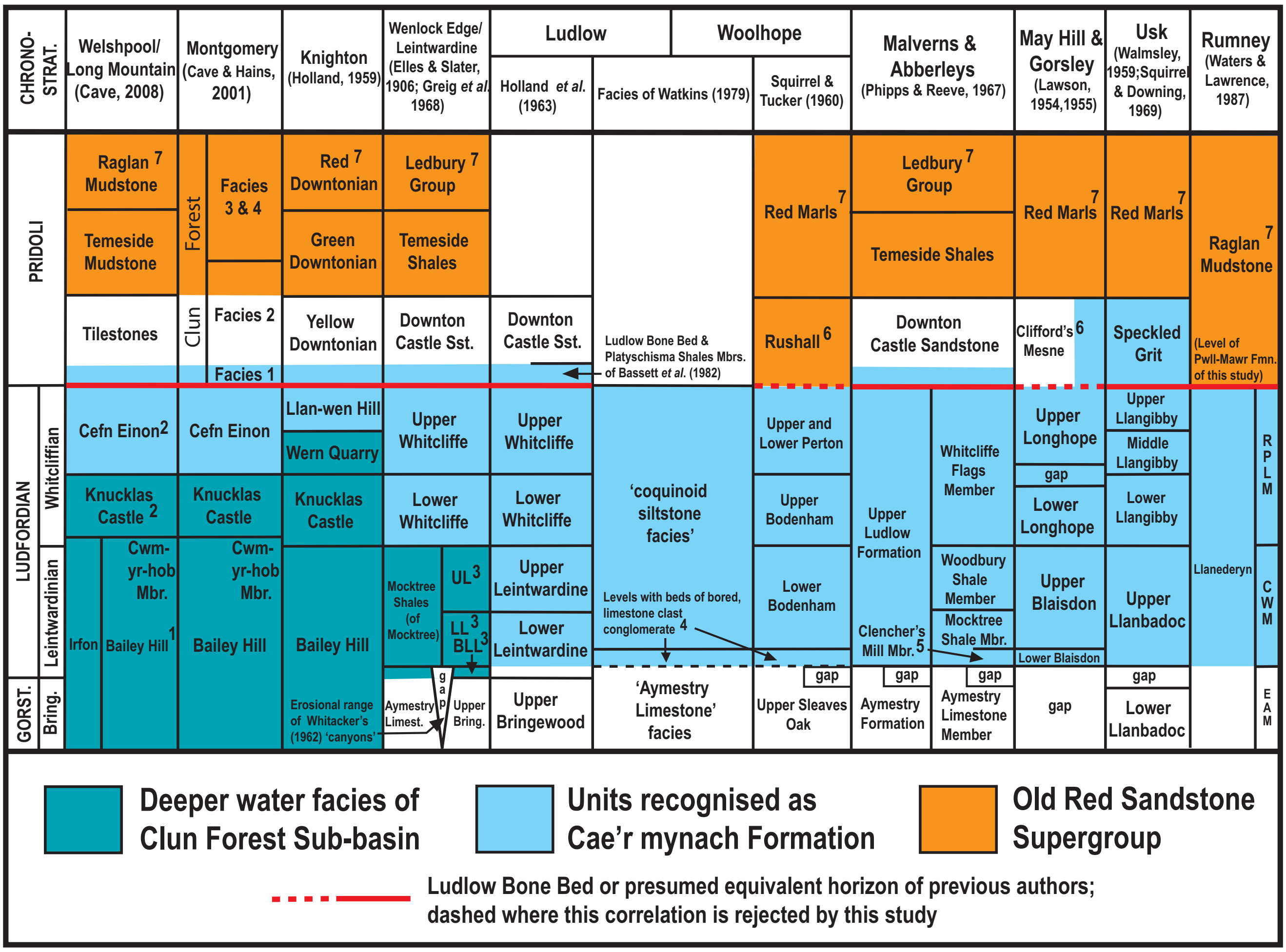

Figure 4. (Colour online) Former stratigraphical nomenclature for the Ludlow and early Pridoli successions of the North-Eastern and South-Eastern provinces (inc. Long Mountain, Clun Forest and Ludlow areas and the eastern Silurian inliers) after the named authors, focusing on those units recognized herein as Cae'r mynach Formation (CarF). 1, Long Mountain Siltstone Formation of Palmer (1970); 2, Causemountain Formation of Palmer (1970); 3, Basal Lower, Lower and Upper Leintwardine beds of Whitaker (1962) and Lawson (1973); 4, Leintwardinian facies included by the named authors in underlying, predominantly Bringewoodian divisions; 5, sense of Worssam *et al.* (1989); 6, units previously believed to correlate with the Downton Castle Sandstone Formation of the Ludlow area, but here interpreted as elements of a younger succession (see Figure 1); 7 units now recognized as Moor Cliffs Formation (Barclay *et al.* 2015). Abbreviations: Bring., Bringewoodian; Gorst., Gorstian; EAM, Eastern Avenue Member; for other abbreviations, see Table 1.

TilF) Province, a North-Eastern (or DCSF) Province and a South-Eastern Province, which includes the region of the Clifford's Mesne Sandstone Formation (CMSF) deposition (Figure 1). In the latter province, local sandstone facies commonly contain biotite, but it was also a region of widespread erosion and sedimentary omission.

Shelly macrofossils, principally brachiopod and bivalves, have been studied extensively in the past and remain significant for dating of Ludfordian marine strata. Key Ludfordian and Pridoli ostracod species have also proved that significant and vertebrate remains are important in the terrestrial strata. However, spore assemblages have increasingly been relied upon and considerable palynological research has been undertaken in Wales and the Borderland (Anglo-Welsh Basin) to establish a spore zonation for the late Ludfordian to Pridoli interval (e.g. Richardson & Lister, 1969; Richardson & Edwards, 1989; Burgess & Richardson, 1995; Edwards & Richardson, 2004) (Figure 5). In addition, Higgs (2022) has recently identified new Pridoli spore assemblages from Pembrokeshire that do not match the established zonation and reviewed the reasons for this. The only new biostratigraphical work undertaken as part of this study has been palynological, focusing on spores (Figure 6; Supplementary Figure 1), and to a lesser extent acritarchs and chitinozoans (Figure 7). Samples were studied from the Cae'r mynach Formation (CarF), TilF and PALF in the Western Province, and the Rushall Formation (RF) in the South-Eastern Province.

Since the erection of the Pridoli Series, the LBB and its correlatives (see Section 3.c below) have been taken to mark the base of the series in Wales and the Welsh Borderland (White & Lawson, 1989). Many of the microfloral taxa present in the 'bone bed' and in the succeeding strata have not been recovered from the underlying succession and are recognized as Pridoli markers. However, Loydell and Frýda (2011) interpret the isotope excursion they discovered spanning the LBB and extending into the overlying stratigraphy (see Figure 1), as the global Lau Event. This, if confirmed, would demonstrate a late Ludfordian age for these strata and, by default, their fossil assemblages. Turner *et al.* (2017) have sought robustly to defend the *status quo*. It is not the place for this study to arbitrate and the assumption of an early Pridoli age continues, with caution, to be applied herein.

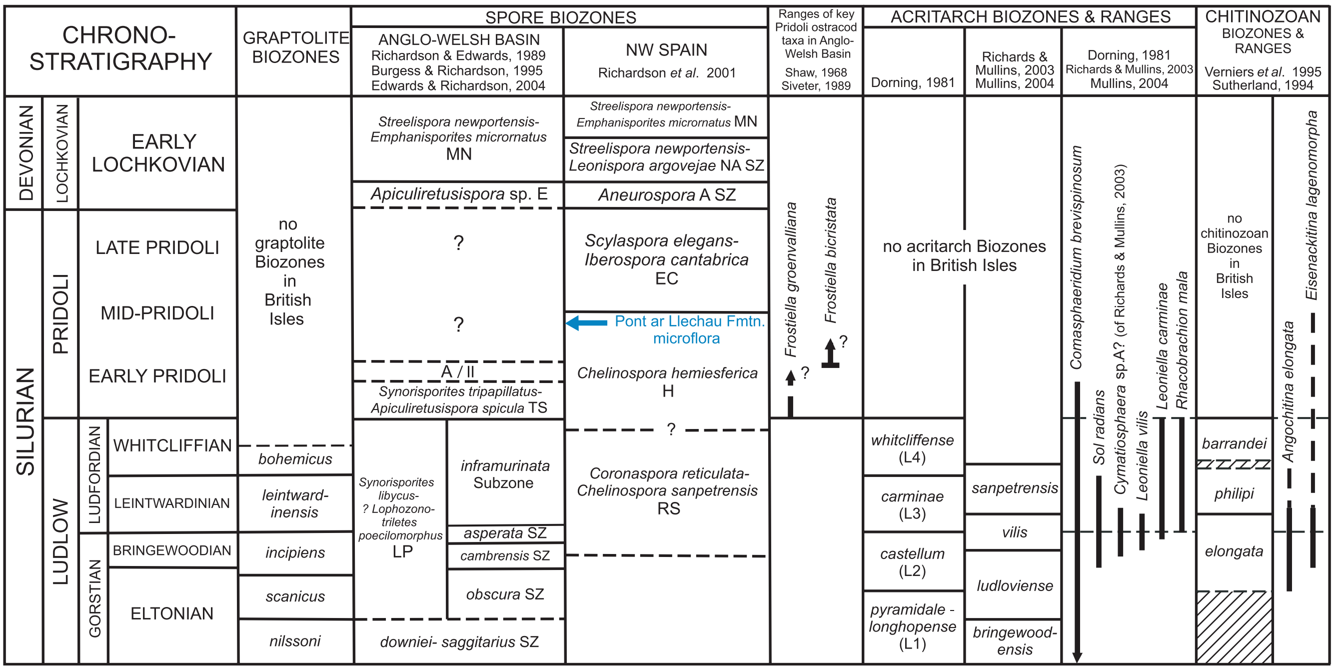

Figure 5. (Colour online) Chronostratigraphical subdivisions of the Ludlow and Pridoli highlighting late Silurian–Early Devonian Graptolite and spore zones of Wales and the Welsh Borderland with the ranges of key early Pridoli ostracod taxa. The spore zonation of NW Spain is shown to demonstrate the proposed correlation of the PALF with that of the Anglo-Welsh Basin. There are currently no formal subdivisions for the Pridoli Series, the usage here follows that of Higgs, 2022.

3.b. Early Leintwardinian flooding event

The dating and impact of this flooding episode are well established throughout the study area. East of the WBFS, both in the type Ludlow succession and more widely, the onset of calcareous siltstone deposition above limestone-rich facies typical of the Bringewoodian is widely acknowledged to record a transgressive deepening (Cherns *et al.* 2006; Cherns, 2011). These transgressive facies commonly yield *leintwardinensis* Biozone graptolites, but such faunas are known locally to appear first in facies that form part of preceding, principally Bringewoodian, lithostratigraphical divisions. Aymestry Limestone facies of Leintwardinan age occur at the Ludfordian stratotype in Sunnyhill Quarry (Cherns, 1988; Lawson & White, 1989) and in the Malverns (Phipps & Reeve, 1967; Barclay *et al.* 1997). Waters & Lawrence (1987) recognized the earliest Leintwardinian faunas in the otherwise Bringewoodian Eastern Avenue Member in the Rumney inlier. Where developed, these earliest Leintwardinian levels underlie gradational contacts with the succeeding transgressive strata. However, in the Church Stretton area and in the successions of the southern Malverns and the Woolhope and May Hill inliers, where the contact between Bringewoodian and Leintwardinian facies is sharp, there is evidence of widespread omission and erosion. Beds of conglomerate that comprise bored clasts of limestone are abundant in the basal few metres of the Leintwardinian succession. Bringewoodian limestones were the source of the clasts in some of these units, but others may testify to the destruction of contemporary hardgrounds and show that there were sites of condensed deposition during the earliest phase of Leintwardinian deepening (Cherns, 1988; Watkins, 1979). Siliciclastic pebbles overlie the erosive base of the Usk Inlier Ludfordian succession. The non-sequence in the Gorsley Inlier, where Ludfordian rocks overlie a contact with Wenlock limestones that displays evidence of karstic dissolution, emphasizes the active role played by the Gorsley Axis.

West of Ludlow, in the Leintwardine and Wigmore areas, graptolite-bearing, early Ludfordian rocks are associated with features linked to the cut and fill of contemporary submarine canyons and associated slump scars formed along the margin of the Clun Forest Sub-Basin (Whitaker, 1962, 1994; BGS, 2000). In the deeper water sub-basinal successions to the west, evidence of Leintwardinian deepening is recorded by the graptolitic Cwm-yr-hob Member (Cave & Hains, 2001). In the Western Province, in the Cwm Craig-Ddu area, the lowest levels to yield *Saetograptus leintwardinensis leintwardinensis* evidence a more muted lithological response (Williams, 2003). Further south, the mud-prone Fibua Formation (Schofield *et al.* 2004) marks the onset of an abrupt deepening. The age of its basal graptolite fauna at Fibua Quarry (SN 8913 3932), consisting solely of subspecies of *Bohemograptus bohemicus*, has been reassessed. It is no longer seen as indicative of the *Bohemograptus* proliferation interval, as suggested by Schofield *et al.* (2004), but to demonstrate a pre-*leintwardinensis* Biozone age (James Wilkinson pers.comm., 2019). It follows that the current BGS mapping of the Mynydd Epynt region (see Schofield *et al.* 2004; Barclay *et al.* 2005; BGS, 2005a,b) is in error. These findings, in concurring with the report by Whitaker (1962) of *B. bohemicus* from the basal 'Lower Leintwardine Beds' in the Downton Gorge, imply that, though principally a Leintwardinian episode, the transgression had its origins late in the Gorstian *incipiens* graptolite Biozone.

In the Sawdde area, it is the erosive contact between Trichrug Formation red beds and the conglomerates at the base of the marine CarF that records the Leintwardinian transgression (e.g. Siveter *et al.* 1989; Schofield *et al.* 2009). This is supported by acritarchs, chitinozoans and macrofauna from the overlying succession (see Section 3.e.2). Faunas recovered from the Cennen Road section confirm that marine conditions had also extended on to the eastern flank of the Golden Grove Axis during the Leintwardinian (see Section 3.e.2). In more westerly sections,

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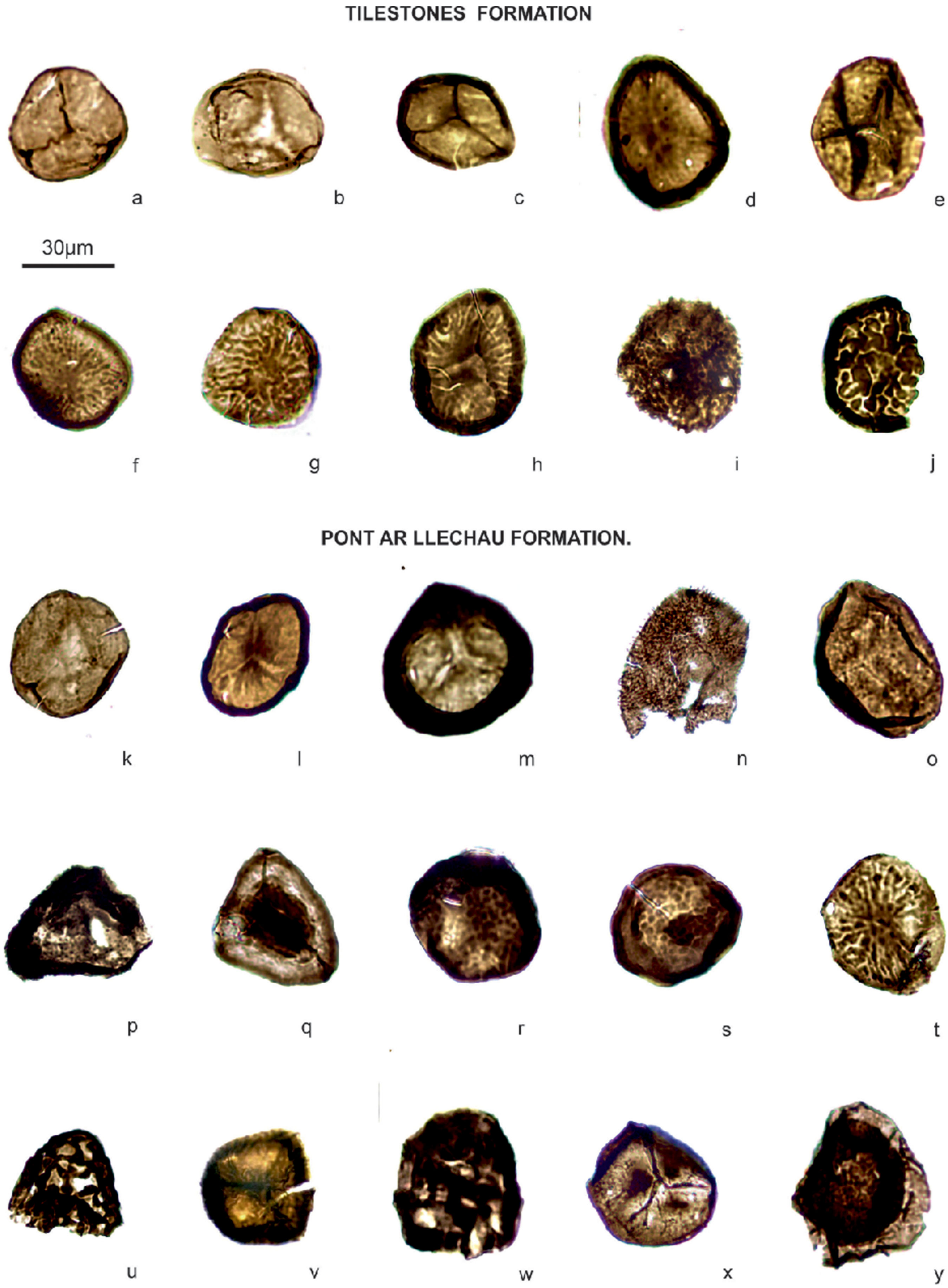

Figure 6. (Colour online) Selected trilete spore taxa from the Tilestones Formation (a–j) and Pont ar Llechau Formation (k–y) identified in this study. (a). *Retusotriletes* cf. *warringtoni* Richardson & Lister, 1969. MPA 55422, slide 2A, F15/3, MPK 14781; (b). *Retusotriletes charulatus* McGregor & Narbonne, 1978. KH/CH4, G26; (c). *Ambitisporites dilutus* (Hoffmeister) Richardson & Lister, 1969. KH/CH2, S24; (d). *Archaeozonotriletes chulus* var. *chulus* Richardson & Lister, 1969. KH/CH3, T25; (e). Apiculiretusispora sp. C Richardson & Lister, 1969. KH/CH2, O19; (f). *Scylaspora scripta* Burgess & Richardson, 1995. KH/CH4, K28; (g). *Stellatispora inframurinata* var. *inframurinata* Burgess & Richardson, 1995. KH/CH2, P16; (h). *Stellatispora inframurinata* var. *inframurinata* Burgess & Richardson, 1995. KH/CH2, U16; (i). *Insolisporites* sp. MPA 55422, slide 1A, J18/4, MPK 14782; (j). *Chelinospora obscura* Burgess & Richardson, 1995. KH/CH2, O15. (k). *Retusotriletes* sp. A Burgess & Richardson, 1995. MPA 55404, slide 2B, R11/0, MPK 14783; (l). *Ambitisporites avitus* Hoffmeister, 1959. MPA 55406, slide 1A, G35/4, MPK 14784; (m). *Archaeozonotriletes chulus* var. *chulus* Richardson & Lister, 1969. MPA 55406, slide 1A, Q11/0, MPK 14785; (n). *Apiculiretusispora spicula* Richardson & Lister, 1969. MPA 55403, slide 1B, N21/2, MPK 14786; (o). *Apiculiretusispora* sp. C. Richardson & Lister, 1969. MPA 55406, slide 1A, M33/3, MPK 14787; (p). *Apiculiretusispora synorea* Richardson & Lister, 1969. MPA 55406, slide 1A, J20/2, MPK 14788; (q). *Concentricosiporites sagittarius* (Rodriguez) Rodriguez, 1983. MPA 55404, slide 2B, P19/3, MPK 14789; (r). *Synorisporites verrucatus* Richardson & Lister, 1969. MPA 55404, slide 2B, E12/0, MPK 14790; (s). *Synorisporites verrucatus* Richardson & Lister, 1969. MPA 55404, slide 2B, N14/2, MPK 14791; (t). *Stellatispora inframurinata* var. *inframurinata* Burgess & Richardson, 1995. MPA 55404, slide 1B, X21/0, MPK 14792; (u). *Chelinospora* cf. *hemiesferica* (Cramer & Diez) Richardson, Rodriguez & Sutherland, 2001. PAL3C, R13; (v). *Chelinospora* cf. *lavidensis* Richardson, Rodriguez & Sutherland, 2001. PAL3C, F30; (w). *Chelinospora cantabrica* Richardson, Rodriguez & Sutherland, 2001. PAL3C, V24; (x). *Scylaspora* cf. *elegans* Richardson et al. 2001. MPA 55403, slide 2A, R10/0, MPK 14793; (y). *Breconisporites* sp. MPA 55403, slide 2A, X8/1, MPK 14794.

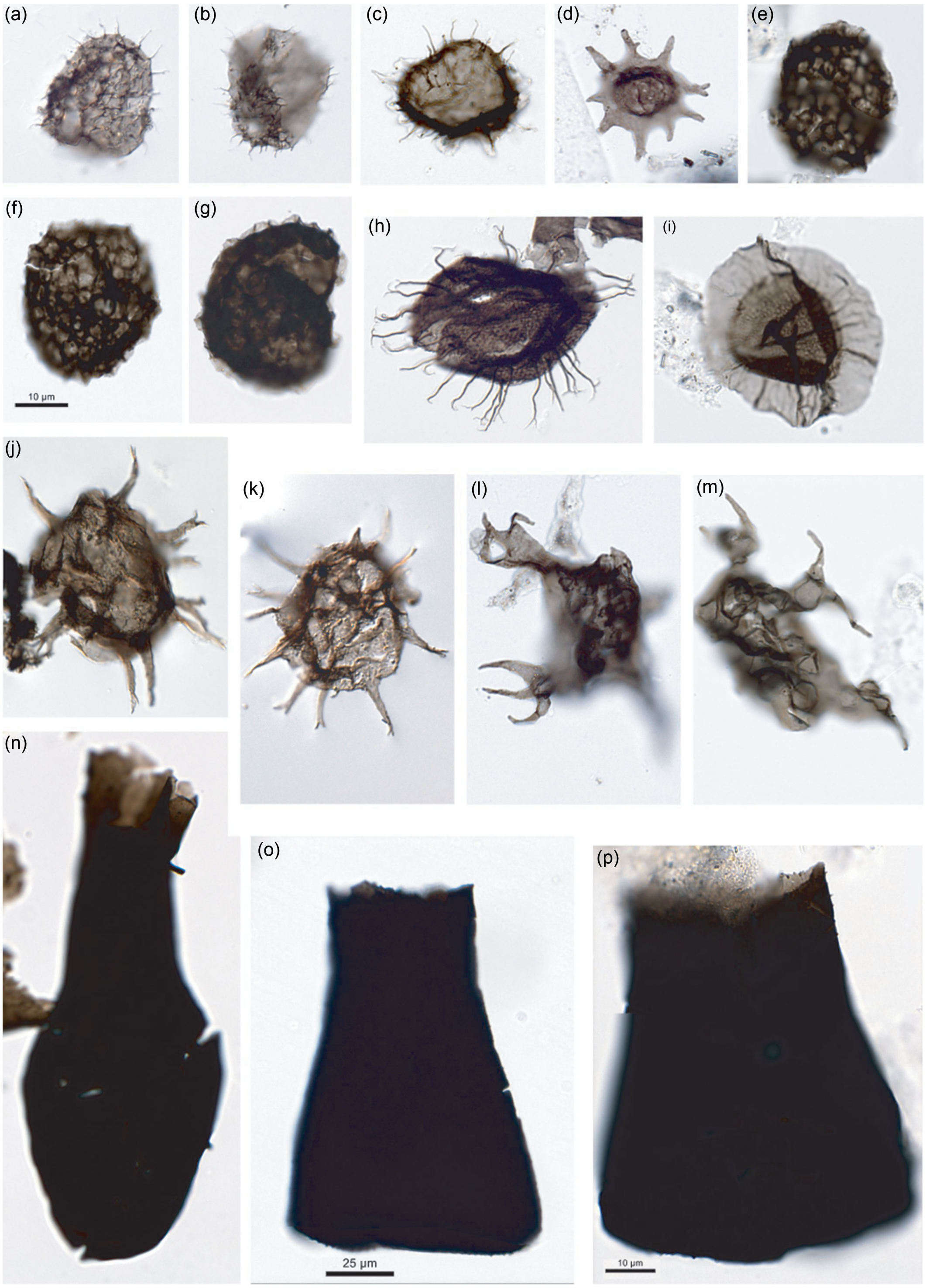

Figure 7. (Colour online) Late Silurian acritarchs (a–d, h, j–m), prasinophytes (e–g, i) and chitinozoans (n–p) identified during this study. Scale bar in (f) = 10 μm for (a–m); scale bar in (o) = 25 μm for (n, o); scale bar in (p) = 10 μm. (a) *Comasphaeridium brevispinosum* (Lister, 1970) Mullins, 2001, Cae'r mynach Fm. (CarF1), Sawdde Gorge, MPA 55414, slide 1, M4/2, MPK 14795; (b) *Comasphaeridium brevispinosum*, Cae'r mynach Fm. (CarF1), Sawdde Gorge, MPA 55414, slide 1, P3/0, MPK 14796; (c) *Comasphaeridium brevispinosum*, Cae'r mynach Fm. (CarF1), Sawdde Gorge, MPA 55414, slide 1, U30/1-2, MPK 14797; (d) *Sol radians Cramer, 1964*, Cae'r mynach Fm. (CarF1), Cennen Road, MPA 55415, slide 1, P21/2, MPK 14798; (e) *Cymatiosphaera* sp. A? of Richards & Mullins, 2003, Cae'r mynach Fm. (CarF1), Cennen Road, MPA 55415, slide2, M8/1, MPK 14799; (f) *Cymatiosphaera* sp. A?, Cae'r mynach Fm. (CarF1), Sawdde Gorge, MPA 55411, slide 2, F18/4, MPK 14800; (g) *Cymatiosphaera* sp. A?, Cae'r mynach Fm. (CarF1), Sawdde Gorge, MPA 55411, slide 2, M24/4, MPK 14801; (h) *Percultisphaera stiphrospinata* Lister, 1970, Cae'r mynach Fm. (CarF1), Sawdde Gorge, MPA 55412, slide 1, F8/3-4, MPK 14802; (i) *Pterospermella foveolata* Lister ex Dorning, 1981, Cae'r mynach Fm. (CarF1), Cennen Road, MPA 55415, slide 1, U6/0-2, MPK 14803; (j) *Rhacobrachion mala* (Cramer, 1964) Dorning, 1981, Cae'r mynach Fm. (CarF1), Sawdde Gorge, MPA 55411, slide 1, X30/3, MPK 14804; (k) *Rhacobrachion mala*, Tilestones Fm. (TilF3), Capel Horeb Quarry, MPA 55422, slide 2A, Q18/2, MPK 14805; (l) *Leoniella carminae* Cramer, 1964, Cae'r mynach Fm. (CarF1), Sawdde Gorge, MPA 55414, slide 1, L12/0-3, MPK 14806; (m) *Leoniella vilis* Kiryanov, 1978, Cae'r mynach Fm. (CarF1), Sawdde Gorge, MPA 55412, slide 2, R10/3, MPK 14807; (n) *Angochitina elongata*? Eisenack, 1931, Tilestones Fm. (TilF3), Capel Horeb Quarry, MPA 55422, slide 2A, D17/3, MPK 14808; (o) *Eisenackitina lagenomorpha*? (Eisenack, 1931), Tilestones Fm. (TilF3), Capel Horeb Quarry, MPA 55422, slide 2B, M24/0-1, MPK 14809; (p) *Eisenackitina lagenomorpha*?, Cae'r mynach Fm. (CarF1), Sawdde Gorge, MPA 55412, slide 1, F16/4, MPK 14810.

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between Llandeilo and Carmarthen, the period of piedmont erosion that preceded this marine advance is recorded as an unconformity, increasing in magnitude westwards. However, this is a compound feature. It intervenes between Ludfordian terrestrial deposits and rocks that range from Wenlock to Neoproterozoic in age but conflates the impacts of multiple erosional episodes.

3.c. Ludlow Bone Bed flooding event

The abrupt changes in macro- and microfossil assemblages that take place across the LBB explain why it has gained such stratigraphical importance. Yet opinions have varied about the nature of the event it marks. In its type area, the LBB *sensu stricto* (Antia, 1980; Bassett *et al.* 1982) is the lowest of several bone-bearing levels present within an up to 0.3 m thick interval recognized by Bassett *et al.* (1982) as the Ludlow Bone Bed Member (LBBM). Gastropods, bivalves, ostracods, eurypterids, fish and plant remains are the dominant fossil components in and above this unit (e.g. Murchison, 1839; Elles & Slater, 1906; Bassett *et al.* 1982; Siveter *et al.* 1989; White & Lawson, 1989; Miller, 1995; Lane, 2000).

Early models saw this assemblage as offering evidence of an abrupt shoaling and associated changes in salinity. Richardson & Rasul (1990) sought to explain the pronounced changes to palynological assemblages that occur at the base of the LBBM as evidence for such an event. However, the select assemblage of articulated brachiopods hosted by the LBBM (e.g. Bassett *et al.* 1982) supports a majority of studies that recognize the bone beds as reworked lags formed in a storm-stirred setting that, if not fully marine, faced the open sea (see Section 6.c) and, further, that see the LBB itself as marking the onset of a period of rising sea level and reduced sediment supply (e.g. Allen & Tarlo, 1963; Antia, 1979, 1980; Allen, 1985; Smith & Ainsworth, 1989; Ainsworth, 1991; Veevers & Thomas, 2011). Recently, Hauser & Gold (2023) have sought to emphasize the role played by autogenic sedimentary processes during the accumulation of the LBBM and the succeeding early Pridoli succession. Such processes are acknowledged likely to have been influential during Ludfordian episodes of delta advance, but the current study confirms that marine base-level changes of regional, if not global reach were significant during the early Pridoli.

Bone-bearing levels that have been correlated with the LBBM have been taken to testify to the impact of this deepening episode in many areas of the North-Eastern and South-Eastern provinces (Allen, 1974b; Bassett *et al.* 1982). The findings reported herein call some of these correlations into question. The relevant phosphate and bone-bearing levels seen in the Woolhope, Gorsley and May Hill inliers, and that underlie the RF and CMSF, are believed to be significantly younger (see Sections 3.d, i and j). The current study allows for transgressive bone beds preserved in the Malverns, Usk and Rumney successions (e.g. Phipps & Reeve, 1967; Squirrell & Downing, 1969; Waters & Lawrence, 1987) still to be viewed as correlatives of the LBB. Objective proof for this and of the early Pridoli age of the overlying restricted marine succession is lacking. Bone beds seen in the Tites Point and Brookend Borehole sucessions (Cave & White, 1971) on the south side of the Bristol Channel have also been cited as equivalent to the LBB, but, being located to the south of the Severn Estuary Fault Zone (Wilson *et al.* 1988), are considered palinspastically displaced.

Where the LBBM is absent, it is faunal or lithological changes believed to mark the onset of the associated deepening episode that have been widely adopted as the proxy base of the Pridoli Series (Cocks *et al.* 1992). In the Clun Forest area, the series boundary is taken at the base of the '*Platyschisma* Beds' of Earp (1938; see Cave & Hains, 2001) and in the Western Province at the base of the TilF (Schofield *et al.* 2009). However, in the absence of graptolites from late Ludlow and Pridoli rocks in the UK (Zalasiewicz *et al.* 2009), such correlations have relied on fossil evidence that the current study finds deficient.

3.d. Early Pridoli Hiatus

A significant finding of the current study is a widespread intra-early Pridoli erosional event believed to record the impact of a forced regression (Figures 1 and 3c). Sites that display the evidence for this event, including channelling and calcretization affecting the top of the TilF and DCSF, are listed in Section 6. In the South Eastern Province, it is manifested by an erosion surface overlain by bone beds in the Woolhope, Gorsley and May Hill inliers. Accordingly, these levels are no longer correlated with the LBBM (see Sections 3i and j). The erosion surface at the base of the ORS in the Rumney Borehole (Waters & Lawrence, 1987) is also interpreted as the early Pridoli Hiatus. However, the bone bed that lies 7 cm below the hiatus is still considered to be a correlative of the LBBM. Only the Usk Inlier succession fails to preserve obvious impacts of the early Pridoli Hiatus. The recognition of the Hiatus is reflected in the stratigraphical labelling used for units that pre- and postdate its impacts, the rocks that overlie it here considered to be mid-early Pridoli in age.

3.e. Cae'r mynach Formation (CarF)

3.e.1. Introduction

The CarF (Schofield *et al.* 2004, 2009; Barclay *et al.* 2005) was erected for the marine, sheeted heterolithic facies of Ludfordian age in the Western Province. It is here expanded to include similar Ludfordian facies throughout the study area (CarF 1), and also lithogically comparable, but faunally more restricted, early Pridoli facies (CarF 2 and CarF 3). Figure 4 shows the plethora of previously used local terms used for the rocks here included in this extended usage of CarF.

3.e.2. Cae'r mynach Formation of Ludfordian Age (CarF 1)

The long-standing nomenclature used for Ludfordian and Pridoli strata in the Type Ludlow area and throughout the Welsh Borderland is here abandoned. Our study of sedimentary facies found little lithological basis to distinguish the Lower and Upper Leintwardine formations and the Lower and Upper Whitcliffe formations of Holland *et al.* (1963) and also Holland *et al.* (1980). Each of these historical divisions comprises a heterolith of bioturbated, more or less calcareous silty mudstones with abundant sandstone sheets and a diverse marine macrofauna. Holland *et al.* (1963) based their subdivisions on faunal incomings and outgoings, yet recognized all four units as belonging to a single 'calcareous shelly siltstone facies' (Holland & Lawson, 1963). Watkins (1979) concurred and assigned these 'formations' to a single 'coquinoid siltstone facies', and the sedimentary logs presented by Siveter *et al.* (1989) make clear their lithological similarities. The biostratigraphical validity of criteria cited by Holland *et al.* (1963) are open to debate, but it is certain that they cannot form the basis for lithostratigraphical subdivision. Ludfordian successions east of the Church Stretton Fault Zone are typically thinner and more calcareous than those to the west but in term of gross facies and age are otherwise comparable to the Western Province CarF. Miller *et al.*

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(1997) interpreted the presence of slump beds and 'turbidite' sandstones in the Cefn Einon Formation of the Montgomery district (Figure 4; Earp, 1940) as evidence of deeper water sedimentation. However, the evidence provided by hummocky cross-stratification for shallow, storm-influenced conditions (Cave & Hains, 2001; Cherns *et al.* 2006) is consistent with its inclusion, together with the Llan-Wen Hill Formation (Holland, 1959) of the Knighton area, in the CarF.

Throughout much of its outcrop, the base of the CarF succession is marked by the facies changes linked to the Leintwardinian flooding event. Associated fossil assemblages, that widely include graptolites, provide widespread proof of age (see Section 3.b and Figure 3). Graptolites are less common in western successions, where dating relies more strongly on shelly and microfossil indicators. These warrant additional comment in the light of new findings.

In the Western Province, adjacent to the Golden Grove Axis, the trilobite and brachiopod fauna in the lower part of the attenuated 4.8 m thick CarF succession in the Cennen road section (Figure 1) can be correlated with the 'Leintwardine Beds' of the Ludlow area (Potter & Price, 1965; Squirrell & White, 1978). Palynological investigation of samples (MPA 55415–MPA 55417) from the formation in this section (Figures 2, 7 and 21) yielded species that are consistent with an early Ludfordian age, based on comparison with records from the Welsh Borderland. The acritarchs *Sol radians*, reported from the upper Bringewoodian to the Leintwardinian (Dorning, 1981), probable *Rhacobrachion mala*, not known below the Leintwardinian (Lister, 1970; Dorning, 1981), and common specimens of a prasinophyte provisionally identified as *Cymatiosphaera* sp. A? of Richards & Mullins (2003), which ranges from the upper Bringewoodian to the lower Leintwardinian, all occur in the lowest sample (MPA 55415). *Leoniella carminae*, reported to range from the top of the Bringewoodian to the Whitcliffian in the Welsh Borders (Dorning, 1981; Richards & Mullins, 2003), was recorded from the sample above (MPA 55416). The lowest sample contains the most diverse assemblage of marine palynomorphs (acritarchs, chitinozoans) in the section, the diversity decreasing upwards. Miller (1995) has re-examined anomalous ostracod specimens from the CarF in the Cennen road section assigned by Squirrell & White (1978) to the earliest Pridoli taxon *Frostiella groenvalliana*. He found them to be poorly preserved and almost exclusively internal moulds best referred to as *F.* cf. *groenvalliana*.

Farther west in the Sawdde Gorge, the CarF comprises a 10 m thick basal conglomeratic Cribyn Du Member overlain by 76 m of sheeted heterolithic facies (Figure 1). A sample (MPA 55411), from just above the base of the heterolithic facies, contains common *Rhacobrachion mala* and abundant *Cymatiosphaera* sp. A? of Richards & Mullins (2003) which suggest an early Ludfordian, early Leintwardinian age (Figure 7). From 10 m (MPA 55412) above the base of the heterolithic facies, the acritarchs *Leoniella carminae* and *L. vilis*, together with abundant specimens of the chitinozoan *Eisenackitina lagenomorpha*?, support an early Ludfordian Age. *Leoniella carminae* ranges from the top of the Bringewoodian through the Ludfordian, but *Leoniella vilis* is the eponymous species of the *L. vilis* acritarch Biozone, which spans the late Bringewoodian and earliest Leintwardinian (Richards & Mullins, 2003; Mullins, 2004). Although not identified with certainty in the Sawdde Gorge samples, *Eisenackitina lagenomorpha* was reported by Sutherland (1994) from the early Bringwoodian to early Leintwardinian but is only numerically significant across the base of the Leintwardinian. Verniers *et al.* (1995) indicated a longer range for the species, from the base of the Ludfordian into the Pridoli Series, but again noted its increased importance at or around the base of the Ludfordian on Gotland and in Estonia as well as in the Welsh Borderland. The prasinophyte *Cymatiosphaera* sp. A? and chitinozoan *Angochitina elongata*? from a sample 43 m above the base of the heterolithic facies (MPA 55413) further support a Leintwardinian age (Sutherland, 1994; Verniers *et al.* 1995; Richards & Mullins, 2003). Higher in the succession, specimens of the acritarch *Comasphaeridium brevispinosum* were recorded from a higher sample (MPA 55414) 34 m below the base of the TilF. The species ranges through the Ludlow Series, but Lister (1970) noted a morphological development through the succession. Specimens with longer and more closely spaced processes, like those from MPA 55414, occur in the upper part of the succession, notably in the Whitcliffian although here probably Leintwardinian. Samples from the topmost 3 m of the CarF (MPA 55408-MPA 55410) in the Sawdde section yielded no biostratigraphically significant palynomorphs. However, at Capel Horeb, to the north-west, a single specimen of *Cymatiosphaera* sp. A? of Richards & Mullins (2003) in a sample just below the base of TilF 2 (MPA 55421) implies that there the whole of the underlying CarF succession is Leintwardinian.

Shelly faunas broadly support these finding but offer evidence of facies control. In the Sawdde section, the trilobite *Alcalymene puellaris* (identified by Derek Siveter) from a level 42 m above the base accords with the report by Potter & Price (1965) of the Leintwardinian indicators *Neobeyrichia lauensis, Hemsiella maccoyiana* and *H. canalis* from the lower half of the formation. However, Leintwardinian indicators are absent from levels of the formation that closely underlie the TilF successions in both the Sawdde and Capel Horeb areas. Potter & Price (1965) recognized that the upper part of the CarF (their Upper Roman Camp Beds) at Capel Horeb contained a low diversity shelly assemblage that lacked typical Leintwardinian forms but took this to indicate a Whitcliffian age. The faunal transition that marks the Leintwardinan–Whitcliffian boundary in the Ludlow-type area was likely as much a reflection of a regional change in palaeoecological conditions as a biostratigraphical event. The new microfossil data shows that, in western areas, open marine Leintwardinian taxa, including key graptolite, brachiopod and ostracod taxa, were excluded much earlier from settings adjacent to the TilF's river-influenced deltaic shoreline. Only longer ranging forms were able to tolerate these pro-delta locations (see Figure 1, note 9).

In the South-Eastern Province, limestone conglomerates are locally associated with the base of the CarF and include the Lower Blaisdon Beds and Clenchers Mill Beds of the May Hill and Malverns areas, respectively (Lawson, 1955; Worssam *et al.* 1989). Biotite-rich sandstones are a feature of the South-Eastern Province succession, where the presence of bone and phosphate pebble-bearing lags was seen by Lawson (1954, 1955) to testify to a shallower and more frequently scoured setting. He linked two more persistent horizons (here formally named the Lower & Upper Linton Pebble beds (LLPB and ULPB); Figure 1) to periods of more widespread and sustained erosion and omission affecting the Gorsley and May Hill successions that testify to the active nature of the Gorsley Axis. The LLPB lies at the base of the Whitcliffian succession seen in Linton Quarry (SO 6770 2570). The surface on which the ULPB rests represents the early Pridoli Hiatus and marks the base of a younger division of the regional CarF succession (see Sections 3i and j) (Figure 1).

In contrast to other areas, the base of the CarF in the Clun Forest Sub-Basin is diachronous and records the gradual decline in sediment input from the south. Here, the establishment of shallow water conditions was delayed until the Whitcliffian and postdates *Bohemograptus* proliferation faunas locally present in the underlying Knucklas Castle Formation (Holland & Palmer, 1974; Cave & Hains, 2001).

The stratigraphical relationships documented by this study confirm that the TilF and DCSF record multiple episodes of deltaic sandbody advance into the Cae'r mynach Seaway, and that this was ongoing throughout the Ludfordian and early Pridoli. CarF successions display complementary coarsening and thickening upwards trends and reducing levels of faunal diversity (e.g. Watkins, 1979; Barclay *et al.* 1997; Aldridge *et al.* 2000). Some specific facies changes may serve to corroborate the timing of the principal phases of deltaic outbuilding (see Section 7). The appearance of facies rich in the brachiopod *Shaleria ornatella*, recognized as the Woodbury Shale Member by Phipps and Reeve (1967), appears to record a significant late Leintwardinian paleoecological event affecting the Malverns area (Watkins, 1979). Renewed erosion accounts for the absence of late Leintwardinian strata from the vicinity of the Gorsley Axis. The newly recognized sandstone-prone Aston Munslow Member that underlies the LBB north-east of Ludlow, and sandy facies that predate the main DCSF progradation into the Clun Forest area (Figure 1), attest to a preceding late Whitcliffian phase of delta advance. Evidence for a coeval shoaling affecting much of the South-Eastern Province is lacking, perhaps largely due to subsequent intra-Pridoli erosion. However, Waters & Lawrence (1987) cite amalgamated, phosphate pellet and fish scale-bearing sandstones, interbedded with micaceous mudstones, in their Roath Park Lake Member as evidence for a late Whitcliffian shallowing affecting the Rumney area.

3.e.3. Cae'r mynach Formation of Early Pridoli age (CarF 2 and CarF 3)

In a further significant change from past practice, this study recognizes the LBBM and Platyschisma Shale Member (PSM) of the Ludlow area (Bassett et al. 1982; Figure 4), though their fauna testify to accumulation under more restricted marine conditions, as sedimentologically comparable to the underlying succession. Whilst their distinctive biota supports their retention as members, they are here recognized as a younger succession of CarF facies, labelled CarF 2. The PSM includes the Downton Bone Bed of Elles and Slater (1906) and Hauser and Gold (2023). We restrict use of the term DCSF to the sandstone-dominated strata that Bassett *et al.* (1982) recognized as their now redundant 'Sandstone Member' (see Section 3g below). In the Ludlow area, early Pridoli *S. tripapillatus* – *A. spicula* (TS) Assemblage Biozone spores make their first appearance in these units (Richardson & Lister, 1969; Richardson & McGregor, 1986; White & Lawson, 1989; Edwards & Richardson, 2004), as does the ostracod *F. groenvalliana* and the remains of new species of bony fish (White & Lawson, 1989).

These reassigned Ludlow area strata are here seen to form part of an extensive early Pridoli CarF succession that is also present in the Malverns, Gorsley, May Hill, Usk and Rumney inliers (Figures 1 and 4). In the Usk area, this includes the 'Speckled Grit' of Walmsley (1959); see also Squirrell & Downing, 1969), strata shown as DCSF on some BGS digital maps, but which are more comparable to CarF facies. These Pridoli levels form part of an unbroken Usk Inlier succession that ranges through the Ludfordian into the early Pridoli. In contrast, the successions seen in the Gorsley, May Hill and Rumney inliers are incomplete and include levels that postdate the early Pridoli Hiatus. In the Gorsley area, these comprise the 1.3 m thick interval of flaggy micaceous mudstones and siltstones with a very restricted fauna that intervenes between the ULPB and the base of the CMSF at Linton Quarry (Figure 1). These strata thicken southwards and in the southernmost part of the May Hill inlier replace the whole of the CMSF (see Section 3i below). They are exposed in a stream section (SO 6936 1671) near Wood Green where they comprise a sheeted heterolith of siltstones and sandstones. The omission surface that underlies these facies, and which increases in magnitude northwards (Lawson, 1955), makes the case to label them as a separate, younger division of the CarF succession (CarF 3) (Figure 1).

Overlying the early Pridoli Hiatus, the ULPB is up to 2.5 cm thick and comprises rolled phosphate pebbles and granules in a silty sand matrix with scattered fish remains. New spore assemblages obtained from the overlying CarF 3 interval at Linton Quarry (LQ1and LQ2) contain *Synorisporites tripapillatus, S. verrucatus, Cymbosporites echinatus and Apiculiretusispora spicula.* These new findings accord with those of Richardson & Lister (1969) in showing that lower levels of the CMSF at Linton Quarry contain early Pridoli TS Assemblage Biozone miospores. Early Pridoli ostracods reported by Worssam *et al.* (1989), though listed as from the CMSF, are likely from an equivalent level on the eastern side of the May Hill inlier. Though imprecise, these fossil findings are consistent with the mid-early Pridoli age implied for these rocks by new regional correlations (see Sections 3i and 6 below). Lawson (1955) viewed the attenuation and local absence of the CMSF in the south of the May Hill inlier as evidence of overstep at the base of the ORS. A transition into Car3 and unrecognized faulting associated with the steep to overturned limb of a local fold offers an alternative explanation preferred here.

3.f. Tilestones Formation (TilF)

3.f.1. Introduction

The TilF (Strahan *et al.* 1907; Schofield *et al.* 2004, 2009; Barclay *et al.* 2005) crops out between just west of the Cennen Valley, near Llandeilo, and the Wye Valley, near Builth Wells. The base of the TilF is taken at the onset of sandstone bed amalgamation. A reassessment of the brachiopod and ostracod faunas, allied to new palynological dating (Supplementary Figure 1), shows that the TilF is diachronous, ranging in age from early Ludfordian to early Pridoli, and is largely coeval with the CarF. Moreover, when integrated with the paper's sedimentological findings, this biostratigraphical analysis demonstrates that the formation's extensive linear outcrop, rather than representing a single sandbody, as previously presumed, is composite in character and charts the development of at least four separate progradational events (Figure 1). The two earliest progrades (TilF1 and TilF2) are Leintwardinian in age. The third prograde (TilF 3) appears to span the Leintwardinian–Whitcliffian boundary, with only the youngest prograde (TilF 4) likely to be of early Pridoli age.

After their work on the Western Province succession, Potter & Price (1965) followed Straw (1929) in viewing the base of the 'Tilestones' (their Long Quarry Formation) as unconformable, arguing that, as it was traced south-westwards, it overstepped onto successively older rock divisions. Subsequent studies adopted this putative break as the *de facto* regional base of the Pridoli Series and of the ORS (e.g. Bassett *et al.* 1982; Siveter *et al.* 1989). It was seen to overlie marine Ludfordian and, in containing a similar restricted fauna of bivalves, gastropods and ostracods, to equate with the DCSF of the Ludlow area (e.g. Straw, 1929; Potter & Price, 1965; Squirrell & White, 1978). Strata equivalent to the Capel Horeb Member of Almond *et al.* (1993) in the Sawdde Gorge are here recognized as part of the CarF. The recognition of multiple TilF units also renders Almond *et al.*'s (1993) Long Quarry Member redundant. The eponymous 'long quarry' of Cilmaenllwyd is sited in TilF 2 (see Section 6.b).

The position of the formation's base in key sections purported to show the unconformity has been disputed in the past (compare Potter & Price, 1965; Friend & Williams, 1978; J. Almond, unpub. PhD thesis, University of Bristol, Almond, 1983, and Almond *et al.* 1993; Barclay *et al.* 2005). Following its re-survey of the region, BGS recognized the TilF as conformable with the underlying, marine Ludfordian, CarF (Schofield *et al.* 2004, 2009; Barclay *et al.* 2005). This has been confirmed by the detailed sedimentary logging undertaken as part of the current study. Only close to its western limits, astride the Golden Grove Axis west of the Cennen Valley, where facies of TilF 1 rest on late Gorstian rocks (Mynydd Mydffai Sandstone Formation), is the formation's base recognizably unconformable.

3.f.2. Tilestones Formation progrades 1 and 2 (TilF 1 and TilF 2)

Sedimentary logging of the Cennen road section, near the western feather edge of the TilF outcrop, demonstrates the presence of a basal prograde and the lower levels of a second. From the basal part of TilF 1 exposed in the Cennen road section, Squirrell & White (1978) reported the brachiopod *Hyattidina canalis* and the ostracod *F. groenvalliana* and recovered the former also from trenches immediately to the west. The presence of *F. groenvalliana* was regarded as proof of an early Pridoli age. However, in the type Ludlow area and elsewhere, *H. canalis* is unknown above the 'Lower Leintwardine Beds' and their correlatives and therefore is older than the Pridoli. Squirrell & White (1978) recognized that the occurrence of *H. canalis* with *F. groenvalliana* was anomalous but regarded the former as having an extended local range. Miller's (1995) re-evaluation of the *F. groenvalliana* specimens from the Cennen section shows that these that can no longer be relied up on, and since TilF 1 contains the same macro faunal elements as the underlying CarF, it follows that this is also early Leintwardinian in age (see Section 3.e.2).

No macrofossil or palynological data have been obtained from TilF 2 in the Cennen section. However, stratigraphical and thickness considerations (see Figures 1 and 23) suggest that it was only this youngest of the Cennen progrades that extended into the Sawdde Gorge and Capel Horeb areas. There it succeeds entirely Leintwardinian CarF successions (see Section 3.e.2). At Capel Horeb, the presence of probable Leintwardinian acritarchs and chitinozoans in beds near the base of the succeeding TilF 3 prograde (see Section 3.f.3) provides evidence that the TilF 2 advance was confined to the Leintwardinian.

3.f.3. Tilestones Formation prograde 3 (TilF 3)

TilF 3 facies exposed in Capel Horeb Quarry contain four productive palynological levels (Figures 6 and 13). Those from the near the base of TilF 3 (KH/CH2, KH/CH3 and MPA 55422; Supplementary Figure 1) are found in mudstones associated with the most distal facies of the prograde that ovelie its defining flooding surface. Those at higher levels (KH/CH4 and MPA 55423) were obtained from mudstone partings in more proximal facies. Stratigraphically, the most significant spore species is the distinctive Ludfordian form *Stellatispora inframurinata* var. *inframurinata* present in samples KH/CH2-4 and MPA 55422. In terms of the Anglo-Welsh spore zonation scheme, the assemblages belong to the youngest subzone of the *libycus-poecilomorphus* (LP) Assemblage Biozone of Burgess & Richardson (1995). According to these authors, the *Stellatispora inframurinata* var. *inframurinata* Assemblage Subzone ranges from mid-late Ludfordian in age.

Sample (MPA 55422) yielded the most diverse assemblage of marine palynomorphs (acritarchs and chitinozoans) in the section, in keeping with its distal setting, including abundant *Rhacobrachion mala*. Also present, however, are single specimens of the actitacrch *Leoniella vilis*?, and the chitinozoans *Angochitina elongata*? and *Eisenackitina lagenomorpha*? Although identifications are provisional (based on single, poorly preserved specimens), these forms continue to support a Leintwardinian age (see sections 3.e.2 and 3.f.2). The absence of Leintwardinian taxa from the low diversity assemblage provided by sample MPA 55423, though it lacks definitive indicators, may show that TilF 3 extends into the Whitcliffian.

3.f.4. Tilestones Formation prograde 4 (TilF 4)

A thin (<7 m), poorly exposed succession outcrop of TilF extends from north-east of Capel Horeb to just west of the Wye Valley (Schofield *et al.* 2004; Barclay *et al.* 2005). Though undated, palaeogeographical considerations suggest that much of this more northerly development of the formation was the product of a separate and early Pridoli delta advance (TilF 4). The most westerly outcrop of north-easterly derived DCSF deltaic facies is in the Wye Valley at Llanstephan (Figure 2). No LBBM is present. However, c.13 km north-east, in a new quarry at Gwernilla, a LBBM succession present below the DCSF, as in its type area, is taken to be early Pridoli in age (Figure 2). The DCSF records delta advance into the same Cae'r mynach Seaway that fronted the TilF progrades. It seems inconceivable that sufficient of this seaway survived after the DCSF advance to host a still younger TilF prograde from the north-west; and, since the converse is equally true, it seems necessary to view TilF 4 and the DCSF as essentially coeval. The proximity of sections in TilF 4 west of the Wye Valley to exposures in coeval DCSF facies east of the CSFZ likely reflects, as discussed more fully in Section 6h, a juxtapositioning brought about by lateral movements along the fracture belt. It is clear, nevertheless, that there must once have existed a lateral interface between the two sandstone units in the region between Mynydd Epynt and Clun Forest (Figures 1 and 3b).

3.g. Downton Castle Sandstone Formation (DCSF)

The term Downton Castle Sandstone was first proposed by Elles & Slater (1906) for the prominent sandstone unit well exposed in the Downton Gorge. Its recognition as the basal division of the former Downtonian (e.g. Allen, 1974a) underpinned the useage proposed by Bassett *et al.* (1982) and its subsequent assignment to the Pridoli Series (e.g. White & Lawson, 1989). As noted above, divisions previously included as members in the DCSF by Bassett *et al.* (1982) are here excluded from it (Figure 4). The base is now defined as the appearance of sandstone bed amalgamation in the sandstone prone sequence. Though the high-energy sandstones of the DCSF are largely unsuited for the preservation of spores and ostracods, *F. groenvalliana* has been found in the basal 0.75 m (David Siveter pers. comm.) and the formation is believed to fall entirely within the range of this taxon (Siveter, 1989).

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The labelling of strata as DCSF on BGS digital maps of the Woolhope, Mayhill and Usk areas is incorrect. Some of these units are not sandstone-dominated and their stratigraphical relationships do not compare. Herein, the DCSF is recognized as an early Pridoli deltaic sand body that, with the arguable exception of the Malverns area, is preserved princiapally to the north of the Neath Disturbance.

Deltaic sandstones present in the Knighton, Clun Forest and Long Mountain areas are recorded in the literature as 'Yellow Downtonian' (Holland, 1959; Palmer, 1970). Cave & Hains (2001) included these strata in their early Pridoli Clun Forest Formation but did not recognize or map a major sandstone unit. Investigations as part of the current study have confirmed that the DCSF is present (e.g. Stonehouse Dingle) but in many localities is cut out by faulting. The sandstone units display sedimentological differences from those in the Ludlow area (see below), but the current study confirms that they were deposited by the same north-easterly sourced delta system (Figures 1 and 3b). The LBB is not recognized in these westerly successions, but the interval underlying the sandstones that contains the same brackish water fossil assemblage as the Platyschisma Shales Member has been taken as evidence for an early Pridoli age (e.g. Cave & Hains, 2001).

Strata worked for tiles in the Long Mountain area and mapped by BGS as TilF (BGS, 2008b; Cave, 2008) are also better viewed as a local representative of the DCSF. A local equivalent of the LBBM has been recognized in the underlying succession (Palmer, 1970). From overlying levels seen as equivalent to the 'Platyschisma Shales', Miller (1995) recovered what he considered to be early Pridoli microfossil assemblages.

In the Malverns area, heterolithic facies included in the CarF, for example at Brockhill Quarry (S.J. Veevers, unpub. PhD thesis, University of Birmingham, Veevers, 2006), Woodbury Quarry and Woodfield Farm (White *et al.* 1984), intervene between a local bone bed and a sandstone unit for which the label DCSF may continue to be appropriate. Penn (1987) suggests that the DCSF was encountered in the Maesteg No. 1 Borehole (SS 8528 9245), but gamma ray and acoustic log responses across the interval are similar to those for calcareous sandstones in the overlying MCF.

3.h. Temeside Mudstone Formation (TemF) and Moor Cliffs Formation (MCF)

3.h.1. Stratigraphy

Description, dating and historical background for these units is provided by Barclay *et al.* (2015). Two geographically separate developments of the TemF are recognized in this account (Figure 1). TemF 1 predates the early Pridoli Hiatus and TemF 2 postdates it.

The type succession of TemF, in the Welsh Borderland and English Midlands, widely referred to as the 'Green Downtonian' (e.g. Earp, 1938; Holland, 1959) is TemF 2 of this account. It comprises a distinctive suite of green mudstones with calcretes that intervenes between the DCSF and the 'red bed' facies of the MCF. It is from the TemF 2 succession of the Ludlow area that Richardson & Edwards (1989) report the enigmatic mid-early Pridoli Biozone A miospore assemblage (see below). The bulk of TemF 2 is widely acknowledged to fall within the range of *F. groenvalliana*. The late early Pridoli ostracod taxon *Frostiella bicristata* first appears at the top of TemF 2, in the Temeside Bone Bed (Shaw, 1969; Siveter, 1989). Throughout the North-Eastern Province and northern part of the Western Province, this type succession succeeds the early Pridoli Hiatus (Figure 1). Lawson (1955) invoked erosion at the base of the MCF to explain the absence of TemF from the May Hill area and also from the successions of the other south-eastern inliers. The correlation of early Pridoli rocks proposed herein offers an alternative, passive explanation.

The TemF in the Western Province (TemF 1) together with the underlying AF includes the strata shown on BGS maps as 'Green Beds' (Strahan *et al.* 1907; Squirrell & White, 1978). MCF facies that succeed them are also older than their Welsh Borderland equivalents. Straw (1929) suspected a lateral passage between these and strata further east and the current study confirms that they form part of the alluvial to deltaic facies continuum that includes the various TilF progrades. The presence of micaceous, channel-filling sandbodies in the local TemF 1 and MCF successions has long been seen to provide evidence of such a linkage (Straw, 1929). Recent work in south Pembrokeshire (e.g. Hillier *et al.* 2019, and references therein), confirmed by the current study, has shown that the accumulation of the alluvial and coastal plain components mirrored the advance of the TilF delta system and occupied a depositional tract that expanded throughout the Ludfordian and early Pridoli.

There are also separate pre- and post-hiatus developments of the MCF distinguished as MCF 1 and MCF 2, respectively, on Figure 1. It is acknowledged that these divisions may warrant separate nomenclature. Where MCF 2 red beds succeed the TemF, they overlie a gradational and conformable contact. To the south of the Neath Disturbance, these red beds locally succeed the RF, CMSF, CarF 3 and Pwll-Mawr Formation (PMF). MCF facies that overlie the impacts of a second, mid-Pridoli incision event that appears principally to have affected the Western Province are shown as MCF 3.

3.h.2. Note on the Biozone A miospore assemblage

In the Ludlow area, Richardson & Edwards (1989) erected spore Biozone A (also known as Biozone II) above the TS Assemblage Biozone (Figure 5), and it was adopted as a key division of the regional late Silurian spore zonation. Biozone A was defined in only broad generic terms and no key zonal taxa were named. In addition, Edwards & Richardson (2004) reported that the nominal spore species of the older TS Assemblage Biozone are absent from the TemF Biozone A assemblages. Biozone A is only known from the TemF of the Ludlow area (Richardson & Edwards, 1989; White & Lawson, 1989; Edwards & Richardson, 2004). However, the number and location of Biozone A samples in the TemF have never been published. The lower part of the formation is poorly exposed in the Ludlow area, and it is the formation's upper levels, containing the Temeside Bone Bed, that have been most widely reported on in the past (Elles & Slater, 1906). The main section in the River Teme was inaccessible during the present study and at the time of writing the stratigraphic entry level of Biozone A spores is unknown.

3.i. Clifford's Mesne Sandstone Formation (CMSF), Rushall Formation (RF) and Pwll-Mawr Formation (PMF)

The CMSF (Lawson, 1954; 1955) is present in the Gorsley and May Hill inliers. At Gorsley and around Clifford's Mesne, the formation comprises up to 24 m of thick-bedded, pale orange, fine- to medium-grained sandstones, quite unlike the DCSF of the Ludlow area. In the May Hill Inlier south of the NW-SE trending Glasshouse Fault, it comprises a finer-grained succession of massive siltstones and silty sandstones (Lawson, 1955, see also Gardiner, 1920; Lawson, 1982). As described above, the CMSF overlies a succession of silty shales with a restricted marine fauna, referred here to CarF 3. These shales, seen at Linton Quarry in the north and Longhope Quarry in the south, contain faunas and spores that confirm an intra-Pridoli age for the CMSF.

Secondary reddening offers a plausible alternative explanation for red mudstones interbedded within the upper parts of the CMSF in the M50 road cutting that might otherwise be taken to suggest a gradational passage into the succeeding MCF (Allen & Dineley, 1976).

The RF was first recognized by Squirrell & Tucker (1960) in the Woolhope Inlier and extends to the north in a faulted inlier at Shucknall Hill (Figure 1). It comprises up to 27 m of coarse- to fine-grained sandstones and olive grey and green mudstones and siltstones. The coarser and finer lithologies are present in roughly equal measure and exhibit rapid lateral and vertical changes in facies (Brandon, 1989). Articulated brachiopods, likely reworked, are confined to the basal few centimetres of the formation. The presence of inarticulated brachiopods and abundant eurypterid and fish remains supports sedimentological evidence for deposition in a shallow and restricted, brackish water setting; locally preserved green beds with calcrete nodules testify to periods of emergence (see Section 4.b.8).

The prominent erosion surface at the base of the RF marks the early Pridoli Hiatus. It is widely overlain by a 2.5 to 30 cm thick bone-bearing unit. The latter comprises a dark grey, locally conglomeratic, carbonaceous sandstone bed with fish bones, scales and phosphate pebbles and locally contains boulders eroded from the underlying CarF (Stamp, 1923; Gardiner, 1927). This bone bed's sparse fauna is dominated by comminuted eurypterid remains, together with plant fragments and carbonized algae. Inarticulate brachiopods and stratigraphically important ostracods have also been recovered. CarF facies that underlie the erosion surface exhibit no evidence of pedogenic alteration.

Squirrell & Tucker (1960) correlated the bone-bearing level with the ULPB of the Gorsley and May Hill successions and followed Lawson (1955) in interpreting them as LBB correlatives. They found the RF difficult to match with either the DCSF or TemF of the Ludlow area due to its heterolithic character. They correlated it with CMSF of the Gorsley and May Hill areas, but mistakenly considered it also to be the latteral equivalent of the Speckled Grit of the Usk area and the DCSF of the Malverns. These are all areas where the TemF is absent.

Confirmation of an early Pridoli age for the RF is provided by the presence of ostracods, including *F. groenvalliana*, from exposures of the basal beds in Perton Lane (Brandon, 1989; Miller, 1995). Spores from the same locality are of the TS Assemblage Biozone (Fanning *et al.* 1991; Edwards & Richardson, 2004), and this is confirmed by a sample (Pert 1) taken from 0.55 m above the base of the formation at this locality. This sample yielded the following spore taxa, *Synorisporites tripapillatus*, *S. verrucatus*, *Cymbosporites echinatus*, *Archaeozonotrilletes chulus* var. *chulus*, *Apiculiretusispora spicula* and *A. synorea*. In the Rumney Borehole, the basal 13 m of strata previously included in the Raglan Mudstone Formation (Waters & Lawrence, 1987) are here recognized as the newly named PMF. Its basal erosion surface marks the early Pridoli event. The formation is dominated by a heterolith of dark purple and reddish-purple mudstones with laminae and thin beds of siltstone and fine sandstone. Bioturbation is locally present as are lingulids, some preserved in life position. A single calcrete profile is associated with a unit of massive red mudstone. Spore assemblages recovered by Burgess & Richardson (1995) from a 0.8 m thick unit of grey-green laminated mudstone with plant debris, present just below the top of the formation in the Rumney Borehole, are of the TS Assemblage Biozone.

In the Usk Inlier, a thin interval of mottled red and green mudstones intervenes between the local CarF succession and fully terrestrial MCF facies. These mark an extension of the PMF into the Usk region, but there they form part of a succession lacking evidence for the early Pridoli Hiatus (see Section 6.d.3).

3.j. A new model for the correlation of early Pridoli rocks in the Welsh Borderland

Underpinning established early Pridoli correlations has been the assumption that the basal bone-bearing beds that underlie both the RF and CMSF equate with the LBB and, consequently, that both formations correlate with the overlying Ludlow area succession (e.g. Lawson, 1954, 1955; Squirrell & Tucker, 1960; Brandon, 1989; Bassett *et al.* 1992). The Speckled Grit (Walmsley, 1959) of the Usk area has also been seen as a correlative of the DCSF and is shown as such on BGS paper and digital maps. However, there are sedimentological and palaeogeographical reasons to question these long-held assertions and a rigorous reassessment of the biostratigraphical evidence permit alternative correlations of early Pridoli rock units.

The first option is to accept the long-standing correlation with the Ludlow area succession. In this scenario, the bone and locally boulder strewn erosion surface at the base of the RF and CMSF relates to the shoaling episode marked by TilF 3 and the Aston Munslow Member and was cut prior to the main early Pridoli phase of delta progradation. The RF might then be regarded as having formed in a back-barrier, estuarine or lagoonal setting landward of the contemporary delta. However, the basal erosion surface evidently testifies to a significant base-level event. Carbonate-rich facies are known to undergo rapid lithification. Nevertheless, boulder-grade clasts derived from the underlying succession imply a level of induration consistent with a period of burial and their excavation testimony to significant incision. Evidence that the earlier shoaling episode culminated in comparable levels of erosion elsewhere along the margins of the Cae'r mynach Seaway is lacking. It then becomes difficult to envisage how this level of incision could have been generated in a setting located alongside a passively prograding deltaic shoreline. Nor is it obvious where this shoreline was located. The subsequent DCSF delta advance was from the north-east, yet the crop of the brackish RF lies well to the south of the Ludlow area of progradation and to the west of the DCSF of the Malverns. The RF occupies a region that palaeogeographical reconstructions might reasonably envisage to be on the seaward side of these deltaic coastlines.

The southwards failure of the TemF is also difficult to account for. A lateral passage from green, seawards facing coastal plain facies into a region of MCF red bed accumulation located to the south again lacks palaeogeographical credibility. Unconformity has been invoked to explain this anomaly, yet where seen, the contact between the TemF and MCF is gradational.

Seeking to resolve these palaeogeographical difficulties obliges us to question the long-held assumption that faunas recovered from and above the Woolhope, Gorsley and May Hill bone beds offer unambiguous evidence of a correlation with the LBB. They do not. The ranges of the key miospore and ostracod taxa clearly permit a second option. The lowest levels of the RF, CarF 3 and likely the whole of the PMF in the Rumney Borehole are all of TS Assemblage Biozone age. The unknown position of the base of

Biozone A in the Ludlow area allows for the lower parts of TemF 2 and the CMSF to be of TS Assemblage Biozone age as well. All these levels fall within the range of *F. groenvalliana*, and it is feasible to view them all as lateral correlatives (Figure 1).

Such a model accounts for the significant differences in composition and sedimentary context between the Woolhope, Gorsley and May Hill bone beds and the LBB. In this model, the early Pridoli Hiatus is viewed as testimony to a widely felt forced regression that resulted in the emergence, incision and pedogenesis of regions north of the Neath Disturbance, during the TS Assemblage Biozone. In contrast, the response to this event further south was marine ravinement. This promoted the widespread removal of earlier deposits, including levels equivalent to the LBB and then the accumulation of winnowed bone-rich lags on the erosion surface. The correlations implied by this interpretation, as depicted in Figure 1, allow TemF 2, RF and CMSF to be viewed as a palinspastically sensible succession of coastal plain, back-barrier and barrier deposits, and as evidence for a post-hiatus, mid-early Pridoli episode of delta progradation. A fuller explanation of this model, which envisages CarF 3 and PMF as the coeval deposits of a remnant southerly seaway and its westerly coastline, is given in Sections 6.d.2 and 6.d.3.

Finally, it is interesting to note that Allen & Dineley (1976) also suggested that the CMSF and RF are younger than the DCSF and overlie a substantial break. Their evidence was based on the absence of an overlying TemF and the presence of the mid-Pridoli ostracod *Kloedenia wilckensiana* in the basal CMSF and RF (Lawson, 1956; Squirrell & Tucker, 1960). Their suggestion never gained traction, however, probably as *K. wilckensiana* in the RF was later shown to be misidentified and to be the earlier *F. groenvalliana* (Brandon, 1989). The CMSF records are almost certainly similar misidentifications (David Siveter personal communication).

3.k. Mid-Pridoli Hiatus and Pont ar Llechau Formation (PALF)

The PALF (Almond *et al.* 1993; Barclay *et al.* 2015) is limited to the Western Province and confined to a narrow tract between just east of the Cennen Valley and just east of Rhyblid (Figures 1, 2 and 3d). Its usage here differs from the Pont ar Llechau Member of Almond *et al.* (1993). The formation mainly comprises up to 43 m of red brown, bioturbated, gritty argillaceous sandstones with scattered units of sandstones and green mudstones heterolith. A restricted marine fauna is present throughout the bulk of the formation, but units of interbedded sandstones with subordinate green mudstones contain a more diverse fauna.

Based solely on its stratigraphical position, the formation was interpreted by Almond *et al.* (1993) to be exclusively Pridoli in age. BGS (2008a; see also Barclay *et al.* 2015) viewed it as ranging from late Ludfordian into the early Pridoli. Five palynology samples (Figure 6) from three units of grey-green heterolith in the Sawdde Gorge have yielded spores that underpin a radical reappraisal of the formation's age and setting. The assemblages contain many of the spore taxa recorded in the TilF at Capel Horeb but include additional stratigraphically important taxa. These include *Apiculiretusispora spicula*, *A. synorea*, *A.* sp. C, *Chelinospora cantabrica*, *Chelinospra* cf. *hemiesferica*, *Chelinospora* cf. *cassicula*, *Chelinospora* cf. *lavidensis* and *Scylaspora* cf. *elegans*.

In terms of Richardson & Edwards' (1989) Anglo-Welsh spore biozonaton, these assemblages would be placed within the TS Assemblage Biozone. However, the presence of several *Chelinospora* taxa (particulary *Chelinospora* cf. *lavidensis*) and *Scylaspora* cf. *elegans* is regarded as stratigraphically significant. The *Chelinospora lavidensis* assemblage has recently been described from the FEF in south Pembrokeshire (Hillier *et al.* 2019; Higgs, 2022), where it was assigned an early mid-Pridoli age based on a palynological correlation with the San Pedro Formation in north-west Spain. In that region, Richardson *et al.* (2001) established a Ludfordian–Pridoli spore biozonation for the Spanish succession in which *Chelinospora lavidensis* characterized the upper part of the *Chelinospora hemiesferica* H Biozone of early mid-Pridoli age. However, the rare occurrence of *Scylaspora* cf. *elegans* in the base of the PALF (sample MPA 55403) may imply a slightly younger Pridoli age for the formation in the Sawdde section. In Spain, *S. elegans* is a biozonal index species for the mid- to late Pridoli *Scylaspora elegans* – *Iberospora cantabrica* EC Biozone. Additional samples need to be studied to determine whether the PALF should be assigned to this younger biozone.

These findings underpin the belief that the both the PALF and FEF lie above a regional, mid-Pridoli Hiatus and are associated with the development of separate, but largely coeval incised valley systems (Hillier *et al.* 2019). The incision surface also serves to distinguish a younger division (MCF 3) from early levels of the MCF (Figure 1). Though evidently a significant feature in the west, this hiatus level remains unrecognized in eastern red bed successions (see Section 6h).

4. Lithofacies analysis

4.a. Methodology

Our research has focused primarily on the analysis of sedimentary lithofacies within the *circa* 120-km-long crop of the late Ludfordian to mid-Pridoli rocks that extends from south Pembrokeshire, in south-west Wales, to the Type Ludlow area of the Welsh Borderland (Figure 1) and which includes the CarF, TilF, DCSF, AF, CMSF, RF, PMF, TemF and PALF. Sections in the Clun Forest area to the NW and in the eastern Silurian inliers at Woolhope, Malverns, May Hill, Gorsley and Usk have also been assessed. Facies analysis of the Rumney Borehole near Cardiff has also been undertaken. Numerous small exposures cited by previous workers have also been examined and are referenced individually in the succeeding text. In addition to Kirk's (1951) published work, additional data for the poorly exposed tract between Presteigne and Brecon that sits astride the WBFS has been obtained from her unpublished field maps and manuscripts archived by the National Museum and Galleries of Wales (Kirk, unpublished manuscript) and her unpublished PhD thesis, University of Cambridge, Kirk, 1947. In total, 33 sections were logged in detail, and these field observations were supplemented by the examination of selected petrographic thin sections. The principal sections comprise mainly former 'tilestone', building stone and aggregate quarries, road cuts and stream sections. Many former exposures of the LBB and its equivalents have suffered as a result of over-collecting, but fresh sections were examined at Downton Weir Quarry near Ludlow and at a previously unrecognized locations at Gwernilla and on Bradnor Green Golf Course in the Clun Forest area. At the time of writing, permission had not been granted to access the type section of the TemF along the River Teme at Ludlow.

Samples from selected sections and intervals have been processed for palynological analysis. Information for each specimen referred to in the text includes sample number (prefixed

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MPA for BGS samples), slide number, England Finder slide co-ordinate (e.g. M4/2) and specimen number. Specimens with the prefix 'MPK' are stored in the collection of Type and Figured micropalaeontological specimens of the BGS, Keyworth, Nottingham, UK. Specimens with the prefix KH and PAL are stored in the School of Biological, Earth and Environmental Sciences, University College Cork.

4.b. Lithofacies

4.b.1. Introduction

This study focuses principally on the lithofacies associated with the Ludlow to Pridoli sandbodies and the processes and factors that influenced their progradation. These provide a record of deltaic, estuarine, coastal plain and fluvial processes. However, some assessment is first needed of the offshore Ludfordian facies that formed during the onset of the Ludfordian depositional cycle and across which the younger sandbodies prograded. Detailed analysis of the alluvial red bed lithofacies that comprise the MCF is provided by Williams & Hillier (2004) and Hillier *et al.* (2019) and not repeated here.

4.b.2. Precursor Cae'r mynach Formation lithofacies

The deepest water Ludfordian sediments, not dealt with here, are confined to the Clun Forest Sub-basin (Figures 1 and 4) and represent a continuation of sedimentation patterns established during the Gorstian. They record deposition below storm-wave base, a gradual shallowing and the abandonment of southerly point sources. Where it succeeds these offshore sediments, the CarF (CarF 1) records a continuation of upwards shoaling, but in many areas it was the lithofacies that characterize this division that were introduced by the early Ludfordian transgression. Critically, deposition of the CarF established the setting throughout much of the study area into which the main Ludfordian sandbodies prograded. The bulk of the formation comprises a thin-bedded heterolith within which variably calcareous, bioturbated mudstones and siltstones occupy the intervals between abundant very fine-grained sandstone beds and laminae. Limestone beds are also locally common. The sandstones are typically non-amalgamated, sharp-based and highly lenticular. The impacts of burrowing are pervasive. Planar-lamination is the dominant tractional feature to be preserved, but wave and current cross-lamination and, in some thicker beds, hummocky cross-stratification are also present. Limestone units occur as shell-rich lags and lenses at the bases of some sandstones as well as forming discrete, diagenetically modified beds and nodules. In addition to its typically high bioturbation index, the facies yields a diverse marine macrofauna that includes abundant brachiopods, bivalves, trilobites and ostracods.

This dominant CarF facies is widely accepted to display the features of a subtidal, storm-influenced setting where sheet sandstone event beds were emplaced below normal wave base (Figure 1) (Elles & Slater, 1906; Holland & Lawson, 1963; Holland *et al.* 1963; Bailey, 1969; Watkins, 1979; Siveter *et al.* 1989; Bassett *et al.* 1992; Bailey & Bailey, 2019). This has been viewed as a 'proximal shelf' or 'inner neritic' environment (Richardson & Rasul, 1990). In the context of this study, all but the uppermost levels of the CarF are best viewed as deposits on a storm-influenced Ludfordian prodelta sea floor that lay offshore to the complex array of lithofacies (described below) associated with the progradation of shallower water sandbodies and subsequent periods of emergence.

4.b.3. Lithofacies 1: Distal river- and wave-influenced delta front

This lithofacies characterizes the uppermost part of the CarF (in many sections, including the LBBM and the PSM, CarF 2) as well as similar, but more sandstone prone facies in the Usk and May Hill inliers (CarF 3). It is characterized by low bioturbation indices, having a restricted shelly fauna and exhibiting synaeresis cracks and wrinkle structures. The lithofacies comprises a heterolith of non-amalgamated, very fine- to medium-grade sandstones and silty mudstones (Figures 8a-c). Sandstones are buff to grey, commonly cm- to dm-bedded and sharp-based. Bed bases may be erosive and strewn with mudstone intraclasts and/or skeletal debris. Some beds infill erosive gutters. Internally, beds are predominantly parallel-laminated or contain hummocky cross-stratification, current or wave ripple cross-lamination (Figures 8a and b). A minority of beds exhibit convolute lamination, and some are massive. Bed tops commonly preserve plane bed parting lineation and wave or current ripples (Figure 8d). Some bed tops preserve wrinkle structures. Common are erosively based, guttered sandstone beds that contain hummocky cross-stratification (Figure 8e). Sandstone beds grade upward into cm- to dm-thick grey or olive green mudstones and siltstones which are commonly graded. These are generally parallel- or cross-laminated and contain mm-thick very fine- to fine-grained graded sandstone laminae or cm-thick, lenticular or wavy-bedded sandstones. Common are sandstone-filled synaeresis cracks (Figure 8d). Some mudstone bedding surfaces preserve wrinkle structures (Figure 8f). In Clun Forest, bedsets in this lithofacies comprise m-thick, disorganized units of interbedded sandstone and mudstone deformed beds above soft sediment shear zones. Internal deformation is dominated by asymmetric or isoclinal folds with low-angle duplex thrust faults. Overall, sandstone beds thicken- and coarsen-upward within units of this lithofacies.

Bioturbation is generally low to moderate (Ichnofabric Index (II) Droser & Bottjer, 1986, of 1 to 3), being dominated by *Arenicolites*, *Planolites*, *Palaeophycus*, *Chondrites* and *Skolithos* (Figure 8d). Preserved macrofaunas are dominated by bivalves and gastropods, the latter including *Turbocheilus helicites* (the *Platyschisma helicites* of earlier reports); a restricted assemblage of articulated brachiopods forms a subordinate component and is absent from some sections. Many sandstone and mudstone beds contain carbonized plant debris.

Common in sections in the north and east of the study area are mm- to cm-thick phosphatic bone-rich sandstone laminae or beds that, on weathering, take on the characteristic gingerbread colour and texture (Bassett *et al.* 1982; Figures 8b, 9a-c and 10a-c) of the LBBM, but bone, fish scale and phosphatized mudstone pellet and pebble-bearing levels are present at lower levels of the CarF successions of the eastern inliers (e.g. Lawson, 1955). These bone-bearing levels occur either as discrete beds traceable over the scale of the exposure, or more commonly as discontinuous lags in erosive gutters or at bases of sandstone beds. They may be parallel-laminated or worked into wave or current ripples. The bone beds comprise thelodont and acanthodian fragments, inarticulate brachiopods, phosphate nodules and quartz granules (Antia, 1979; Bassett *et al.* 1982; Dineley, 1999).

The lithofacies is interpreted as forming on the distal reaches of river- and wave-influenced delta fronts, below fair-weather, but above storm-wave base, in settings that its limited assemblage of articulated brachiopods confirms was open to the sea. Sandstone beds and laminae were primarily emplaced by fluvially derived

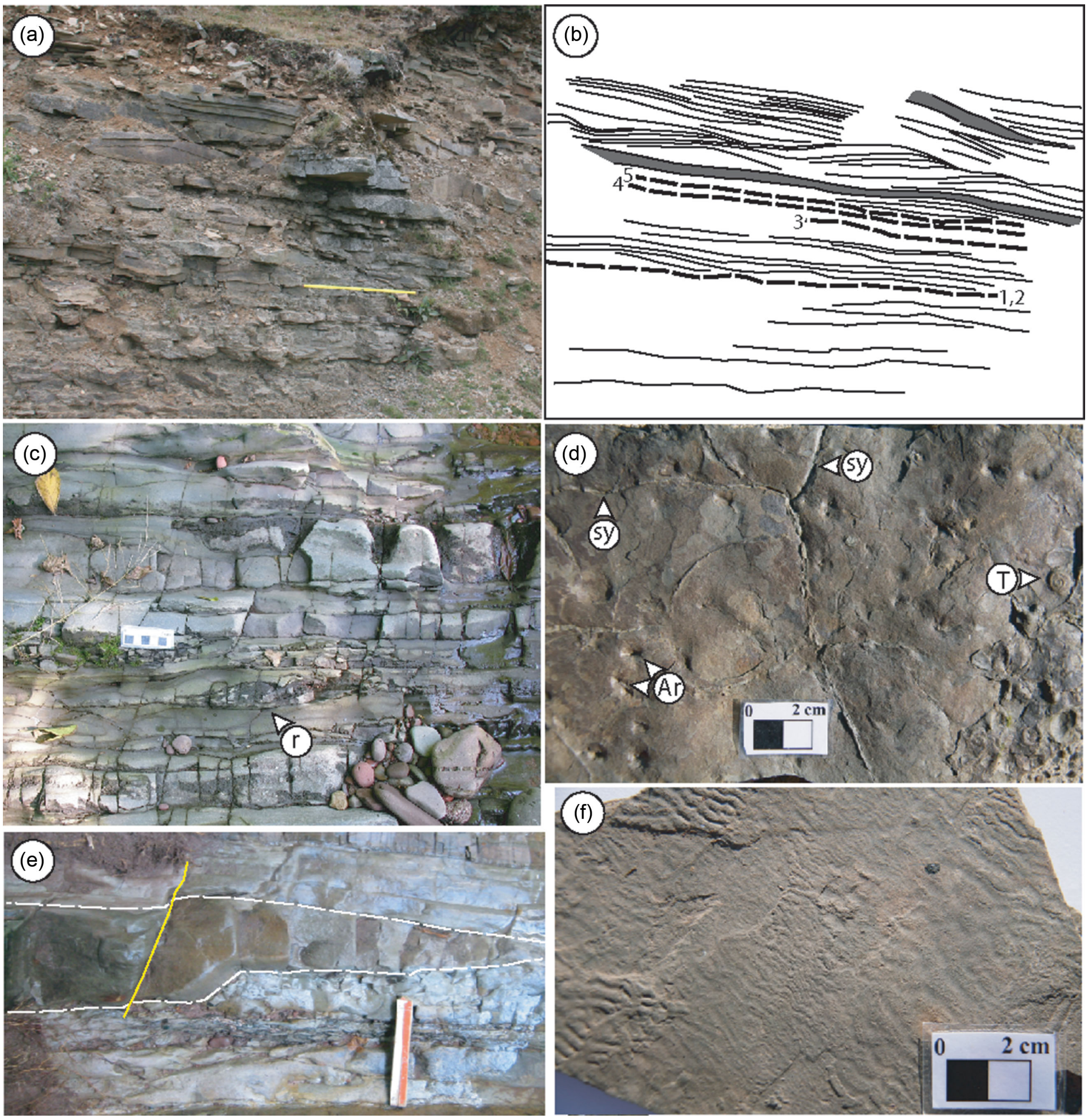

Figure 8. (Colour online) Distal river- and wave-influenced facies association. (a–b) Heterolithic bedset with hummocky cross-statification, Bradnor Green Golf Course, scale bar 0.5 m (0 to 2 m Figure 10c). Dashed lines 1 to 5 represent position of denticle-rich vertebrate bone beds of the Ludlow Bone Bed Member, with bed 1 being the local equivalent of the Ludlow Bone Bed. Grey intervals in (b) represent laterally continuous mudstone interbeds. Note similar style of stratification above and below basal bone bed. (c) Interbedded, cross- and parallel-laminated sandstone beds and muddy siltstones, Sawdde Gorge (Cae'r mynach Formation). Note typical sheeted and lenticular geometries and isolated current-rippled sandstone lenticle (r); scale bar 5 cm. (d) Bed top view of rippled fine-grained sandstone, veneered with mudstone with well-developed sandstone-filled synaeresis cracks (sy). Note paired *Arenicolites* burrow entrances (Ar), and preservation of the gastropod *Turbocheilus* (T); loose block, Capel Horeb Quarry. (e) Guttered sandstone bed (with small-scale fault offset) with well-developed wing; internally, bed contains hummocky cross-stratification; Sawdde Gorge, scale bar 0.25 m (3 m on Figure 19). (f) Siltstone bed with well-preserved wrinkle structures, Werngwilym (0.25 m, Figure 22d). Note variable wavelengths of wrinkle structures and flat-topped morphology.

gravity flows or from suspension; hummocky cross-stratification and wave ripples provide evidence of storm-wave reworking (e.g. Dafoe *et al.* 2010; Olariu *et al.* 2010; Bailey & Bailey, 2019). Interbedded mudstones and siltstones were deposited as fair-weather suspension fallout deposits, or as hyperpycnal fluid mud (Bhattacharya & MacEachern, 2009). The common synaeresis cracks are interpreted as being formed by salinity variations associated with freshwater plumes or freshets (MacEachern *et al.* 2005, 2007). Guttered bedsets, commonly containing hummocky cross-stratification, are interpreted as the deposits of erosive events created either by fluvial-derived downflows or storm-generated, downwelling coastal jets. The layer-parallel faulted intervals with convolute lamination are interpreted as slide-bound slumps generated by slope instability and/or of offering evidence of seismic events.

Trace fossils comprise an impoverished mixed *Cruziana*–*Skolithos* ichnofacies. The generally suppressed nature of bioturbation supports the interpretation of a stressed environment of deposition (Bann & Fielding, 2004; Fielding *et al.* 2007; Gani *et al.* 2007; MacEachern *et al.* 2007). The wrinkle structures are interpreted as matgrounds that developed primarily atop sandstone event beds (Bailey & Bailey, 2019) but also on fair-weather fine-grained interbeds. Their occurrence in this environment is well documented from Phanerozoic and Palaeozoic examples (Mata & Bottjer, 2009), a prerequisite for formation appearing to be low levels of bioturbation due to environmental stress (Hagadorn & Bottjer, 1997, 1999; Pflűger, 1999). A similar lithofacies is observed in the Wenlock age Gray Sandstone Formation, where salinity variations associated with freshwater

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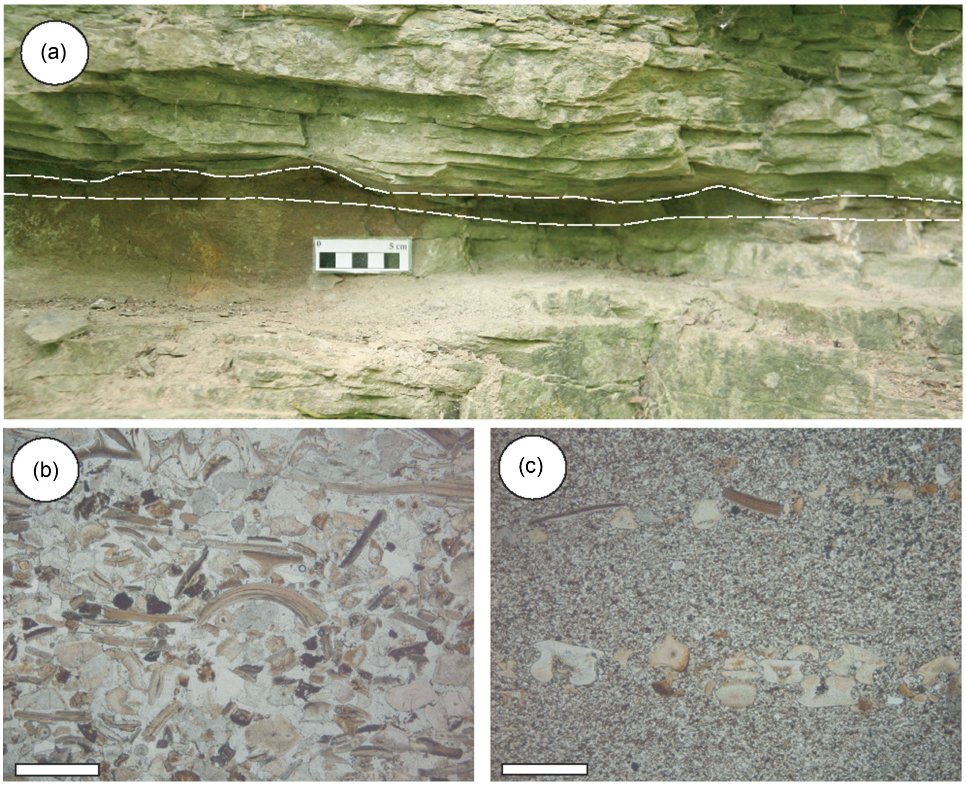

Figure 9. (Colour online) (a) Rippled Ludlow Bone Bed Member at Downton Weir Quarry (North), 2.95 m Figure 10a. (b) Thin-section photomicrograph of the Ludlow Bone Bed Member shown in Figure 9a. Note dominance of vertebrate bone fragments and spines; plane-polarized light, scale bar 1 mm. (c) Thin-section photomicrograph of two vertebrate bone-rich laminae in Ludlow Bone Bed Member from Bradnor Green Quarry (0.95 m of Figure 10c). Laminae directly overlie underlying fine-grained sandstone hummocky bedform and laterally amalgamate and thicken into adjacent topographic lows. Plane-polarized light, scale bar 1 mm.

plumes are interpreted as leading to impoverished infaunas and subsequent matground colonization of the sea bed (Hillier & Morrissey, 2010). Nicholls (2019) also identifies such features in deep water deposits of western mid Wales formed during the period of environmental flux associated with the Late Ordovician glacioeustatic lowstand. Salinity-induced environmental stress has been interpreted as the causative mechanism for changes in macrofauna across the basin during Late Ludlow times (Allen & Tarlo, 1963; Holland & Williams, 1985). The matgrounds would have formed a prolific food source for the grazing gastropod faunas (Palmer, 2000), although Peel (1984) proposed that the abundant *Turbocheilus helicites* may have had a sedentary, ciliary-feeding habit.

Analysis of delta deposits in the rock record has recognized the similarity of shoreface and wave-dominated delta-front deposits (e.g. Dafoe *et al.* 2010). Trace fossil assemblages have been a useful tool in discriminating between deltaic environments containing ‘stressed’ ichnological assemblages with reduced ichnodiversity and bioturbation intensity and non-deltaic shoreface deposits (e.g. Bann & Fielding, 2004; Dafoe *et al.* 2010). In addition, the abundance of traces attributed to suspension feeding organisms and the general poorly developed *Skolithos* ichnofacies has been inferred as a discriminator between river- and wave-dominated deltas, with river-dominated deltas having a prevalence of the *Cruziana* ichnofacies (MacEachern *et al.* 2005; Dafoe *et al.* 2010). In this study, such distinction has not been possible, and we interpret this lithofacies as a mixed process one (river- and wave-influenced).

4.b.4. Lithofacies 2: Proximal wave-influenced delta front

This lithofacies mainly occurs in the DCSF and CMSF. It comprises a lithofacies dominated by micaceous, very fine- through to medium-grade, buff to grey/green well-sorted sandstones. Individual beds have erosive bases, often strewn with mudstone rip-up clasts or skeletal debris (Figures 10a-c). Bed bases are planar, or more commonly erosive and convex-up. Internally, beds are dominated by hummocky and swaley cross-stratification, and planar-lamination (Figures 11a and b). Occasionally, convolute lamination is observed (Figure 11c). Beds often fine-upward into micaceous finer-grained sandstone, or less commonly, micaceous siltstone. The latter contain common synaeresis cracks. Beds are generally of dm-scale thickness, and they commonly amalgamate. Bedding surfaces preserve both wave and current ripples. Bedsets within this lithofacies reflect upward-thickening and -coarsening above deposits of the distal river- and wave-influenced delta-front lithofacies described above (Figures 10a-c). The Ichnofabric Index is low (1 to 2), comprising *Arenicolites*, *Planolites* and *Skolithos*. Beds locally preserve abundant plant debris.

The lithofacies was deposited on the proximal front of a wave-dominated delta above fair-weather wave base (e.g. Coates & MacEachern, 2007; Dafoe & Pemberton, 2007). Vertical amalgamation of bedsets and the preservation of swaley cross-stratification towards the top of some cycles reflect high-energy progressive sorting associated with wave and current reworking. Convolute lamination is likely to be the product of wave loading and/or rapid sedimentation. Salinity variations induced by freshwater plumes led to the development of synaeresis cracks. Trace fossils comprise an impoverished *Skolithos* ichnofacies.

4.b.5. Lithofacies 3: Proximal river-influenced delta front

This lithofacies mainly occurs in the TilF but is locally present in the DCSF. It is dominated by dm- to m-thick, fine- to coarse-grained sandstone beds that are locally pebbly (Figures 12a-c). Parallel-lamination (with associated parting lineation) is common, with subordinate massive sandstone beds. In the latter, floating outsized mudstone and vein quartz granule clasts may be present.

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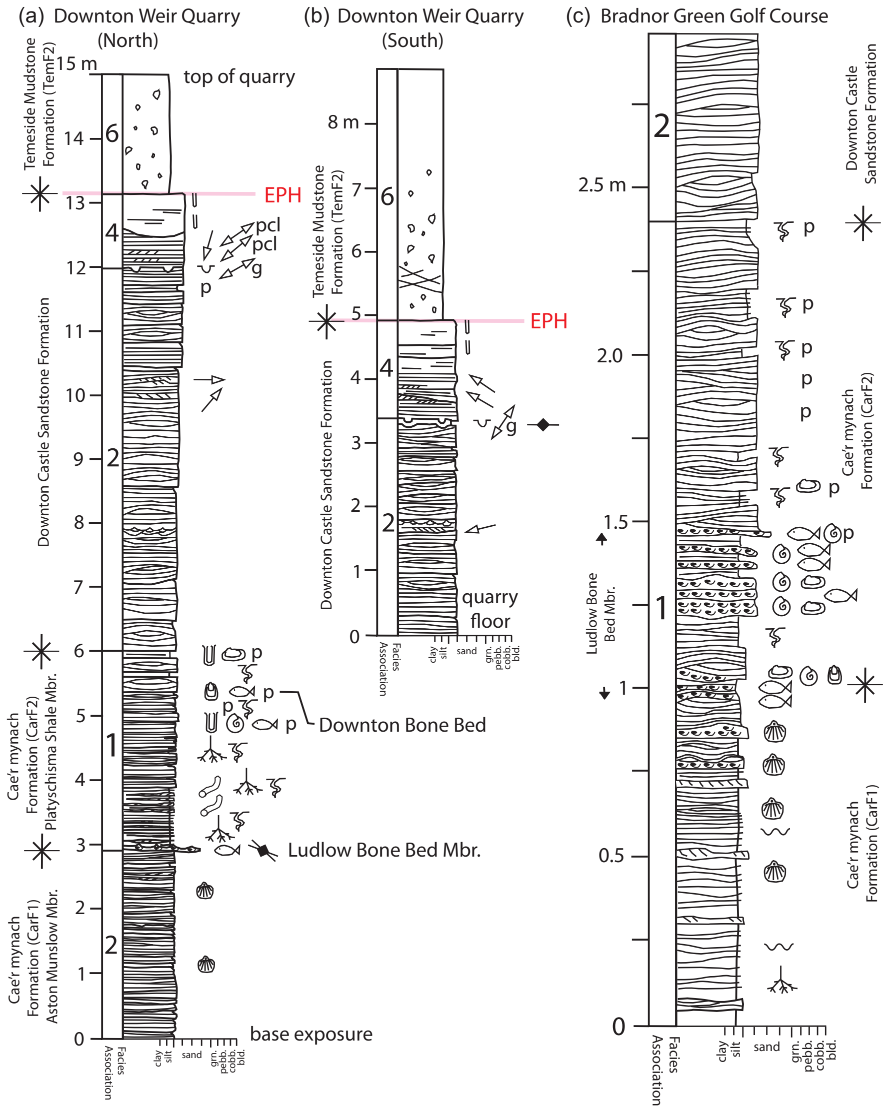

Figure 10. (Colour online) Graphic logs through upward coarsening and thickening parasequences. (a) Downton Weir Quarry (north side of River Teme). (b) Downton Weir Quarry (south side of River Teme). (c) Bradnor Green Golf Course (note change in scale). Key to logs in Fig. 13. EPH, early Pridoli Hiatus surface.

Bed bases preserve bounce marks and are locally erosive. Occasionally, thick principally massive beds, but with subordinate convolute lamination are locally developed attaining a maximum observed thickness of 2.8 m (Figure 12a-c). Bedding is predominantly planar and erosional over the scale of the exposure. A few bedset boundaries are erosional and convex-up, with overlying dm-thick sandstone beds containing hummocky and swaley cross-stratification (Figure 13). Decimetre-thick planar-laminated and hummocky beds often have a fining-upward signature. Small-scale current ripple development is occasionally preserved. Rarely developed are thin, micaceous mudstone interbeds, some of which contain sandstone injections (up to 10 cm long) from underlying beds. Bioturbation is uncommon and extremely impoverished (Ichnofabric Index of 1 or 2), being dominated by *Skolithos linearis*. Skeletal concentrations of gastropods, crinoid ossicles, bivalves and less common brachiopods are observed as lags at bed bases, or in discrete erosional hollows. Plant debris is locally common.

This lithofacies is interpreted as being dominated by deposits of proximal delta-front river-fed hyperpycnal flows based on the dominance of parallel-laminated sandstone beds (e.g. Olariu *et al.* 2005; Plink-Björklund & Steel, 2005; Enge *et al.* 2010; Olariu *et al.* 2010). Massive beds offer evidence of deposition from high-energy, high-concentration gravity flows, with some thicker beds that display convolute lamination, formed by the over-steepening and subsequent collapse of mouth bars (e.g. Olariu *et al.* 2010). Wave and storm influence is limited to the preservation of swaley and hummocky cross-stratification. Sandstone injection phenomena were presumably created by rapid sedimentation and associated elevated pore pressure. The impoverished ichnofauna reflects the environmental stresses associated with riverine discharge, salinity variation and high sedimentation rates (e.g. Dafoe & Pemberton, 2007; Coates & MacEachern, 2007).

At Stonehouse Dingle, bedsets arranged in a low angle, inclined architecture preserve the form of a delta-front clinothem (Figures 12b and c) consistent with outbuilding from the NE into an offshore region of moderate water depth. The low diversity, poorly developed archetypal *Skolithos* Ichnofacies attests to the highly dynamic, high-energy depositional environment.

4.b.6. Lithofacies 4: Distributary Mouth Bars

The lithofacies locally sits at the top of upward coarsening and thickening cycles in the TilF and DCSF. It comprises planar-

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Figure 11. (Colour online) Proximal wave-influenced delta-front facies association. (a) Amalgamated bedset comprising predominantly low angle and swaley cross-stratification, Downton Weir Quarry (south), 0.5 to 3 m Fig. 10b. (b) Closeup of bedset with swaley cross-stratification beneath 5 cm scale bar, and hummocky cross-stratification above it, Downton Weir Quarry (North). (c) Convolute lamination displaying symmetrical deformation, Pentre Jack; hammer is 0.3 m long.

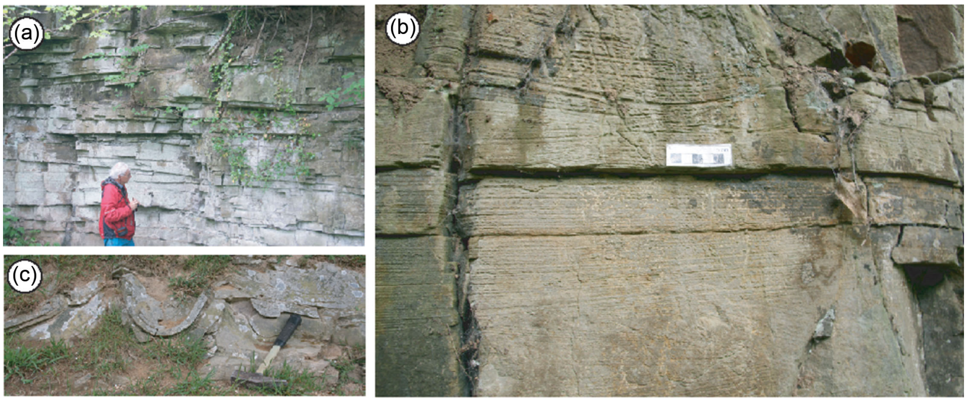
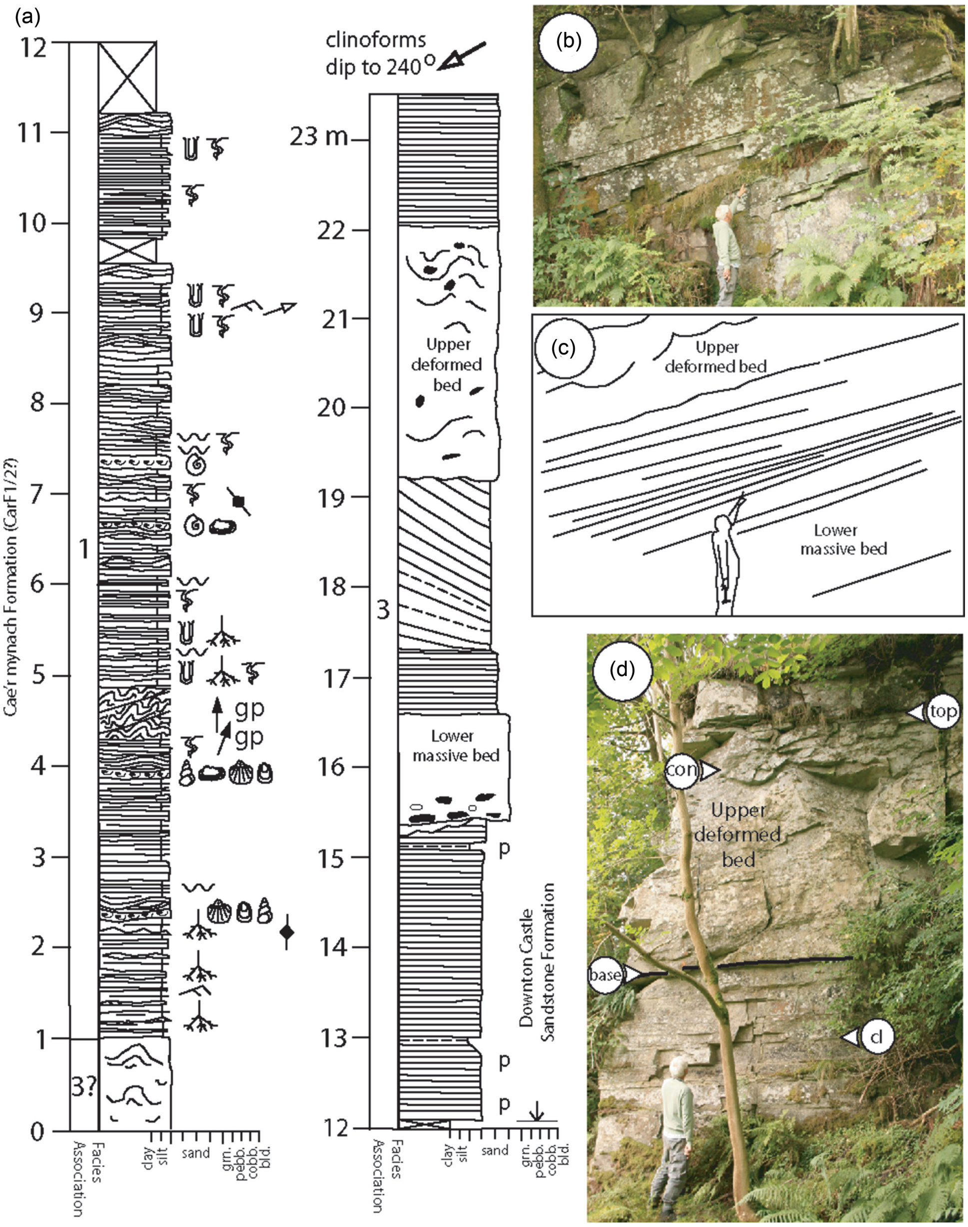


Figure 12. (Colour online) Proximal river-dominated delta-front facies association at Stonehouse Dingle. (a) Graphic log of the exposed succession in Stonehouse Dingle, exposing an upward-coarsening and -thickening interval of distal river- and wave-influenced facies association overlain by the proximal river-dominated delta-front facies association. Key to logs given in Fig. 13. (b–c) Quarry face (14.5 to 21.5 m Fig. 12a) containing a lower massive, and upper deformed bed separated by massive to parallel-laminated clinoform bedsets which dip to 240°. (d) Quarry face orthogonal to clinoform dip direction comprising the upper deformed bed with convolute lamination (con; top and base indicated). Deformed bed overlies massive to parallel-laminated clinoform bedsets (cl).



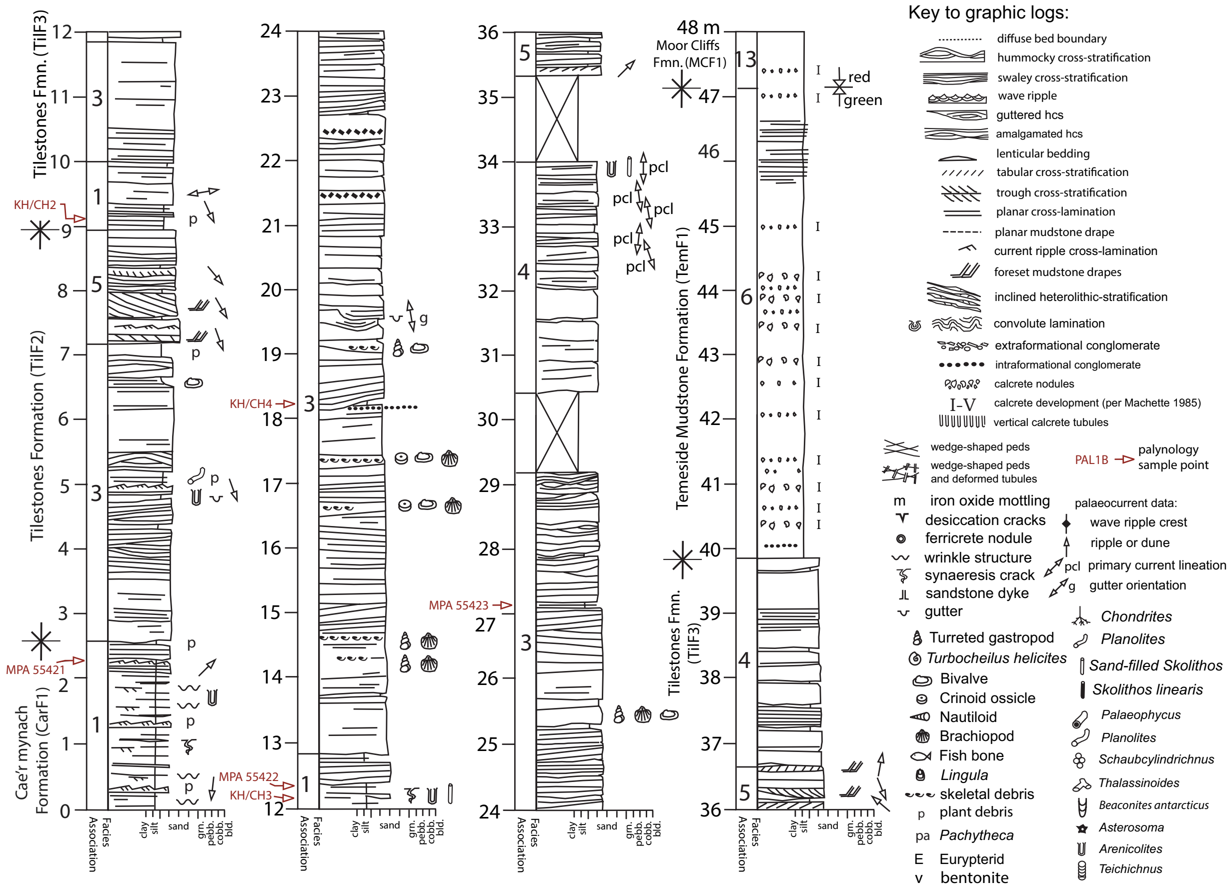


Figure 13. (Colour online) Graphic log through section at Capel Horeb Quarry.

laminated, massive or subordinate trough or tabular cross-stratified, dm- to m-thick, fine- to coarse-grained sandstones (Figures 10a, b and 14a-c). Some cross-bedded units contain bipolar palaeocurrents and have mudstone-draped foresets. Beds are tabular or infill broad scours. Bases are generally planar to mildly erosive, commonly with guttered bases. Erosion surfaces may be strewn with mudstone rip-up clasts. Beds display amalgamation and internal scour surfaces. Current ripples are subordinate to larger-scale bedforms and often are arranged in climbing ripple trains. Parting lineation is common. Bedsets sometimes contain convolute lamination, with deformed cross-lamination often comprising small-scale asymmetric folds. Mudstone interbeds are uncommon and comprise micaceous, well-laminated, mm- to cm-thick discontinuous lenses and beds, some with preserved plant debris. Bioturbation is generally absent, although *Skolithos* is locally observed. Sandstones often contain common plant debris. Some sandstone beds contain ovoid or tubular carbonate nodules (e.g. Figure 10a, 14c and 15a), the latter often bifurcate downwards. Although not corroborated in this study, it is likely this lithofacies at Bradnor Hill has yielded fish faunas, including heterostracans, thelodonts, osteostracans and acanthodians (Figure 8c and d; Banks, 1856; Dineley, 1999).

The lithofacies is interpreted as the deposits of delta distributary mouth bars (e.g. Olariu & Bhattacharya, 2006; Olariu *et al.* 2010; Li *et al.* 2011) and contains both subaqueous and subaerial elements. Unidirectional traction deposits dominate the preserved architecture and represent energetic, high sedimentation events as fluvial delta distributaries discharged into the coastal zone as hyperpycnal underflows. Bipolar palaeocurrents and mudstone drapes are attributed to tidal influence. The massive sandstone beds represent high-energy, high-concentration gravity flows (Olariu *et al.* 2005; Plink-Björklund & Steel, 2005). Interbedded parallel-lamination, massive and ripple cross-lamination may represent waxing and waning of underflows (Olariu *et al.* 2010). Convolute lamination was developed through possible over-steepening of the mouthbar, accentuated by high sedimentation rates. The ovoid carbonate nodules represent poorly developed calcrete palaeosol horizons (Stage 1 per Machette, 1985), with tubules representing calcified root traces (Klappa, 1980) or burrow fills. The calcretes developed following prolonged subaerial emergence of delta lithosomes associated with the early Pridoli Hiatus and as such are not viewed as linked to mouth bar sedimentation (see Section 6.d below).

4.b.7. Lithofacies 5: Terminal distributary channel

This lithofacies is locally present in the TilF, DCSF and CMSF. It is dominated by dm-bedded, fine- to medium-grade micaceous sandstones that are moderate to well-sorted and locally pebbly (Figure 14c and d). Sandstone beds have erosive, planar to mildly erosive bases. Internally, beds are dominated by tabular and trough cross-stratification that are locally deformed (e.g. Figures 14d and e). Toesets are commonly draped with mudstone laminae (Figure 14c and f). Subordinate beds are massive or normally graded; some contain planar lamination and current ripple cross-lamination, the latter often arranged in climbing bedsets. Conglomerate beds include intra- and extraformational

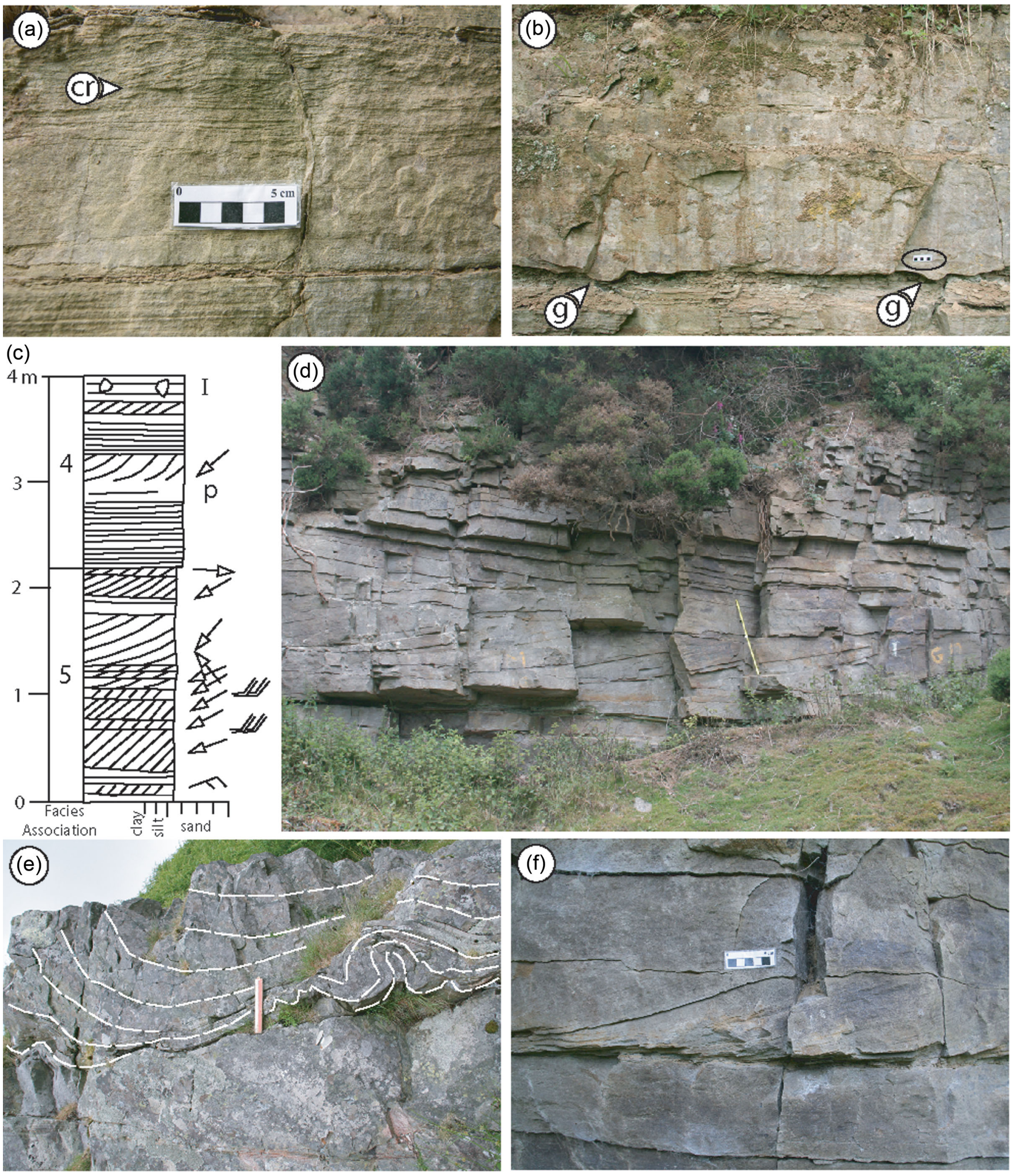


Figure 14. (Colour online) (a) Planar and current ripple (cr) cross-laminated sandstone of the distributary mouth bar facies association, Downton Weir Quarry (south); 3.75 m Fig. 10b. (b) Planar-laminated distributary mouth bar facies association with guttered bedset base (g), Downton Weir Quarry (south); 3.4 m Fig. 10b. (c–d) Graphic log (c), and image (d) through distributary mouth bar and terminal distributary channel facies associations at Bradnor Green Quarry, scale bar 0.5 m (for key see Fig. 13). (e) Deformed, over-steepened cross-sets with convolute lamination, Rhyblid. Scale bar 0.25 m. (f) Bedform foreset of terminal distributary channel facies association with thin micaceous mudstone drapes; scale bar 5 cm. Bradnor Green Quarry, 1.0 m Fig. 14c.

granule and pebble clasts, including locally abundant angular acid volcanic lithologies. Plant debris and *Skolithos* burrows are locally observed. Bedsets attain a maximum preserved thickness at Bradnor Hill Quarry of 3.9 m (Figure 14c and d). Mudstone interbeds are less common, but where present they are micaceous, laminated and locally contain an abundance of plant debris. Some sandstones contain ovoid carbonate nodules.

The lithofacies represents deposition in terminal, delta-top distributary channels (e.g. Olariu & Bhattacharya, 2006; Charvin *et al.* 2010; Hillier & Morrissey, 2010; Li *et al.* 2011). Stratification is dominated by unidirectional, tractional bedforms of in-channel bars. Mudstone drapes may be indicative of pulsed sedimentation rates or tidal influence, though tidal bundles, or tide-induced cyclicity is not observed. Preserved bedsets appear to comprise principally single-storey sandbodies. Jumps in grainsize between m-scale-thick bedsets may indicate multi-storey architecture, but the limited extent of exposure makes this difficult to ascertain. The abundant plant debris testifies to the proximity of terrestrial floras. The ovoid carbonate nodules represent poorly developed calcrete palaeosol horizons formed following periodic subaerial emergence of channel fills (Stage 1 per Machette, 1985).

4.b.8. Lithofacies 6: Coastal plain

In the TemF and RF, this lithofacies is dominated by olive green to grey mudstones and siltstones and subsidiary green to brown dm-thick micaceous sandstones in cm- to dm-thick besdets. Locally (e.g. at Green Castle), red/maroon colour mottling is observed around desiccation cracks and ped surfaces. Mudstones and siltstones appear massive or are parallel- or cross-laminated. Occasionally, m-thick inclined heterolithic bedsets are observed. Isolated ovoid and tubular carbonate nodules are common as are subhorizontal slickensided fracture surfaces arranged in conjugate sets which rotate previously horizontally bedded carbonate concretions (Figures 15b and 16). Desiccation cracks are commonly observed. Rarely observed are m-thick muddy siltstone beds with low-angle inclined master bedding surfaces (e.g. 60 to 61 m, Figure 16). *Skolithos* is common. Locally developed in the TemF in the north and east of the study area are dm-thick fine- to medium-grade buff or

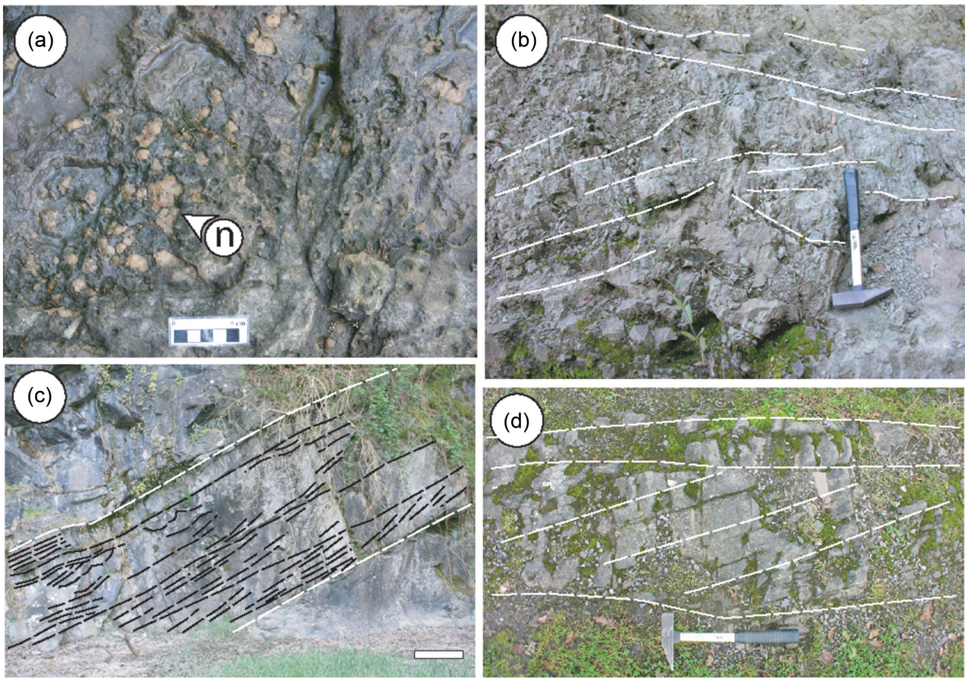


Figure 15. (Colour online) (a) Bedding plane view of topmost Downton Castle Sandstone Formation with well-developed ovoid calcrete nodules (n), Llanstephan (3.6 m Fig. 22c). (b) Massive mudstones of the coastal plain facies association with well-developed wedge-shaped peds (highlighted) and vertic calcrete tubules, Cwmffrwd. Hammer 0.3 m long. (c) Tabular-bedded multistorey fluvial channel encased in coastal plain lithofacies mudstones, Green Castle; scale bar 1 m. (d) Tabular fluvial sheet sandstone bed with solitary cross-bed set, Golwg y Byd; hammer 0.3 m long.

green sandstone sheets that contain current ripple cross-lamination or parallel-lamination. Scattered through some of these sandstones are vertebrate bone and eurypterid fragments, bivalves, gastropods, lingulids and quartz granules (Elles & Slater, 1906; Allen & Tarlo, 1963; Antia, 1981). In addition, Antia (1981) recorded wavy and oncolitic stromatolites at Onibury.

This lithofacies is interpreted as the deposits of a mud-prone low-gradient coastal plain environment (Hillier *et al.* 2019). The mudstones and siltstones represent both traction and suspended-load fallout deposits. Massive mudstones possibly represent soil mud-pellet aggregates deposited as a sheet-flood/ephemeral channel fills, or on in-channel muddy braid bars (Marriott & Wright, 2004). Subsequent compaction of the mud pellets led to a loss of sedimentary structures. The aggregates are thought to be produced during the shrinking and swelling of Vertisols, subsequently reworked and deposited by wind and alluvial processes (Marriott & Wright, 2004; Hillier *et al.* 2007). The horizontal conjugate fracture sets represent wedge-shaped peds created by the shrinking and swelling of the Vertisols generated by seasonal wet–dry cycles (Marriott & Wright, 2004). The carbonate nodules are calcretes formed at the depth of seasonal wetting within the Vertisol profile (Stages 1 and 2 per Machette, 1985). The low-angle inclined master bedding surfaces constitute inclined heterolithic stratification produced at accretionary benches or channel margins. In the east of the study area, the thin sandstone beds that contain vertebrate and invertebrate remains demonstrate a marine, most probably brackish water tidal influence (Allen & Tarlo, 1963; Antia, 1981). The predominance of green lithologies in the TemF and RF reflects primary colouration caused by reducing redox conditions associated with a predominantly high, but fluctuating water table. Colour mottling is interpreted as a redoximorphic indicator of this fluctuation.

4.b.9. Lithofacies 7: Single and multistorey fluvial channels

This lithofacies is restricted to the TemF, MCF and PMF and comprises buff to green or purple/maroon coloured, dm- to m-thick, fine- to medium-grade micaceous sandstones that are moderate to well-sorted and locally pebbly. Sandstone beds are erosive, with planar bed bases locally strewn with intraformational mudstone rip-up clasts. Internally, beds are dominated by tabular and trough cross-stratification. Subordinate beds contain planar lamination and current ripple cross-lamination. Bedsets are observed to fine-upwards from coarse- into fine-grained sandstones. Bioturbation has not been observed. Bedsets attain a maximum observed thickness at Green Castle of 4 m (Figures 15c and 16).

Tractional unidirectional bedforms dominate this lithofacies which is interpreted as the deposits of multi-storey fluvial channels. Metre-thick fining-upward bedsets represent individual storeys. The channels are similar in scale, architecture and grade to other ORS examples described, for example, by Williams & Hillier (2004) and Hillier *et al.* (2007). The lithofacies differs from the terminal distributary channel lithofacies described above in not having mudstone-draped foresets. A solitary *Lingula* preserved in the PMF of the Rumney Borehole indicates a likely tidal influence to this lithofacies within the PMF.

4.b.10. Lithofacies 8: Sheet fluvial heterolithics

This lithofacies is restricted to the TemF, MCF and PMF and comprises grey to green, locally purple and maroon fining-upward sandstone sheets typically of cm- to dm-scale thickness (Figure 15d and 16). Bed bases are sharp and may be erosive or undulatory and are often strewn with intra- and extraformational clasts of granule to pebble grade. Internally beds are dominated by planar lamination, cross-stratification and/or current ripple lamination. Sandstone beds commonly fine-upward into overlying green mudstones that commonly contain desiccation cracks and ovoid and tubular carbonate concretions.

This lithofacies is common in the Siluro-Devonian ORS of the Anglo-Welsh Basin and is interpreted as fluvial sheetflood deposits and crevasse splays/lobes of both perennial and ephemeral rivers (Williams & Hillier, 2004; Hillier *et al.* 2007). Preserved bedforms indicate unidirectional flow. Interbedded mudstones preserve evidence of desiccation and calcrete pedogenesis (Stage 1 per Machette, 1985).

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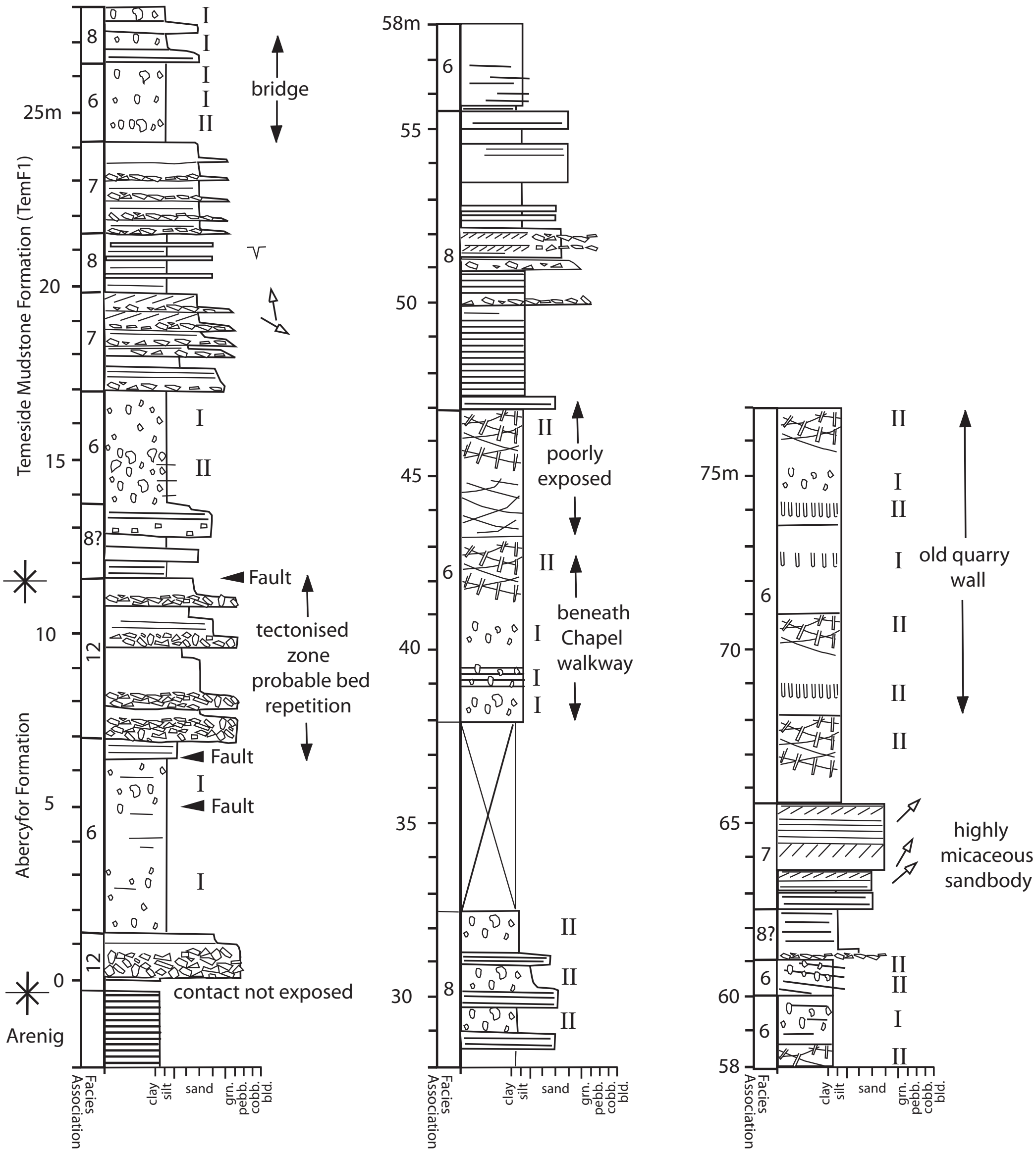

Figure 16. (Colour online) Graphic log of terrestrial facies associations, Cwmffrwd; for key refer to Fig. 13.

4.b.11. Lithofacies 9: Inclined heterolithic tidal channels

This lithofacies occurs locally in the PALF, RF and PMF where it comprises inclined heterolithic bedsets of metre-scale thickness (Figures 17 and 18). Inclined bedset bases are marked by planar or gently undulatory erosion surfaces, which may be defined by discontinuous dm-thick, clast supported extraformational and/or intraformational mudstone clast and calcrete nodule lag conglomerate. Bedsets are dominated by low-angle (typically 15–20 degree) interbeds of fine- to medium-grained sandstone (locally pebbly) and laminated mudstone. Flaser, lenticular or wavy bedding is common. Medium-grained sandstones are sometimes trough-cross-stratified, with some bedsets containing bipolar palaeocurrent indicators and mudstone-draped foresets. Synaeresis cracks are observed. Bioturbation is generally low to moderate (II of 1 to 2), but locally more abundant, comprising *Palaeophycus*, *Planolites*, *Skolithos* sp. and *Skolithos linearis,* with less common *Teichichnus, Schaubcylindrichnus*, *Thallasinoides*, *Arenicolites* and *Asterosoma*. The PALF contains modiolopsid bivalves and *Lingula*. In the RF, *Pachytheca*, plant, fish and eurypterid fragments are common, as are spheroidal phosphate nodules. A solitary bedset of lingulid and plant-bearing deposits occurs in the PMF Rumney Borehole.

The master bedding surfaces represent inclined heterolithic stratification (IHS; Thomas *et al.* 1987) of tidal/fluvial point bars. The basal erosion surface and overlying intraformational conglomerate records lateral migration of the channel thalweg and its lag deposit. Simple sets of trough cross-stratification record the migration of 3D megaripples, and bipolar palaeocurrents and mudstone drapes reflect tidal influence. This lithofacies is similar to described point bars in estuarine bay head deltas (e.g. Allen & Posamentier, 1994; Hillier *et al.* 2019) or in tide-influenced delta plain, distributary channel point bars (e.g. Baker *et al.*1995; Choi *et al.* 2004; Willis, 2005). Bioturbation indicates an impoverished brackish-water *Skolithos–Cruziana* ichnofacies dominated by infaunal traces.

4.b.12. Lithofacies 10: Tidal sandflat

The lithofacies dominates the PALF and overlies inclined heterolithic tidal channel deposits (Figure 18). It comprises red to purple, locally

Figure 17. (Colour online) Bedsets in the Temeside Mudstone Formation of the inclined heterolithic tide-influenced fluvial channel facies association overlain by coastal plain mudstones (contact indicated by dashed line) at the Cae'r mynach stream section. Photograph corresponds to 10.7 to 13.5 m in Fig. 22a.

Figure 18. (Colour online) Tidal sandflat facies association overlying inclined heterolithic tidal channel deposits of the Pont ar Llechau Formation, Sawdde Gorge (24 to 30 m Fig. 19, way up to right).

green, ill-sorted argillaceous, gritty and pervasively bioturbated sandstones with common high- and low-chroma colour mottling. Bedding is tabular and locally wavy, with discontinuous siltstone laminae and mudstone drapes. Common in beds at the top of the lithofacies are ovoid calcrete nodules. Rarely observed are oncoid-like cm-diameter iron oxide ferricretes (Figure 19, 48.8 m). Subordinate red muddy siltstones with sandstone pinstripe laminae contain desiccation cracks, *Skolithos*, *Planolites*, and rare *Beaconites antarcticus* burrows. At Rhyblid, this lithofacies is grey in colour and comprises wavy, flaser and linsen-bedded laminasets with common current ripple and less common wave ripple cross-lamination. Macrofaunas include *Lingula*, modiolopsid bivalves, gastropods and rare rhynchonellid brachiopods (e.g. Figure 19). A thin lingulid-bearing development of this lithofacies occurs in the PMF in the Rumney Borehole above likely Lithofacies 9 deposits (Figure 20).

The lithofacies is interpreted as the deposits of a tidal sandflat that developed marginal to tidal channels. The flats were subject to frequent wetting and drying in response to a fluctuating water table, preserving calcrete palaeosols during episodes of prolonged subaerial exposure (Stage 1 per Machette, 1985). Mottling and ferricretes are interpreted as redoximorphic in nature (Veneman *et al.* 1998; Jacobs *et al.* 2002); similar features are observed in interpreted tidal mixed-flat deposits of the FEF (Hillier *et al.* 2019).

4.b.13. Lithofacies 11: Open bay

Present in the PALF at Rhyblid (Supplementary Figure S2) and comprises heterolithic, non-amalgamated, buff/grey very fine- to medium-grade tabular and wavy-bedded micaceous sandstones and grey/green silty mudstones in cm-thick beds. Mudstone drapes and flasers are observed in upper laminasets. Trace fossils include both *Planolites* and *Skolithos linearis*.

Deposition is envisaged within a marginal marine, tide-influenced, open-bay environment that supported an impoverished infauna largely adapted to brackish salinities (Gingras *et al.* 1999; Buatois *et al.* 2005; MacEachern & Gingras, 2007).

4.b.14. Lithofacies 12: Pediment colluvium

The lithofacies is preserved only in the AF in the SW of the study area (e.g. at Cwmffrwd and Wernbongham) and defines the base of the ORS here. It attains a preserved thickness of up to 16.5 m (at Wernbongham, Supplementary Figure S3) and contains granule to pebble-grade, matrix and clast-supported, texturally immature conglomerate of dm-scale thickness. Clasts are rich in angular to sub-angular vein quartz, acid volcanic debris and mudstones. Buff or grey, locally purple medium-grade sandstones are also observed; these are massive with outsized floating granules and pebbles or locally parallel-laminated or cross-bedded. Localized Fe oxide mottles are observed. Bedsets thin or fine-upwards into

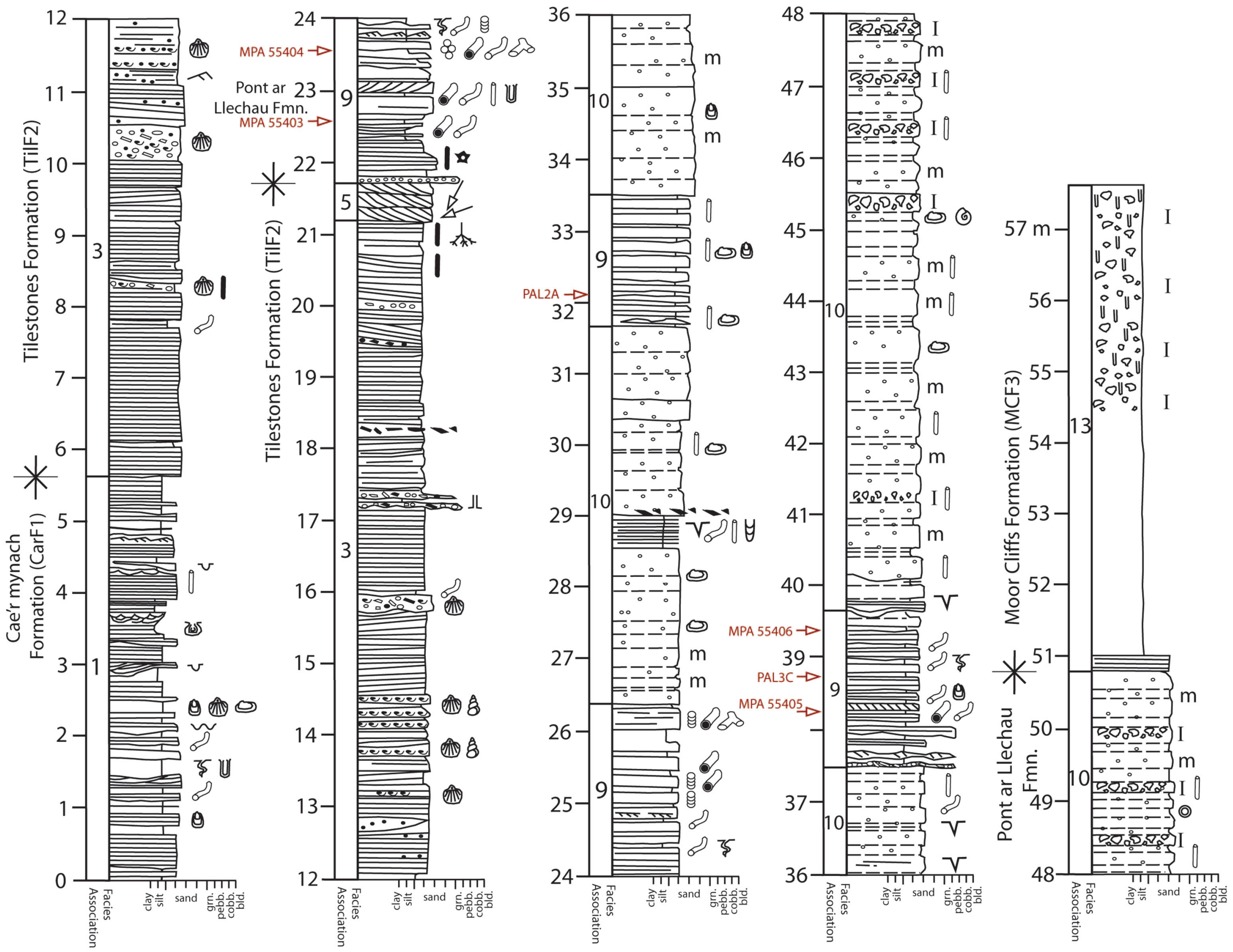

Figure 19. (Colour online) Graphic log, Sawdde Gorge. For key, see Fig. 13. Palynology samples (MPA 55411-14) from the Cae'r mynach Formation discussed in the text (Section 3.e.2) were collected from lower in the section.

parallel-laminated or massive green mudstones that contain ovoid or tubular calcrete nodules.

This lithofacies is interpreted as a semi-arid colluvial mantle containing mass flow conglomerates and pebbly sandstones, deposited as non-channellized subaerial debrites with interbedded dryland mudrocks, with the latter displaying the impacts of poorly developed Vertisol palaeopedogenesis. Fe oxides mottles are pedogenic redoximoprhic indicators. The colluvium was deposited above the basal ORS pediment surface (see Hillier *et al.* 2019 for a further discussion).

4.b.15. Lithofacies 13: Dryland alluvium

This comprises a heterolith of red silt- and mudstone and fine-grained sandstone in the MCF and PMF. Common are bedsets comprising alternating dm-thick beds of planar or cross-laminated sandstones and siltstones arranged in inclined or non-inclined geometries up to 3 m thick. These are interbedded with massive, parallel- or cross-laminated mudstones. Ovoid and tubular carbonate nodules are common, as are conjugate sets of wedge-shaped fractures. Desiccation cracks are common.

This lithofacies is widespread in the ORS and is interpreted as deposits of dryland, ephemeral muddy point bars and flood-out zones (see Marriott & Wright, 2004; Hillier *et al.* 2019 for further discussion). Mudstones and siltstones represent both traction and suspended-load fallout deposits of ephemeral channel fills, possibly soil mud-pellet aggregates. Calcrete nodules and wedge-shaped fractures reflect Vertisol pedogenesis as per Lithofacies 6.

5. Process regime associations

5.a. River-influenced delta association

Riverine influences dominated the progradation of a north-westerly sourced TilF delta system into the Western Province. Mapping and dating criteria outlined in Section 3 underpin the recognition of four separate TilF river-influenced delta parasequences (TilF 1 to TilF 4, Figure 1), each comprising upward-coarsening and -thickening bedsets 10 to 15 m thick (e.g. Figures 12, 13, 19, 21 and 22). The transition from the distal into proximal river-influenced delta-front deposits is characterized by a gradual amalgamation of sandstone beds and progressive reduction in silt and mudstone interbeds reflecting depth-dependent fluid power and reworking of fine-grained sediments. Across this transition, there is in general a marked reduction in ichnofaunas and macrofossil assemblages. The upward transition into distributary mouth bars and/or terminal distributary channels is linked to a grain-size jump (e.g. Figures 19 and

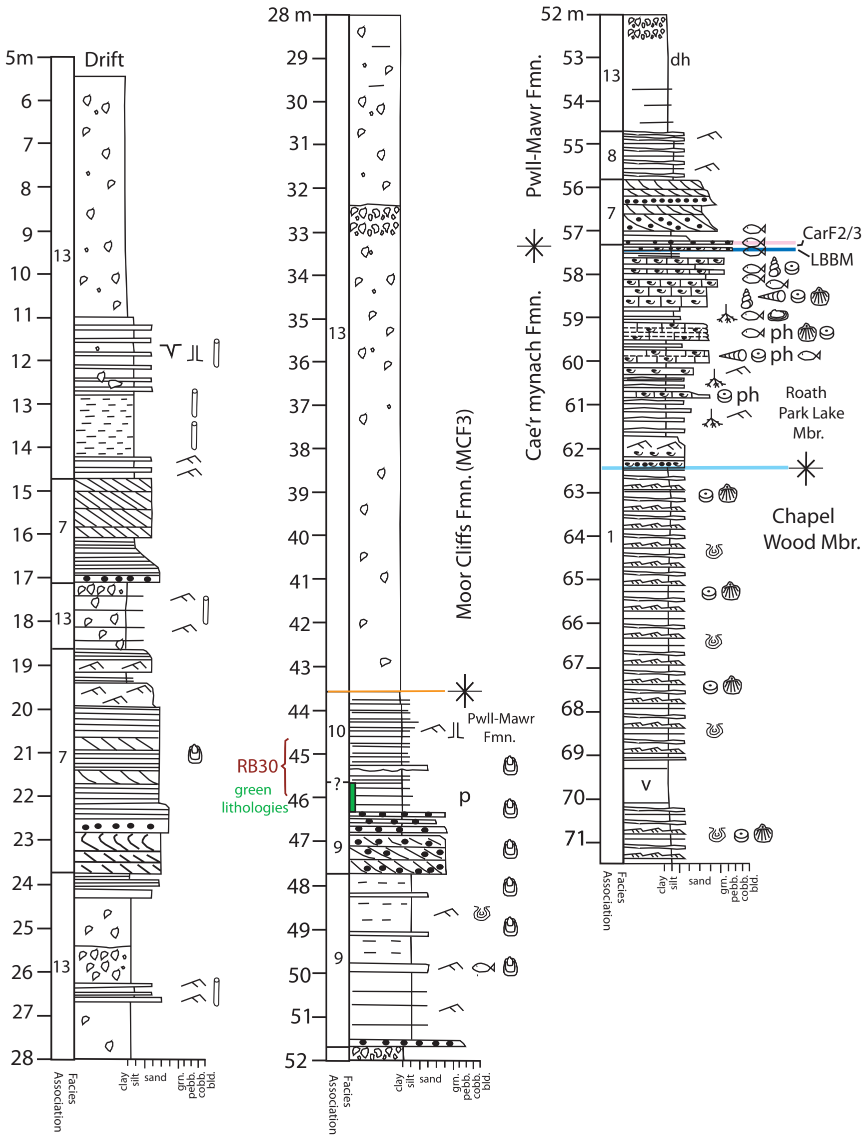

Figure 20. (Colour online) Graphic log of Rumney Borehole. For key, see Fig. 13. LBBM, Ludlow Bone Bed Member.

21) and a reduction in the estimated mica content of sandstone beds. The transition into overlying coastal plain or inclined heterolithic tide-influenced fluvial channel lithofacies associations is sharp in all observed instances and commonly defined by erosion surfaces and/or winnowed conglomerate lags (see below).

5.b. Wave-influenced delta association

Wave-related processes exercised a strong influence on the early Pridoli DCSF delta system, Hobson's (J.S.C.Hobson, unpub. PhD thesis, University of Birmingham, Hobson, 1960) 'Welsh Delta', which advanced from the north-east. In its type area, the latter appears to comprise a single parasequence of upward-coarsening and -thickening bedsets up to 10 m thick, but in more westerly and distal settings, at Gwernilla, two separate progradational parasequences are recognizable (Figure 22e). The transition from the distal into proximal wave-influenced delta-front deposits is gradual in nature. Where present, the upward transitions into distributary mouth bar and/or terminal distributary channel lithofacies are abrupt. Such lithofacies, together with the palaeoseaward-dipping delta-front clinoforms observed at Stonehouse Dingle, serve to locate points of fluvial supply to otherwise wave-influenced deltaic coastlines. An earlier prograde of wave-influenced delta association is locally recognized in the Aston Munslow Member.

5.c. Wave-influenced, forced regression delta association

This association is restricted to the successions in the Woolhope, Gorsley and May Hill inliers where it comprises facies of both the RF and CMSF (the Woolhope Delta of Hobson, unpub. PhD, thesis, University of Birmingham, Hobson, 1960). The latter formation comprises a single deltaic parasequence of upward-coarsening and -thickening bedsets similar to that of the DCSF with back-barrier deposits of the RF (Figure 24a). However, it differs from the DCSF in its provenance and regional geometry. It

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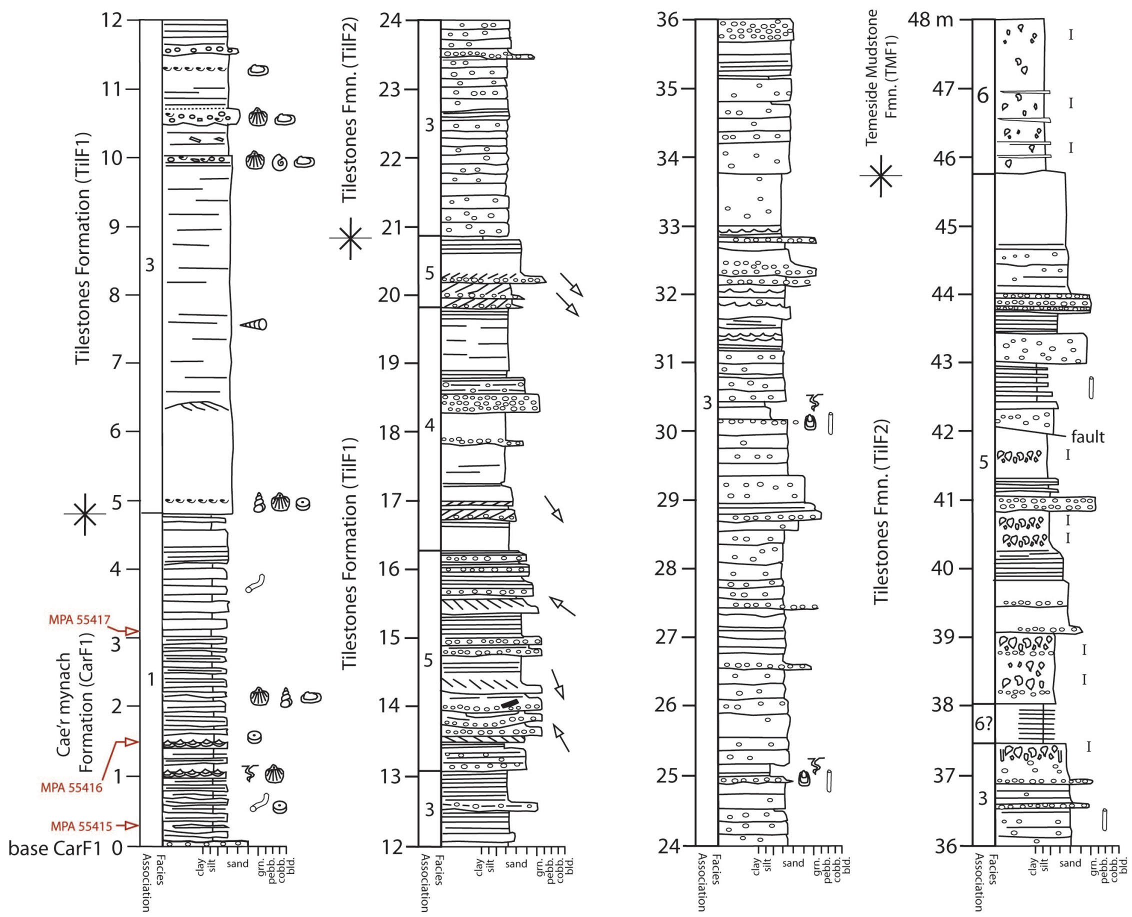

Figure 21. (Colour online) Graphic log, Cennen Valley roadcut. For key, see Fig. 13.

represents a narrow NW/SE-orientated deltaic barrier sand bar supplied from the east and sited south-west (seaward) of an extensive back-barrier RF tract (Figures 3c and 24a). The latter was the site of heterolithic tidal channel lithofacies with thin developments of coastal plain lithofacies.

Both formations sit above thin deposits containing granule and pebble-grade phosphate nodules and that locally yield vertebrate and brachiopod debris, exemplified by the ULPB of the Gorsley and May Hill inliers (Figure 24b-c). We interpret these basal beds as regressive lags comprising cannibalized detritus from underlying formations. An assessment of current dating information (see Section 3) allied to local and regional lithofacies analysis (sections 4 and 6) allows both these basal features and the succeeding facies association to be viewed as the products of a widely felt forced regression.

5.d. Incised valley fill association

The tract between the Cilmaenllwyd Quarry and Rhyblid is unusual in its absence of the TemF (Figure 1). Here, the PALF infills a major incision feature and comprises a suite of estuarine units of predominantly tidal sandflat and inclined heterolithic tidal channel lithofacies (Figure 23a). Up to 29 m of such facies are present in the Sawdde Gorge and an estimated 32.5 m at Rhyblid (Supplementary Figure S2), where facies formed in an open-bay setting are also present. The process and location of valley incision accounts for the local absence of the TemF.

5.e. Old Red Sandstone continental association

The predominantly green lithofacies that make up the AF and early TemF existed initially alongside the sandy Ludfordian deltaic systems and, in this context, could be viewed as forming a contiguous, pediment colluvium and delta-top association. However, the subsequent more widespread accumulation of the TemF and MCF justifies their inclusion in what became an exclusive and long-lived ORS continental association. Moreover, in the majority of sections where continental overlie deltaic lithofacies, the contact is sharp and the topmost delta deposits display evidence of palaeopedogenesis including calcrete nodules and calcretized root traces. In contrast, transitions between the green coastal plain and red alluvial lithofacies are conformable and gradational.

In the TemF, calcrete-bearing mudstones host single and multistorey fluvial channel sandstones and units of sheet fluvial heterolithic lithofacies. The sandstone units, commonly richly micaceous, overlie sharp erosive surfaces and fine upwards, but their distribution appears random and parasequences are not readily apparent. Palaeocurrent vectors in the south-west that are more variable than in contiguous deltaic associations may reflect deposition within meandering channels and/or the influence of local topography. Hillier *et al.* (2019) speculate that this system comprises an embryonic range-front alluvial network, with fluvial sandbodies possibly representing stream capture events. That fluvial sandbodies are less common in the late Ludfordian TemF implies either a reduction in fluvial supply or the establishment of a

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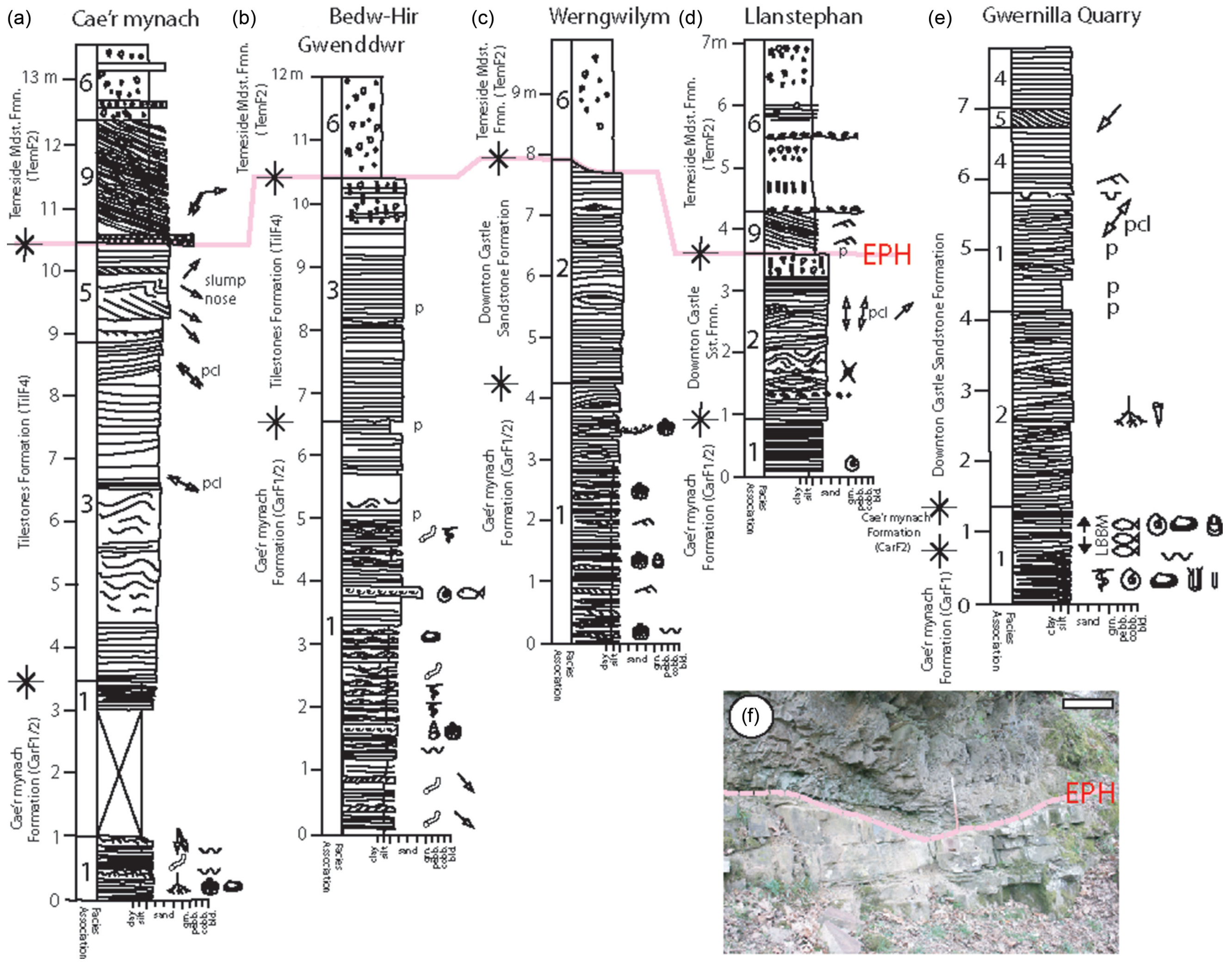

Figure 22. (Colour online) Graphic logs illustrating proximal to distal parasequence variations. (a) Cae'r mynach stream section. (b) Bedw-Hir, Gwenddwr stream section. (c) Llanstephan, River Wye (beneath road bridge). (d) Werngwilym waterfall section. (e) Gwernilla log. (f) Erosive base of Temeside Mudstone Formation at Werngwilym (7.8 m Fig 22d); scale bar 0.5 m. For key to logs, see Fig. 13. LBBM, Ludlow Bone Bed Member; EPH, early Pridoli Hiatus surface.

more mature coastal plain that was host to well established and more stable fluvial pathways.

The green lithofacies reflect the prevalence of a reducing diagenetic regime and of an elevated water table typical of a coastal plain environment. Restricted marine faunas confirm that deposition must have taken place close to sea level and that tenuous links to the open sea were maintained. The rapid, but gradual colour change from predominantly green to red lithologies that marks the base of the MCF records the transition into a better drained alluvial plain that was host to a deeper, fluctuating water table and promoted the oxidation of soil profiles.

6. Regional synthesis

6.a. Earliest Leintwardinian

The new architectural model presented for rocks of Ludfordian to early Pridoli age in Wales and the Welsh Borderland (Figures 1 and 23), together with their facies diagnosis, permit a level of parasequence-scale analysis and palaeogeographic reconstruction hitherto unachievable for this time interval. In the Western Province, the AF colluvium is overlain by TemF coastal plain mudstones. Rising base levels accommodated the deposits of this broad coastal plain with well-developed calcrete Vertisols, multi-storey and sheet fluvial lithofacies. The latter are observed at Green Castle and also Cwmffrwd, where some poorly to moderately well-sorted sandstones contain granule- to pebble-grade exotic clasts at their bases (J. Almond, unpub. PhD, thesis, University of Bristol, Almond, 1983; Figure 16, 0–61 m) and others contain abundant detrital white mica of Caledonian provenance (e.g. Figure 15, 61–65.5 m). Palaeocurrents from individual micaceous sandstones at Green Castle, Cwmffrwd and Golwg y Byd indicate palaeoflow from the north-west, south-west and west, respectively (Figure 25). Such variation illustrates the likely persistent influence of local topography in a setting where Ludfordian strata overstep much older rocks and terrestrial conditions were largely maintained.

These rivers negotiated a locally complex, fault-influenced topography to supply the Leintwardinian TilF delta of the Cennen region (TilF 1) (cf. Straw, 1929). Here, the Golden Grove Axis served as a topographical hinge that separated emergent tracts to the west from the subsidence prone Cae'r Mynach Seaway to the

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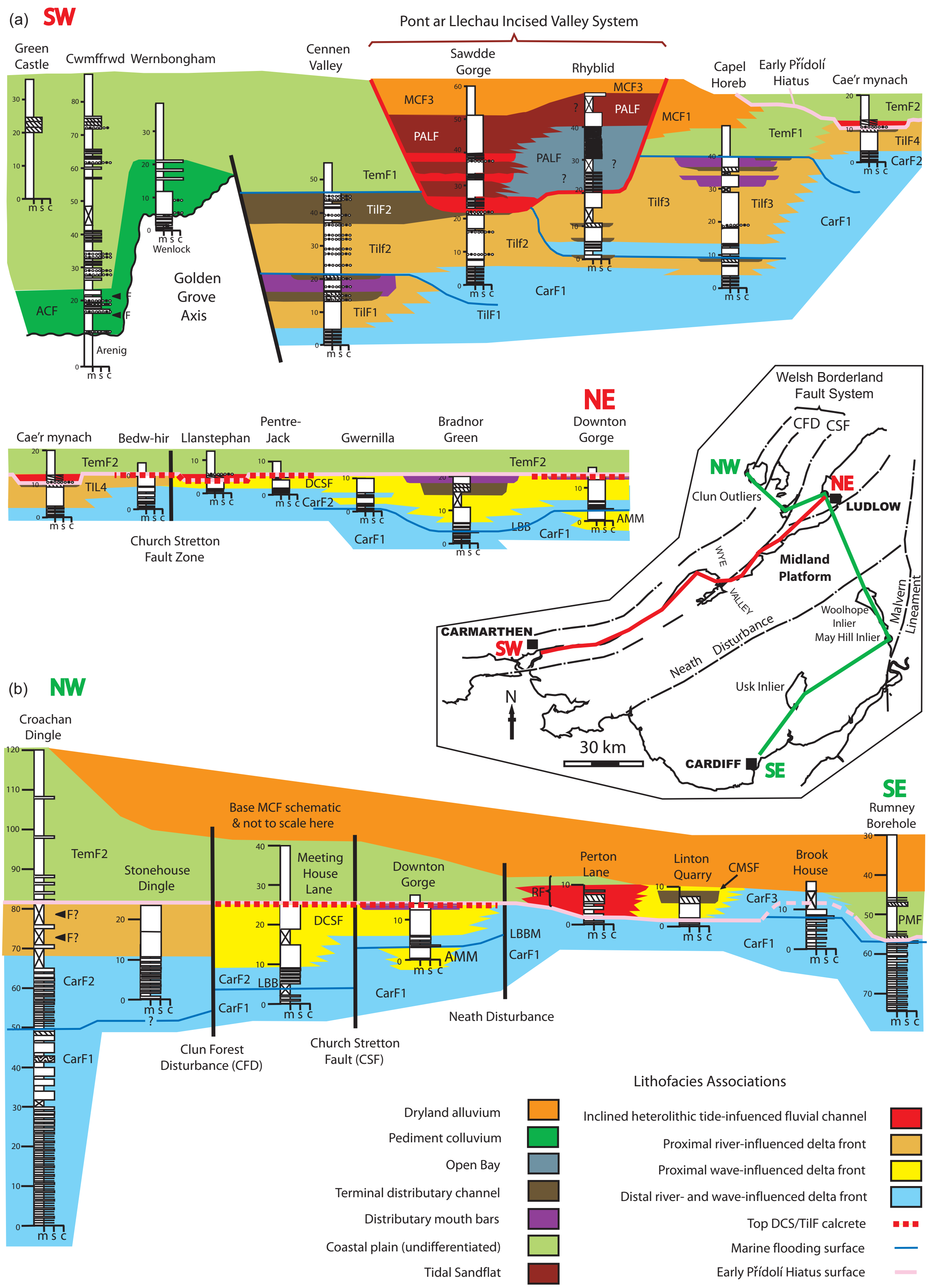

Figure 23. (Colour online) (a) South-west to north-east correlation illustrating lithofacies variations between measured sections. (b) North-west to southeast correlation illustrating proximal to distal variations in lithofacies associations.

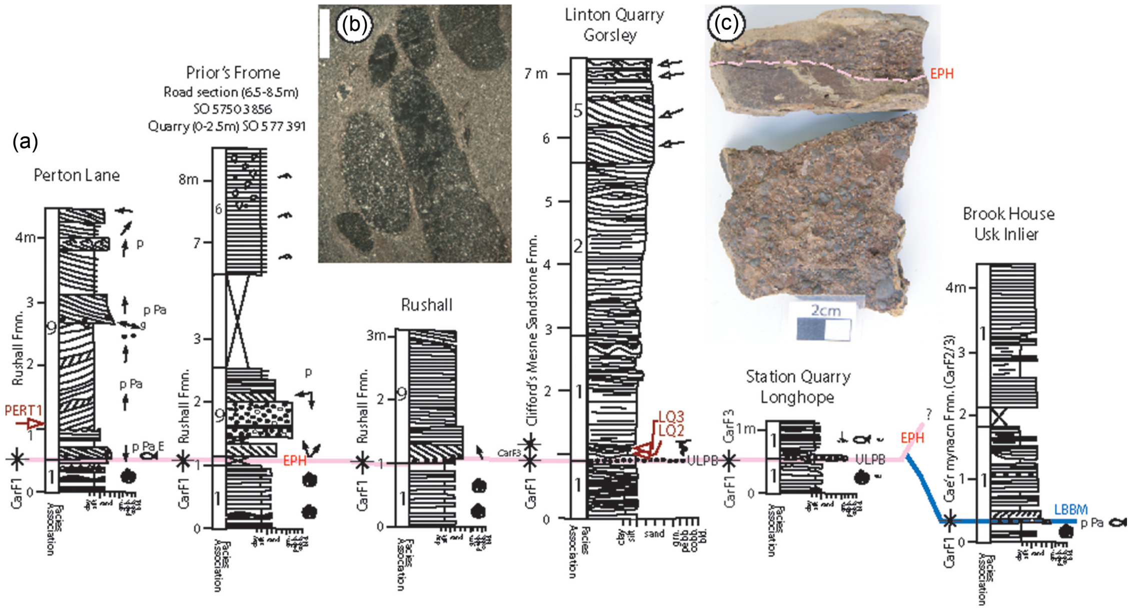

Figure 24. (Colour online) (a) Graphic logs from north-west to south east sections through the Woolhope to May Hill inliers, extending to Brook House in the Usk Inlier detailing lithofacies of the early Pridoli forced regression. (b) Thin-section photomicrograph of Upper Linton Pebble-Bed (ULPB) at Linton Quarry illustrating well-rounded phosphate intraclasts in plane-polarized light (scale bar 100 microns). (c) ULPB at Station Quarry, Longhope. Top image shows cross-sectional view of ULPB with erosional base into underlying Cae'r mynach Formation mudstone; lower image showing ULPB top, scale bar 2cm. EPH, early Pridoli Hiatus surface; CarF, Cae'r mynach Formation; LBBM, Ludlow Bone Bed Member.

east and provided a seeding point for the TilF delta system. The axis had links to transfer faults that connected the Carreg Cennen Disturbance, part of the Church Stretton Fault Zone, to fractures of the Pontesford Lineament. An uplifted footwall region generated by Ludfordian inversion of the Meusydd Fault (BGS, 1977) appears to have been most influential.

This early river-influenced delta faced a storm-stirred seabed (early Cae'r mynach Seaway) that extended across the former faulted basin margin and adjacent parts of the Midland Platform to cover the whole of south-east Wales and its Borderlands. It attained its greatest depths in the Clun Forest Sub-Basin, where Leintwardinian facies excluded from the CarF, of deeper aspect and southerly provenance, continued to accumulate. Cross-cutting relationships in the vicinity of the Church Stretton Fault Zone near Leintwardine may record local incision by early Ludfordian submarine canyons and/or slump scars which served to route sediment westwards to these deeper settings (e.g. Whitaker, 1962, 1994; Siveter *et al.* 1989; Cave & Hains, 2001; BGS, 2000).

6.b. Early Leintwardinian-Whitcliffian

The supply of Caledonian detritus from the north-west to the deltaic TilF coastline continued throughout the early Ludfordian. The Cennen area remained an initial focus for deposition, but TilF delta parasequences reveal a pattern of progressive progradation and expansion that saw Whitcliffian river-influenced deltaic lithofacies extended as far north as Capel Horeb.

Distal delta-front lithofacies of the CarF (0–4.8 m Figure 21) are seen in the Cennen Valley where they underlie two complete river-influenced TilF deltaic parasequence (TilF 1 and TilF 2, Figure 21, 4.8–20.85 m and 20.85–45.7, respectively). Palaeocurrents from terminal distributary channels and mouthbars in the Cennen Valley and Onen-fawr indicate palaeocurrent flow principally from a NW quadrant, with subordinate NW-directed vectors likely the result of tidal reworking (Figure 25). Primary current lineation supports the interpretation of sediment transport from the NNW, and wave ripple crests indicate a shoreline-oriented approximately WSW-ENE. The calcrete that caps the proximal river-influenced delta-front facies (Figure 21, 20.85–37.4 m) of TilF 2 record its initial emergence and the effects of ongoing Vertisol palaeopedogenesis. Five calcrete profiles are also observed in the succeeding succession of distributary channel fills, implying prolonged subaerial exposure (Figure 21, 38.05–41.6 m). The laminated green mudstone present (37.4–38.05) may record an abandoned channel fill and proximity to coastal plain lithofacies which dominate the overlying TemF1 deposits above.

Both TilF 1 and TilF 2 parasequences are exposed in 'tilestone'workings at Cilmaenllwyd Quarry (SN 6676 2084 to 6614 2048; the 'long quarry' of earlier workers) where parallel-laminated sandstones with well-preserved unidirectional bounce and prod marks typical of proximal river-influenced delta-front deposits were exploited. Intervening ridges of unworked, medium-grained, locally pebbly sandstones displaying convolute lamination and large wave ripples as well as fine-grained sandstones with low-angle lamination are consistent with the distributary mouth bar lithofacies. Purple sandstones previously recorded by Strahan *et al.* (1907) above the 'Tilestones' are here attributed to the PALF tidal sandflat lithofacies and overlie the mid-Pridoli incision surface (see Section 6f).

The Sawdde Gorge was beyond the reach of the initial TilF delta advance (Figure 23a). There, the cross-bedded, terminal distributary channel deposits that cap brachiopod-bearing, river-influenced delta lithofacies were emplaced exclusively by the second (TilF 2) progradation (Figure 19, 5.65–21.7 m). Rhyblid lay within reach of both the second and third TilF progrades (Figure 23a; TilF 2, 0–1.5; and TilF 3, 1.5–20.1 m Supplementary Figure S2). The TilF successions in the Sawdde and at Rhyblid both underlie the PALF incision surface. In contrast, Capel Horeb Quarry to the NE

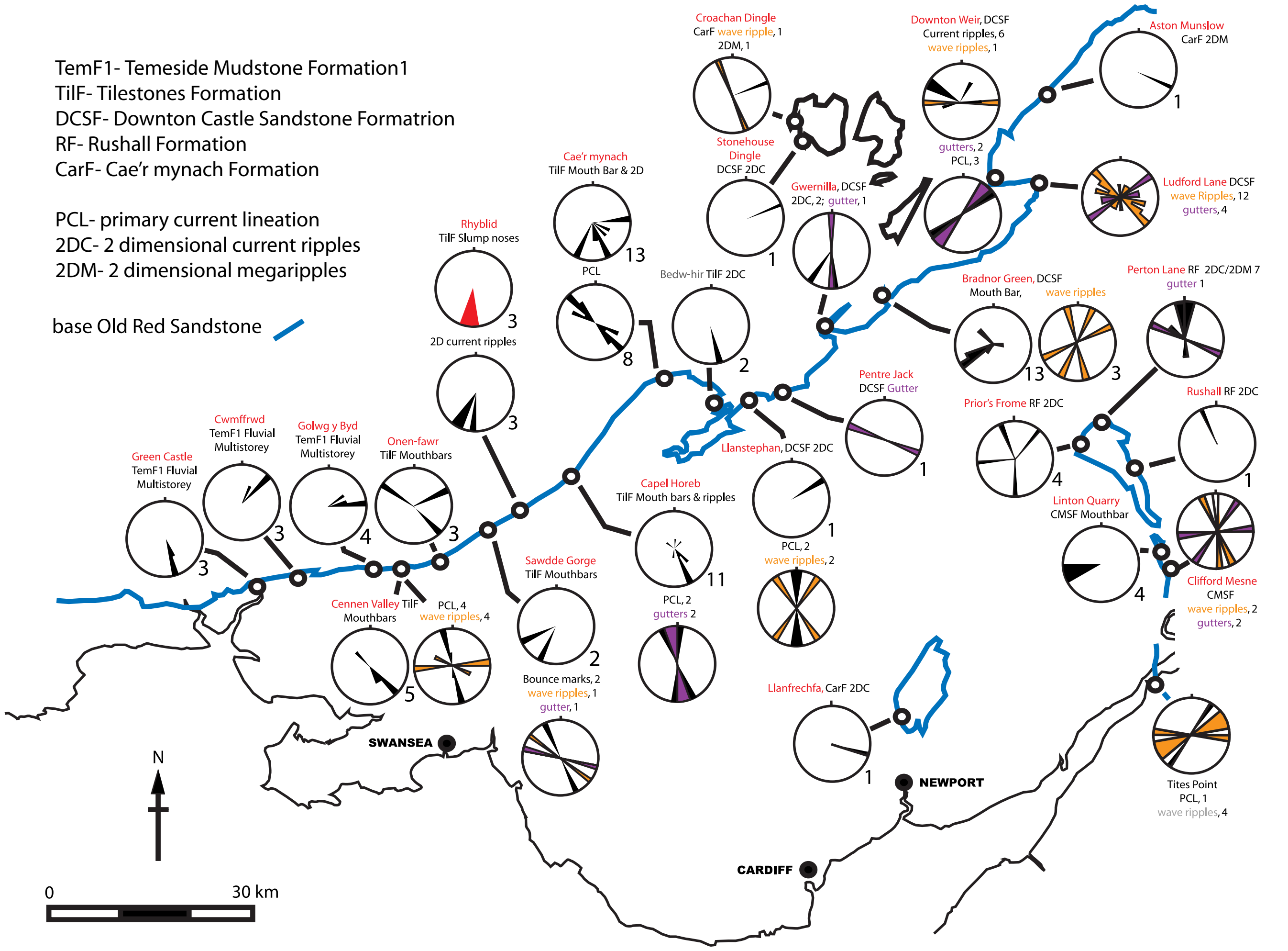

Figure 25. (Colour online) Summary of palaeocurrent data from measured sections in study. Number at side of data plot corresponds to number of data readings except where more than one data type (e.g. gutter, wave ripple crest orientation) is shown graphically in each plot. In this scenario, numbers of data readings are given after each data type (e.g. gutter, 2; wave ripple 3)

lay outside the region of greatest mid-Pridoli incision (Figure 23a), and here a TilF succession that also includes both Leintwardinian and Whitcliffian progrades (Figure 13, TilF 2, 2.6–8.95m; TilF 3, 8.95–39.8m) is abruptly overlain by TemF coastal plain facies.

Sedimentological evidence for shoaling episodes coeval with TilF 1, TilF 2 and TilF 3 in the CarF succession of the South-Eastern Province is ambiguous and may indicate that these episodes of progradation were influenced principally by local changes in accommodation space and sediment supply rather than external base-level events. Nevertheless, the migration into eastern CarF successions, late in the Leintwardinian, of the brachiopod *Shaleria ornatella*, which culminated in the local development of near monospecific shell banks (Phipps & Reeves, 1967), has been seen to offer evidence, if not of shoaling, of an abrupt, regional change in seaway circulation patterns (Watkins, 1979). It is reasonable to speculate that this palaeoecological event was linked to westerly delta advance. Coincidental evidence of renewed scour and omission affecting the Gorsley Axis area offers an indication that tectonic forcing also remained important locally.

The Clun Forest Sub-Basin remained an extant feature for much of the early period of TilF advance. Its gradual demise as a site of deeper southerly sourced facies accumulation and the complementary spread across this region of shallower Cae'r mynach Seaway facies mirrors the pattern of the north-westerly supplied delta spread (Figure 1). However, the sub-basin, though it remained influential as a local depocentre, was abolished as a site of deeper water deposition in mid Whitcliffian times. This marked the period when the storm-influenced, delta facing facies of the Cae'r Mynach Seaway achieved their maximum lateral extent. Evidence that the subsequent shoaling was felt in other parts of the Cae'r mynach Seaway has been alluded to above (Section 3). The newly recognized Aston Munslow Member shows that the earliest wave-influenced deltaic deposits of the North-Eastern Province prograded south-westwards, reaching to the north of Ludlow in late Whitcliffian times. Facies that record coeval shoaling are seen further west (Stonehouse Dingle), and locally in the South-Eastern Province (Roath Park Lake Member), but CarF deposition remained extensive during this interval even at the point of greatest pre-Pridoli deltaic incursion.

6.c. Earliest Pridoli (post-Ludlow Bone Bed transgression)

The LBB transgression, where its impacts are preserved, resulted in a renewed deepening and re-expansion of the Cae'r mynach Seaway. Here, the early Pridoli deposits of this seaway (CarF 2) are envisaged once to have been present throughout much of the South-Eastern Province. Excision during the subsequent hiatus event led to their widespread removal (see below), leaving the lower levels of former 'Speckled Grit' succession of the Usk area and a thin development of CarF (CarF 2) above the LBB in the Rumney Borehole as its principal surviving representatives (Figure 19). The limited fauna present during this early Pridoli period of CarF deposition testify to restricted marine conditions. Locally, notably in the North-Eastern Province, trace fossil assemblages and the preservation of mat grounds (e.g. LBBM, PSM) imply that fluvial run-off remained influential and that deltaic coastlines were situated nearby. Certainly, multiple delta systems soon began to prograde into the newly created accommodation space influenced in part by ongoing regional subsidence.

At Downton Gorge and at Ludford Lane, the LBBM and PSM record distal wave-influenced deltaic deposition prior to the entry of the more proximal deltaic lithofacies that comprise the DCSF. Distributary mouth bar lithofacies locally cap this type succession which appears to offer evidence for a single uninterrupted delta advance. Wave ripple crests and gutter casts suggest sediment was supplied to an E-W-orientated coastline from the NE. Cross-stratification in the DCSF at Turner's Hill, Dudley, observed by Ball (1951), also indicates sediment transport from the NE.

Proximal wave-influenced delta-front lithofacies dominate sections in the DCSF in the vicinity of the Church Stretton Fault Zone (Figure 23b). The sandstone succession in these more distal reaches of the delta system thins south-westwards. Two discrete parasequences are recognized at Gwernilla, but only one of these extends into the much thinner and more distal succession seen at Llanstephan (Figure 22c). It is likely that the two parasequences reflect local autocyclic processes as they are not observed elsewhere. Palaeocurrent vectors suggest that the terminal distributary channel and distributary mouth bar lithofacies seen at Bradnor Green were supplied from the NE (Figure 25).

West of the Church Stretton Fault Zone, in the Clun Forest area, sections at Croachan Dingle and at Stonehouse Dingle are significant in displaying river-influenced DCSF facies (Figure 23b). Proximal river-influenced delta-front lithofacies overlie heterolithic, distal river- and wave-influenced delta-front deposits. The latter contain common convolute-laminated beds and slump units that indicate the importance of mass flow processes in this area. Stonehouse Dingle is notable as the only section where steep delta clinoforms have been observed, and these confirm that the direction of delta progradation in this region, in common with the DCSF-type area, was from the NE. Deltaic deposition at the Croachan and Stonehouse sections occurred astride the axis of the former Clun Forest Sub-Basin, to the west of the Clun Forest Disturbance. It likely remained the region of greatest seaway water depths but also of ongoing seismic instability. East of the Clun Forest Disturbance, at Meeting House Lane, 16 m of proximal wave-influenced delta-front deposits are poorly exposed above distal river- and wave-influenced delta-front deposits. Here and in the Norton Inlier, rock fragments containing denticle-rich laminae, together with the gastropod *Turbocheilus* at the latter, demonstrate the presence, hitherto unrecorded (e.g. Holland, 1959), of the LBBM.

River-influenced deltaic deposition continued in the Western Province where, though the Ludfordian succession as whole thickens to the NE, the TilF thins and is represented, at Fibua, Cae'r mynach and Bedw-Hir, by a single parasequence of the proximal river-influenced delta lithofacies (TilF 4) (Figures 22a, b and 23a). This final prograde marked the conclusion of the series of TilF delta advances into the Western Province that had been ongoing since the early Leintwardinian (Figure 1). However, the pattern of advance depicted by Figure 23a is misleading, the linear TilF crop being largely orthogonal to the dominant south-eastward direction of progradation. The distribution of TilF progrades appears more likely to offer a record of progressive side lap and/or the lateral expansion of the TilF delta system. In truth, the sub-crop extent of each progradation remains unknown, but the active delta front at the point of its early Pridoli culmination may have been extensive and be located in buried stratigraphy well to the east.

The case to view TilF 4 and the DCSF as representing coeval but separately sourced progradations into the Cae'r Mynach Seaway is made in Section 3. At their greatest extent, these separate delta systems likely merged to form a continuous deltaic coastline. River-linked process remained influential on south-east facing TilF shores. Delta-front clinoforms (Stonehouse Dingle), mouth bar and terminal distributary channel deposits (e.g. Downton Gorge, Bradnor Green) show where rivers also traversed south-west to westerly facing shores that were otherwise more strongly influenced by wave activity.

Evidence of any coeval early Pridoli delta advance into the South-Eastern Province was widely obliterated by the subsequent episode of erosion (see Section 6d below). Nevertheless, distal river- and wave-influenced delta-front CarF facies that underlie the local DCSF equivalent suggest that it was an active process in the Malverns area (S.J.Veevers, unpub. PhD thesis, University of Birmingham, Veevers, 2006; White *et al.* 1984).

Throughout the Western Province, to the west and landward of the TilF deltaic shoreline, green, early Pridoli coastal plain facies of the TemF (TemF 1) continued to accumulate in front of coeval MCF red beds. Evidence of intercalation with delta-top TilF facies is seen in the Cennen area TilF 2 parasequence, where thin deposits of green/grey-laminated mudstones interbed with calcrete hosting sandstones and conglomerates of the terminal distributary channel lithofacies (Figure 23). Channellized micaceous sandbodies recognized within both the TemF and MCF locate the sites of south-easterly flowing streams that supplied the delta shoreline (see Sections 3 and 5 above) and offer further evidence of synchronicity.

6.d. Mid-early Pridoli (post-early Pridoli Hiatus)

6.d.1. Western and North-Eastern provinces

The contact between early Pridoli sandstone prone delta lithofacies and the local succession of TemF seen on the northern part of Mynydd Epynt, and throughout the North-Eastern Province, is abrupt. No interdigitation is observed, and there is widespread evidence of omission. The contact locally displays evidence of palaeopedogenic alteration, with calcrete profiles extending into underlying delta deposits. Extensive calcretes affecting upper levels of the DCSF are seen in its type area and at localities futher west (e.g. Gwenddwr, Figure 22b). At Llanstephan, channels incised into the top of the DCSF are filled by deposits that testify to tidal influences (Figures 22c and 23). At Werngwilym (Figures 22d and 22f) and at Gobe Banks (SO 223 557), the TemF drapes a scoured upper surface cut into underlying deposits that has a relief of up to 0.5 m, and at Five Turnings (SO 286 754) Stamp (1918) recorded a thin conglomerate at the DCSF–TemF contact.

In the Western Province, sections seen on Mynydd Epynt show that calcretization also affected the top of the TilF 4, at Bedw-Hir for example. Exposures at Cae'r mynach offer evidence of channel incision overlying a basal conglomerate, with subsequent tidal infill that recall the features seen affecting the top of the DCSF in the Wye Valley. We interpret this regional contact as marking a

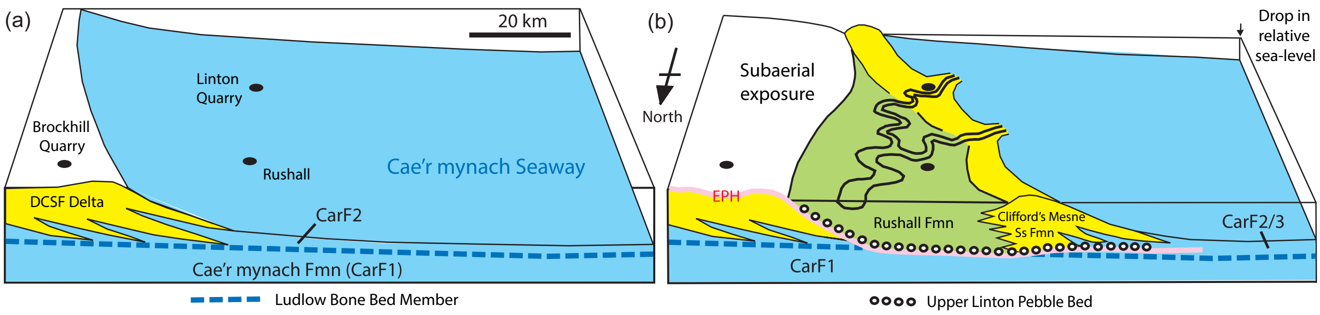

Figure 26. (Colour online) Block diagrams illustrating the early Pridoli Hiatus and forced regression in the Southeastern Province. (a) Downton Castle Sandstone Formation delta coastline of the Malverns area faced the open marine Cae'r mynach Seaway to the south and west. (b) Early Pridoli Hiatus and forced regression with marine ravinement into underlying tracts and subsequent deposition of the Upper Linton Pebble Bed beneath deposits of the Rushall and Clifford's Mesne Sandstone Formations. Note localized erosion of the Ludlow Bone Bed Member. CarF, Cae'r mynach Formation; DCSF, Downton Castle Sandstone Formation; EPH, early Pridoli Hiatus surface.

distinct depositional hiatus associated with a regional base-level fall and forced regression and resulting in widespread omission and local incision.

The TemF (TemF 2) that succeeds the hiatus level records the renewed subsidence and creation of accommodation space that attended a mid-early Pridoli phase of delta advance. The North-Eastern Province and parts of the Western Province lay northwards and landward of the new deltaic coastline and evolved into a region of extensive coastal plain deposition. This passed laterally into the coeval facies belts of the South-Eastern Province (Figure 23a). It follows that this type succession of the TemF is younger than its counterpart (TemF 1) to the west. Whether a level equivalent to the erosional event exists in more westerly MCF red bed successions is unknown. Figure 3c speculates that the impacts of the early and mid-Pridoli erosional episodes combined to create a region of more extensive omission.

6.d.2. South-Eastern Province: Woolhope, Gorsley and May Hill inliers

That the late Ludfordian to early Pridoli successions of the South-Eastern Province differ significantly from those of the more northerly and western regions has been alluded to above. The principal differences relate to the nature of the basal erosion surface, the distribution of the RF and CMSF, and the absence of the TemF. Dating constraints, as outlined in Section 3, permit alternative correlations. Here, we explore a radical reinterpretation of the successions that developed south of the Vale of Neath Disturbance and west of the Malverns Axis, one informed by sequence stratigraphical models for forced regressions (e.g. Plint & Nummedal, 2000; Catuneanu, 2006).

The South-Eastern Province, prior to the Pridoli, had been a region of relative attenuation and local omission. Structural inversion is invoked as explanation for northern regions being uplifted during the early Pridoli to become an emergent, calcrete forming tract. In contrast, across regions south of the Neath Disturbance, it is the erosion surface overlain by bone-bearing levels, previously seen as equivalent to the LBB, that provide the evidence for coeval erosion. Evidence for channelling and calcretization is absent, and the juxtaposition of facies favours marine ravinement as the denuding mechanism (Figures 3 and 24a).

As to the north, the resumption of deposition was in response to a new episode of delta advance accompanied by a change, as least locally, in the provenance of sand-grade sediment (see Section 2). Initially, there was little space to accommodate the deposits of this putative easterly sourced system and, in response to regressive forcing, the nearshore high-energy zone shoreline would have moved rapidly westwards. The regions south of the Neath Disturbance and astride an initially still active Gorsley Axis were sites of greatest exhumation (Figure 3c). Whether earlier facies of the DCSF delta system ever accumulated in this region is a moot point, but the deep scour that accompanied the marine ravinement event extended to depths below levels equivalent to the LBB and into the earlier Ludfordian CarF succession. It was on this regressive surface of marine erosion that the distinctive phosphatic pebble and bone-rich lags of the Woolhope, Gorsley and May Hill successions accumulated and the province's wave-influenced forced regression facies association began to aggrade (Figure 24).

In its proximal reaches, a marked basinward shift in sedimentation is observed at the base of this developing association. RF successions that display inclined heterolithic tidal channels with thin local developments of coastal plain lithofacies (e.g. Shucknall Hill, Perton Lane, Priors Frome Quarry and Rushall in the Woolhope Inlier (Figures 3, 24a and 26), directly overlie exhumed Ludfordian CarF facies of offshore and distal deltaic aspect. In this scenario, these RF deposits accumulated in a setting seaward of the TemF 2 coastal plain, but behind a NW/SE-orientated barrier bar (CMSF) formed by the marine reworking of the putative delta front. The thickest development of these barrier facies between Gorsley and Clifford's Mesne suggests that the Gorsley Axis, a structural feature closely linked to the trace of the Glasshouse Fault, remained active. It served first as a seeding point for barrier aggregation and subsequently to anchor the sand body in place throughout the mid-early Pridoli. These relationships recall the role played by the Golden Grove Axis in the Western Province at the Leintwardinian onset of TilF deltaic deposition (Figure 3). Wave reworking, well seen at Linton Quarry, was influential during much of the barrier's development. Wave ripple crests at Clifford's Mesne suggest that local shoals trended approximately NNW-SSE (Figure 25). Foresets associated with terminal distributary channel deposits seen in the upper part of the formation at Linton Quarry serve to locate the position of a point of fluvial sediment input from the ENE. The finer-grained CMSF succession seen to the south of the Glasshouse Fault, in the Longhope area, represents the seaward-facing facies of the barrier. These in turn passed southwards into the restricted marine facies of the remnant Cae'r mynach Seaway (CarF 3).

6.d.3. South-Eastern Province: Usk and Rumney inliers

The early Pridoli successions of the Usk and Rumney inliers demonstrate coeval deposition on the western side of the remnant seaway. The pronounced erosion surface that underlies PMF facies in the Rumney area offers evidence of a ravinement event coeval with that seen in the Woolhope and May Hill areas (Figure 20). Evidence for such omission remains unrecognized in the early Pridoli succession of the Usk Inlier. The parts of the Usk area CarF succession that were formerly labelled the 'Speckled Grit' formed in a setting sufficiently offshore to escape the erosive reach of the early Pridoli ravinement process that affected more proximal settings to the west and east. A horizon equivalent in time to the hiatus surface must exists at a cryptic level within a Pridoli succession that includes the intervals distinguishable elsewhere as CarF 2 and CarF 3 (Figure 24a). Above the CarF succession, strata with redoximorphic mottling at Llanfrechfa testify to a period of PMF coastline deposition in the Usk area prior to the onset of dryland MCF conditions.

There is no evidence that a sand-prone barrier with well-developed amalgamated sandstone bedsets ever developed in the Usk or Rumney areas. Instead, the presence of PMF facies supports a model that envisages accumulation on the western side of the Cae'r mynach Seaway. In such a setting, the facies of the PMF accumulated landward of a muddy coastline and were able to prograde into and across the restricted seaway deposits (Figure 3c). Levels of red mudstone and calcrete confirm that the predominantly purple PMF succession formed in a setting prone to the periodic imposition of dryland diagenetic conditions. The miospores recovered from just below the base of the MCF in the Rumney Borehole imply that alluvial plain red beds had likely completed their advance into the Rumney area by late TS Assemblage Zone times (Figure 20). This was earlier than along the opposite margins of the seaway where the imposition of north-easterly and easterly sourced red bed facies occurred after the appearance of the Zone A microflora in TemF2. This completes the picture of a mid-early Pridoli depositional tract that resolves many of the palaeogeographical problems arising from previous correlations. Deposition occurred in the wake of the early Pridoli Hiatus, and the new model is underpinned by its recognition.

6.d.4. 'Brecon Anticlinal'

Returning to the Western Province, the tide-influenced fluvial channels that incise the TilF at Cae 'r mynach and the DCSF at Llanstephan, comprise a network comparable to that observed in the RF. The location of these incisions is noteworthy as they are close to the Church Stretton Fault Zone. Experimental studies (e.g. Ouchi, 1985; Jin & Schumm, 1987) demonstrate that the sinuosity of channels commonly increases immediately down-stream of uplifted zones, and Dykstra (1988) observed erosion at the base of channels in association with uplift and the reduction in accommodation space. Incision and sinuosity changes of channels linked to neotectonic uplifts have also been well documented (e.g. A.W. Burnett, unpub, M.Sc. thesis, Colorado State University, Burnett, 1982; Burnett & Schumm, 1983; Ouchi, 1985). Late Ludfordian uplift along the Church Stretton Fault Zone may account for the incision by high-sinuosity channels seen across this region. This zone of uplift echoes the 'Brecon Anticlinal' invoked by Allen (1974a) to explain the facies changes he recognized across this region. It likely formed part of a broader region of structural inversion linked to the abandonment of earlier TilF and DCSF deltas, and that promoted the shift of depocentre into the South-Eastern Province.

6.e. Late early Pridoli

Following the episode of forced regression and basinward shift in sedimentation, the onset of regional subsidence initiated renewed accumulation of ORS continental facies. The younger succession of TemF (TemF 2) began to accumulate across the whole of the North-Eastern Province on an expanding coastal plain with elevated water tables. Elsewhere, in areas where more mature drainage systems were established and water tables depressed, red bed diagenesis was a dominant factor. The subsequent spread of such conditions saw MCF facies established throughout the study area.

Mica and garnet-rich Caledonian detritus now supplied an ORS alluvial plain that, having advanced from the north, covered much of southern Britain. Lingulid and ostracoderm fragments recovered from MCF sandstones at the base of the ORS in the South-Eastern Province (Allen & Dineley, 1976) suggest proximity to a contemporary shoreline. Prior to the continental-scale late Variscan displacements achieved by the Bristol Channel–Bray Fault Line, this ORS coastal realm likely lay to the south of the present-day Bristol Channel and had close links to the Rheic Ocean.

6.f. Mid-Pridoli incision and valley infill

In the mid-Pridoli, widespread ORS alluvial deposition was punctuated by an episode of incision and valley formation within the Western Province (Figures 3d and 23a). Here, incision removed the TemF (Tem1) and 'lower' MCF deposits in the tract between Cilmaenllwyd Quarry and Rhyblid. Here, it is preserved as an estuarine incised valley fill comprising the PALF. The palynological evidence for the mid-Pridoli age of these facies is presented in Section 3. In the Sawdde section, above a basal conglomerate is an alternation of inclined heterolithic tidal channels and tidal sandflat lithofacies (Figure 19, 21.7-50.8 m) describing three parasequences. In contrast, at Rhyblid (6 km along strike) open-bay lithofacies dominate the lower part of the 32.5 m thick succession below an 8.5 m thick capping of tidal sandflat lihofacies (Supplimentary Figure S1).

A *circa* 60 m thick mid-Pridoli estuarine valley fill sequence is documented by the FEF in Pembrokeshire (Hillier *et al.* 2019). Here, valleys were cut into early ORS alluvium with a NW-SE orientation, and there is evidence of some structural control to their location (Figure 3d). The estuarine valley fills are preserved above lowstand coarse-grained alluvium. However, there is no clear evidence of structural control to the location of the PALF Incised Valley System. The possible superposition of mid-Pridoli and early Pridoli hiatuses in this western region has been alluded to (Figure 1). Any impact of the younger event remains unrecognized in easterly wholly red bed MCF successions. There, elevated rates of subsidence were perhaps a factor in minimising its impacts, with one of the abundant calcretized levels present in this succession marking its local manifestation.

6.g. Role of regional tectonism

The tectonism that had been so influential in achieving the Gorstian reconfiguration of the Welsh Basin remained a factor during the Ludfordian as many of the region's deep-seated fracture lines responded to continuing transtension. The WBFS, and the Church Stretton Fault Zone in particular, exercised a significant

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control on the thickness and distribution of lithofacies. The thinner, more carbonate-rich Ludfordian successions present to the east of this fault belt contrast with the much thicker successions that drape it to the west and that host lithofacies, deeper in aspect, which had closer affinities to those of the Clun Forest Sub-Basin (Figure 3a). The Midland Platform evidently remained a structurally positive setting and a region of low accommodation space, at least during the early Ludfordian, that was remote from coarse fraction, siliciclastic input. This contrasted with the pattern of Ludfordian deposition to the west of the Church Stretton Fault Zone. There, following an initial seeding on an active Golden Grove Axis, the subsequent pattern of TilF deposition suggests that an actively subsiding marine trough – the terminal phase of the Clun Forest Sub-Basin – was effective in creating space to accommodate separate episodes of north-westerly sourced delta expansion.

During the Pridoli, though the Clun Forest Sub-Basin was by then no longer a site of deeper facies accumulation, ongoing subsidence may have influenced the position of river channels supplying the south-westward prograding DCSF delta. In so doing, it favoured the development in the Clun Forest area of steep delta-front clinoforms and of gradients necessary to generate mass flow and hyperpycnal deposits (e.g. Olariu *et al.* 2010).

Anomalous features associated with the Church Stretton Fault Zone emphasize the active nature of this fracture belt. The canyon/slump features of the Leintwardine region, though located to the east of the fault belt, likely migrated eastwards from the vicinity of the fault belt in response to headward erosion and/or retrograde, perhaps seismically triggered slumping. Either mechanism implies the presence in early Ludfordian times of a west-facing slope located seaward of an active fault footwall (see Whitaker, 1962, 1994; Cave & Hains, 2001). Thickness variations associated with the Gorsley Axis (e.g. Holland & Lawson, 1963) indicate that Ludfordian tectonism was also locally influential on the Midland Platform. The subsequent impacts of early Pridoli structural inversion and the active roles played by the Church Stretton Fault Zone, the Neath Disturbance and the Malvern Axis have been outlined above.

In the south-eastern region, movements on the NW-SE trending Gorsley Axis resulted in thinning and non-deposition in the Ludlow but thickening in the Pridoli. This can be explained by viewing the footwall region of the Glasshouse Fault first as a seeding point and then as a site that anchored the CMSF barrier and promoted its in situ aggradation. The footwall region to the NE of the fault trace suffered differential uplift with the amount of accommodation space varying through time from Ludlow to Pridoli as recognized by Lawson (1955). Butler *et al.* (1997) recognize the NW-SE trending Woolhope Fault as an important and influential fracture which experienced reversals of movement at different stages in its history. It may serve to view the Glasshouse and Woolhope faults as individual components of a NW-SE trending Woolhope Fault Belt that acted as transfer structures between the Neath Disturbance and Malvern Line/Severn Estuary Fault Zone with the Gorsley Axis its stratigraphical expression. The role of the latter clearly compared with that of the Golden Grove Axis early in the Leintwardinian.

6.h. Variscan versus Caledonian affinities

The Middle Devonian deformation that affected the older fill of the Welsh Basin as well as its successor deposits – commonly ascribed to the 'Acadian Orogeny' – has long been viewed as a late Caledonian event (see Section 2). Woodcock *et al.* (2007; also Woodcock & Soper, 2006; Woodcock, 2012a) reject this assertion. They argue compellingly that this deformation was the consequence of flat-slab subduction that took place along the northern margin of the Rheic Ocean and was by inference a proto-Variscan event. But at which point did plate processes associated with the Rheic Ocean overtake those of Iapetan affinity as the dominant tectonic influence on Wales and the adjoining regions of England? The complex interplay of tectono-sedimentary events associated with the closure of the Iapetus Ocean and the convergence of its contiguous continental masses are reviewed by Woodcock (2012c).

Early Silurian volcanic centres at Skomer and Tortworth were likely a by-product of Rheic subduction, whereas syn-orogenic feldspar and lithic-rich sand supplied to the Welsh Basin during the late Llandovery and early Wenlock was from tracts uplifted within Avalonia during the period of Iapetus closure (Woodcock *et al.* 1996; Davies *et al.* 1997). Evidently, there was an extended period when emerging Variscan and late Caledonian influences operated side by side. Sediment was being shed southwards from uplifting tracts linked to the Iapetus collision zone by mid Wenlock times. Woodcock (2012c) suggests that the foreland basins that accommodated this sediment were responding to regional trans-tension. He envisages strike-slip within the Caledonian Orogen as the mechanism driving the development of such basins. The basins in northern England and North Wales, he suggests, evolved separately from a remnant Ludlow marine basin in Wales that continued to receive sediment from an emergent region to the south. In contrast, Hillier *et al.* (2019) invoke partial uplift and the development on an extensive Gorstian pediment plain covering much of north and west Wales, as key factor in the evolution of the region. The findings of the current study show clearly that subsequent Ludfordian marine, deltaic, coastal plain and alluvial facies belts formed part of a southward advancing sedimentary system and that emergent tracts to the south had by then subsided and been submerged.

The age of the youngest shallow marine Ludlow facies preserved in North Wales, the uncleaved Dinas Brân Formation of the Llangollen area, is poorly constrained, and at youngest early Whitcliffian in age (see Warren *et al.* 1984; Cocks *et al.* 1992; Siveter, 2000). These strata do not preclude the possibility that, throughout much of west and North Wales, red bed ORS facies of late Ludfordian age formed part of the sedimentary overburden that facilitated the development of the Acadian cleavage in underlying Early Palaeozoic mudrocks (Soper & Woodcock, 2003; Woodcock & Soper, 2006). The isolated ORS succession on Anglesey is normally listed as Pridoli to Early Devonian in age, but its deformation implies that it formed part of a once much thicker ORS succession (Treagus *et al.* 2011). Perhaps, in common with the unconformable succession in south-west Wales, it too includes a Ludfordian component. The sediment supplied to both areas was derived from both local and distant Caledonian sources. However, in place of a pediment surface, the Anglesey succession records the burial of an incised local topography developed astride the site of the former Irish Sea Platform (or Monian Terrane) (Allen, 1965). The marine facies and faunas developed southwards of this expanding ORS system were contiguous with those of the Rheic Ocean.

Such a model is at odds with the successions in northern England. There, marine conditions prevailed into the late Ludfordian and possibly early Pridoli during which time the terrestrial–marine interface lay to the north (Woodcock, 2012c). Such relationships speak to the complexity and diachroneity of

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Caledonian alluvial advance. They may also imply that the northern England and Welsh depocentres were widely separated at the time of sedimentation and that their current relative positions were imposed by sinistral displacements affecting the margin of the Monian Terrane during the late Early to Middle Devonian Acadian deformation.

In their re-assessment of the 'Acadian Orogeny', Woodcock *et al.* (2007); Woodcock (2012a) envisage a volcanic arc, later displaced along the Bristol Channel–Bray Fault Line, once to have existed in advance of the Rheic subduction zone. Back-arc extension affecting the 'Avalonian' crust to the north offers an alternative mechanism to generate the transtension needed in Wales to accommodate its Ludfordian to Early Devonian succession. There is no requirement for Caledonian effects to have fully ceased at this time, but the fundamental changes in provenance and subsidence patterns first evident during the late Gorstian can be seen to mark the point at which Rheic plate tectonics became dominant and Wales was more fully incorporated into an evolving Variscan orogenic province. The deposition and tectonic accommodation of late Gorstian–Early Devonian succession in Wales and the Welsh Borderland, as well as its subsequent deformation, uplift and erosion, were components, arguably, of the same proto-Variscan tectono-sedimentary cycle.

Finally, the juxtaposition of NW-sourced river-influenced with NE-sourced wave-influenced deltaic lithofacies associations across the Church Stretton Fault Zone in the region between Cae'r mynach and Llanstephan requires comment. Their current relationship appears difficult to explain by any passive sedimentological model and the suspicion is that it has been brought about by faulting. The WBFS has long been recognized as long-lived fracture belt that, at depth, may correspond to a significant terrane boundary in basement rocks (Woodcock & Gibbons, 1988). Woodcock (1984) has provided evidence of post-depositional, dextral, strike-slip displacements affecting Ordovician rocks within the WBFS, and Hillier & Williams (2004) speculated that Silurian intra-shelf basins were linked to dextral displacements along NE–SW trending faults. The distribution of early Pridoli lithofacies suggests that similar, post-depositional, right-lateral movements also account for the current proximity of deltaic facies produced by different processes along parts of the Church Stretton Fault Zone. For a plausible distribution of facies belts to be achieved, restoration of a displacement in excess of 10 km appears required.

The styles of deformation imposed on the rocks of Wales during the 'Acadian Orogeny' are widely acknowledged to reflect the impacts of sinistral transpression (e.g. Woodcock, 2012a; Woodcock *et al.* 1988). Therefore, any dextral offset of Ludfordian facies belts along the Church Stretton Fault Zone must have been achieved before and/or after this deformation. Woodcock (2012a) suggests that the driving influence on the tectonic development of the southern UK during the Early Devonian was a sinistral Caledonian strike-slip regime. In offering an alternative explanation, Rheic back-arc extension also provides a plausible mechanism to generate dextral displacements on the fundamental NE-SW fracture belts that traverse Wales. However, such early displacements would need to survive a predicted 'Acadian' reversal. Wilson *et al.* (1988) recognize a comparable dextral displacement affecting Early Carboniferous rocks in South Wales along the similarly orientated Severn Estuary Fault Zone. They suggest that intra-Carboniferous movements on NE-SW-orientated faults may have occurred widely throughout Wales. Again, such dextral offsets may have been negated by the sinistral activity that accompanied the Late Carboniferous climax of the Variscan Orogeny (Corfield *et al.* 1996; Davies *et al.* 2014). It is clear that the juxtaposition of Ludfordian lithofacies seen along the Church Stretton Fault Zone, if indeed the consequence of faulting, is the residual effect of several phases of movement, but the principal of which can all be viewed as Variscan in affinity.

7. Conclusions

- New biostratigraphical and sedimentological analysis of facies that span the Ludlow–Pridoli transition from marine to continental deposition in Wales and its borderlands have enabled the establishment of an event framework that underpin a radical reappraisal of the regional stratigraphy and nomenclature. The long-standing terminology used for Ludfordian and Pridoli strata in the Type Ludlow area and throughout the Welsh Borderland is abandoned. The CarF is adopted as ubiquitous for the shallow marine Ludfordian and earliest Pridoli facies of the region.
- The described sedimentary lithofacies record deposition in a range of offshore marine, deltaic, back-barrier and continental coastal plain settings and permit recognition of wave, fluvial and tidally influenced lithofacies associations. Data on sediment provenance is reviewed. Material derived from distant Caledonian uplands increased in importance throughout the Ludfordian, but local sediment sources remained periodically active and may be reflected in the supply of biotite to south-easterly settings.
- The change in sediment provenance, from southerly to northerly, first occurred in late Gorstian rocks and followed the abandonment of the former Early Palaeozoic Welsh Basin as a site of active marine deposition. The thickest Ludfordian successions of the region accumulated in an area – the Clun Forest Sub-Basin – previously occupied by the basin bounding WBFS. Sediment supply to this sub-basin remained from the south and offers evidence of a still extant southern source area.
- Thinner, multi-sourced Ludfordian shallow-water successions characterize the area that flanked the sub-basin in south-west Wales and to the east, on the Midland Platform. A latest Bringewoodian (Gorstian) to earliest Leintwardinian (Ludfordian) deepening event led to an expansion of marine conditions in these regions and the establishment of the storm-influenced Cae'r mynach Seaway. The Whitcliffian abandonment of the Clun Forest Sub-Basin saw the shallower facies of this seaway achieve their maximum extent; the coincident demise of a southern source area likely also permitted the establishment of more direct links to the Rheic Ocean.
- In south-west Wales, the Golden Grove Axis acted as a fault-bounded structural hinge that served to separate the Cae'r mynach Seaway from an extensive piedmont surface to the west. Contemporaneous uplift was evident on the Midland Platform where the earliest Leintwardinan (Ludfordian) was a time of widespread omission, most noticeably along the Gorsley Axis.
- West of the Golden Grove Axis, Ludfordian colluvium deposition (AF) above the pediment surface records the onset of continental facies accumulation. Behind migrating delta coastlines, the green muds that accumulated on coastal plains with elevated water tables (TemF) and the better drained alluvial red beds (MCF) that succeeded them chart the expansion of ORS continental conditions.

- Ludfordian and early Pridoli delta progradation into the Cae'r mynach Seaway resulted in widespread micaceous sandstone deposition. This is recorded in the north-east of the study area as the DCSF and in the west as the TilF.
- The TilF comprises four separate river-influenced delta prograde events supplied from the north-west (TilF 1-4). TilF 1 and TilF 2 both prograded during the Leintwardinian. New microfossil discoveries confirm that diagnostic Leintwardinian shelly taxa were locally excluded from pro-delta CarF settings during the TilF 2 advance. The TilF 3 advance is thought to have extended into the the Whitcliffian, and Til 4 is believed confined to the early Pridoli.
- Only close to its western limits astride the Golden Grove Axis, where the sandstones of TilF1 rest directly on mid Gorstian rocks (Mynydd Mydffai Sandstone Formation), is the formation's base recognizably unconformable. The preserved outcrop pattern of TilF progrades seen to the north-east describes the progressive lateral expansion of the north-westerly sourced delta system.
- The DCSF – pending reconfirmation of the findings of Loydell and Frýda (2011) – is recognized as an earliest Pridoli, predominantly wave-influenced deltaic sandstone body preserved principally to the north of the Neath Disturbance and, arguably, in the vicinity of the Malvern Axis. It was sourced from the north-east. Steep delta-front clinoforms, mouth bar and distributary channel deposits locate points of fluvial supply in its western reaches. The Aston Munslow Member provides evidence of an earlier, late Whitcliffian advance of the DCSF delta system into the Ludlow area.
- Both the LBBM and Platyschisma Shales Member of the Ludlow area succession are here included within the CarF. The previous recognition of strata as DCSF on BGS digital maps of the Woolhope, Mayhill and Usk areas is considered incorrect. Some of these units are not sandstone-dominated, and their stratigraphical relationships do not compare. The DCSF is considered coeval only to the youngest TilF prograde (TilF 4). Current outcrops may reflect a faulted juxtaposion of these separate deltaic successions. Nevertheless it appears likely that, at their point of maximum advance the two systems merged to form a continuous multi-sourced deltaic shoreline.
- The impacts of an early Pridoli depositional hiatus are recorded as a significant non-sequence that preceded deposition of the more northerly and easterly TemF successions. Stuctural inversion and an associated forced regression promoted widespread subaerial exposure to the north of the Neath Disturbance, with evidence of pedogenic calcrete both at the top of the DCSF and the youngest TilF. The effects of local scour and channel incision affecting both sandbodies at this level are seen along tracts close to the Church Stretton Fault Zone.
- Associated regressive marine erosion south the Neath Disturbance generated a bone-bearing phosphatic pebble lag deposit no longer believed to correlate with the LBB. Here, forced regression led to a westward and southward shift in the active delta depocentre. Ensuing subsidence in the Woolhope and May Hill areas promoted accumulation of an extensive, tidally influenced succession (RF) and of a barrier sandbody (CMSF) representing a marine reworked delta front. In the May Hill inlier, the Gorsley Axis acted first as a seeding point for the barrier and later as a site that anchored the aggradation. The newly named PMF records the easterly advance of coeval purple coastal facies that formed on the western side of the remnant Cae'r mynach Seaway.
- Contemporaneous tidally influenced deposits infilled incised channels along tracts close to the Church Stretton Fault Zone.
- New dating of the tidally influenced PALF reveals its likely preservation within an incised valley system comparable to that hosting the FEF of south Pembrokeshire and cut during the same mid-Pridoli episode of denudation.
- Thickness variations, patterns of erosion and the distribution of deltaic parasequences record the evolving impact of regional and local tectonism notably associated with the Church Stretton Fault Zone but also with fracture lines present with the Midland Platform to the east.
- The transtensional regime that had allowed accommodation of the Caledonian detritus supplied to Wales and its borderlands from late Gorstian to Early Devonian times, as well as the subsequent deformation and displacement of these deposits, provide a record of events that were not, as long supposed, part of the Caledonian orogenic cycle, but more probably a response to proto-Variscan plate (Acadian) tectonics.

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