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# Gauging the impact of glacioeustasy on a mid-latitude early Silurian basin margin, mid Wales, UK

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## Abstract

The early Silurian (Llandovery) Gondwanan South Polar ice sheet experienced episodes of ice retreat and re-advance. Marine base level curves constructed for the interval are widely assumed to provide a record of the associated glacioeustasy. In revealing a series of progradational sequences (progrades) bounded by flooding surfaces, recent work on the Type Llandovery succession in mid Wales (UK) has provided an opportunity to test this hypothesis. The grouping of these progrades into three composite sequences underpins the construction of both low order (small amplitude, high frequency) and high order (large amplitude, low frequency) base level movement curves. Revised biostratigraphical datasets for the type succession permit the accurate dating of base level events. The composite sequences record progradational acmes in the *acinaces*, lower *convolutus* and upper

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*sedgwickii-halli* graptolite biozones. A series of transgressions that postdate the Hirnantian glacial maximum culminated in an upper *persculptus* Biozone high-stand. Maximum flooding events also occurred during the *revolutus* and lower *sedgwickii* biozones, and the base of the early Telychian *guerichi* Biozone also marked the onset of a pronounced deepening.

A review of 62 published datasets, including global and other regional base level curves, records of glacial activity, isotope data, patterns of facies and faunal flux and putative climate models, permits an evaluation of the origins of these local base level events. The concept of a Eustasy Index is introduced and shows that the impacts of global sea level movements can only be demonstrated within narrow 'eustatic windows' coincident with times of ice sheet collapse. At other times, the geometry of Llandovery area progrades reflects their accumulation across a faulted basin margin where, during periods of slow ice sheet advance, epeirogenic processes outstripped sea level movements as the dominant forcing factors. Increased levels of Telychian subsidence at first enhanced and then outstripped the influence of glacioeustasy as part of the region's response to the north European Scandian deformation.

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KEY WORDS: Llandovery, Silurian, glacioeustasy, Eustasy Index, sequence stratigraphy, biostratigraphy, epeirogenesis

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## 1 Introduction

Recent studies have shown that, following its maximum in the Late Ordovician (Hirnantian), the early Silurian retreat of the Gondwana-based South Polar ice sheet was punctuated by separate episodes of ice re-advance (e.g. Grahn and Caputo, 1992; Caputo, 1998; Dias-Martinez and Grahn, 2007). Glacioeustasy has been widely cited as significant in shaping Llandovery age successions around the world, including the Type Llandovery succession in mid Wales, UK (e.g. McKerrow, 1979; Johnson *et al*., 1991b), and in influencing the form of Silurian sea level curves (e.g. Haq and Schutter, 2008; Johnson 2010; Munnecke *et al*., 2010). Remapping and extensive biostratigraphical resampling in the Llandovery area have allowed a new sedimentary architecture to be erected and the positions of key biozonal boundaries to be revised (Figs 2–5) (Davies *et al*., 2013). Graptolite discoveries coupled to new microfossil analyses underpin major changes to the biozonal cross-correlations put forward by Cocks *et al*. (1984) that have informed global Llandovery analysis for over a generation. In allowing more precise comparisons with other regional datasets, these revisions have permitted a critical evaluation of the influence of glacioeustasy on the type succession.

Deposition of the Type Llandovery succession took place in a ramp-like setting located along the SE margin of the ensialic Lower Palaeozoic Welsh Basin, in mid-southern palaeolatitudes (Cherns *et al*., 2006; Woodcock and Strachan, 2012). Though traditionally recognised as forming part of the Eastern Avalonia microcraton, Waldron *et al*. (2011) suggest that the Welsh Basin has more complex crustal foundations. However, the term ‘Avalonian’ remains relevant in the biopalaeogeographical sense of Cocks and Fortey (1990) and as a label for a

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group of loosely associated crustal terranes, the ‘Anglo-Acadian belt’ of Cocks and Fortey (1982), that lay to the south of the contemporary Iapetus Ocean (Fig. 1). Docking of these ‘Avalonian’ terranes with the more easterly craton of Baltica took place along the northern European Tornquist Zone, and is recorded in Wales by the late Katian (mid Ashgill) ‘Shelvian’ deformation (Toghill, 1992). By Llandovery times, these once separate crustal elements formed part of a unified tectonic plate and faunal province (e.g. Cocks and Fortey, 1990). Early Llandovery closure of the northern sector of the Iapetus Ocean initiated the Scandian Orogeny in Baltica (e.g. Ladenberger *et al.*, 2012) at the same time as the late stages of the Taconic and Salinic tectonic episodes were being felt in North America (e.g. Ettensohn and Brett, 1998). Hence, tectonism was ongoing during the Llandovery throughout the circum-Iapetus realm where, within migrating foreland basins and faulted-bounded depocentres, evolving patterns of subsidence competed with eustasy in the shaping of sedimentary successions (e.g. Baarli *et al*., 2003).

Nowhere is this more evident than in the Type Llandovery area, where active basin-bounding faults accommodated the subsidence of the basin to the west and uplift of source areas to the east (Davies *et al*., 2013). Notwithstanding this tectonic backdrop, early Hirnantian facies at Llandovery and throughout the Welsh Basin, as elsewhere, record the impact of Late Ordovician glacioeustasy (e.g. Davies *et al*., 2009). Preserved in distal settings are strata that were deposited during the maximum drawdown in sea level, whereas an unconformity records the coincident emergence and deep erosion of proximal regions. Late Hirnantian units record the pulsed transgression that post-dated the glacial maximum, and the resulting re-ventilation and faunal re-stocking of the Welsh Basin and its marginal shelf. The current study seeks to evaluate the role that eustasy, specifically glacioeustasy, went on to play in the shaping of the succeeding Type Llandovery succession.

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Telychian and lower Wenlock rocks at Llandovery provide a record of deep and distal shelfal sedimentation and of increased subsidence and disruption by synsedimentary slides. Coincidental increases in the volume and grade of sediment supplied to the Welsh Basin, sourced from new quadrants and accommodated by active faulting, confirm that the late Llandovery to early Wenlock was a time when regional tectonism was resurgent throughout Wales (e.g. Woodcock *et al*., 1996; Davies *et al*., 1997). However, preceding Rhuddanian and Aeronian rocks comprise a cyclical succession of variably bioturbated and fossiliferous sandstones, sandy mudstones and mudstones that has proved better suited for eustatic analysis. It is these strata, viewed in the context of a clinoform facies model (see Davies *et al*., 2013), on which this study principally focuses (Figs 3, 6).

The parameters used to establish the base level history of the Llandovery area (Sections 3, 4) allow comparison with global syntheses of Silurian sea level change and other regional base level datasets (Fig. 1) that sample tectonic settings ranging from cratonic interiors and passive margins to deep oceans and orogenic belts (Sections 5, 6). They also enable comparison with datasets that, by charting the distribution of glacial facies, changing isotope ratios and faunal flux, purport to chronicle sea level-linked climatic events (Section 7). A novel method of assessing the levels of correspondence between these varied datasets and the record of base level movements in the Type Llandovery area is developed (Section 8).

## 2 Implications of revised biostratigraphical correlations

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The revised cross-correlation of the various macro- and microfossil biozonal schemes applicable to the Type Llandovery area is presented in Figure 5. This forms the basis for the nomenclature and calibration applied throughout the paper. The graptolite biozonal scheme is that developed by Zalasiewicz *et al*. (2009) for the UK Silurian, with wider comparisons based on Loydell's (2011) review of other regional schemes. Further information on relevant aspects of Welsh and global Llandovery biostratigraphy, and on the sources used to compile Figure 5, are provided as Supplementary Data.

Davies *et al*.'s (2013) re-examination of the type succession, and of the Aeronian and Telychian stage GSSPs that it hosts, has important implications for international correlation. Rhuddanian rocks in the type succession range into the *triangulatus* graptolite Biozone, and earliest Telychian rocks pre-date the local FAD of *guerichi* Biozone graptolites. However, to avoid confusion and facilitate global comparisons, the bases of the Aeronian and Telychian stages herein follow the graptolitic definitions of current international usage (i.e. base *triangulatus* Biozone = base Aeronian; base *guerichi* Biozone = base Telychian). The consequences of applying this to the type succession are shown in Figure 5. Moreover, where stage recognition is based on the appearances of key brachiopod taxa, which is true of many non-graptolitic successions in Europe and North America, it is now likely that the regional stage boundaries correlate with neither the Type Llandovery GSSPs nor the graptolite zonal boundaries on which they are based (see Davies *et al*., 2013).

Similarly, correlations based on the A1-4, B1-3 and C1-6 quasi-chronozonal scheme erected in the Llandovery area by Jones (1925), which have been widely adopted as the standard means for subdividing Llandovery strata both in the UK (e.g. Williams,1951; Zeigler,1966; Zeigler *et al*., 1968b; Cocks *et al*., 1970; Cocks *et al*., 1984) and internationally (e.g. Berry

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and Boucot, 1970; Johnson *et al*., 1985; Brett *et al*., 1998), should no longer be relied upon without reference to the primary dating criteria.

## 3 A sequence stratigraphy for the Type Llandovery area

The event stratigraphy of uppermost Hirnantian strata in the Llandovery area has been assessed by Davies *et al*. (2009). The overlying Rhuddanian to Aeronian facies comprise a series of progradational sequences (progrades) bounded by flooding surfaces and correlative unconformities. Such sequences represent transgressive-regressive (T-R) cycles in the sense of Embry and Johannessen (1992; also Catuneanu *et al*., 2011) and 'depositional sequences' as defined by Embry *et al*. (2007; Embry, 2009). Lateral and vertical changes in lithology and biota, including trace fossil assemblages, record the repeated basinward migration of shallower, intensely bioturbated, sandy foreset facies across their deeper, more distal and muddy bottomset counterparts (Davies *et al*., 2013) (Fig. 3). The reduced levels of bioturbation displayed by bottomset facies and a trace fossil assemblage dominated by *Chondrites* are consistent with deposition at depths that lay beyond the colonising reach of contemporary shelly benthos. In contrast, foreset facies belts were home to a diverse and abundant assemblage of soft-bodied, burrowing organisms that lived alongside *Stricklandia* and deeper *Clorinda* community shelly benthic assemblages (e.g. Ziegler *et al*., 1968a). Topset facies were anchored to an active and erosion-prone fault footwall region, but their characteristic *Pentamerus* Community assemblages (Plate 1) extended into upper foreset settings where they serve to identify periods of maximum shallowing (Fig. 6). It is of note that, whereas appearances of *Stricklandia* and *Pentamerus* community assemblages in cratonic interior successions are normally viewed as evidence of off-shore deposition and

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deepening (e.g. Witzke, 1992), in the basin margin setting at Llandovery they are associated with peak shoaling episodes. Truncation surfaces are present locally at the top of each prograde. Shoreline ravinement (e.g. Embry, 2009) may have contributed to the development of these surfaces, but where they merge to form the compound unconformities that characterise condensed proximal successions (Figs 3, 4) subaerial denudation was likely to have been the dominant erosive process.

Ten flooding surfaces define nine (low order) prograde sequences that span the late Hirnantian to Aeronian interval, the tenth and youngest of these flooding surfaces marking the redefined local base of the *guerichi* Biozone and Telychian Stage (Figs 4, 6). Davies *et al*. (2013) labelled these progrades according to their dominant sandstone unit (e.g. Ceg$^{0}$, Ceg$^{l}$, Ceg$^{11}$, etc) (Fig. 4). Differences in the scale, duration (as measured by graptolite biozones) and basinward reach of the progades, as well as the lateral extent and vertical impact of erosion, allow these to be grouped into three compound (or high order) sequences according to the criteria established by Embry (1995) and Schlager (2004) (also Catuneanu *et al*., 2011; Embry, 2009) (Figs 4, 6). In addition, many of the progrades comprise a succession of smaller scale parasequences. Local FADs and/or LADs of key taxa permit these newly recognised sequences to be dated using a range of biozonal criteria, with many FADs linked to flooding events (Davies *et al*., 2013). Radiometric dates available for the Llandovery Series suggest that the study interval spanned c. 6 myr (Cooper and Sadler, 2012; Melchin *et al*., 2012) and, hence, that the average duration of the prograde sequences recognised in the Llandovery area was well under 1 myr.

## 4 Relative marine base level movements

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Facies and faunal variations within each sequence and compound sequence allow the construction of both low and high order relative marine base level movement curves (e.g. Embry, 2009; see also Section 6b) for the upper Hirnantian to lower Telychian succession (Fig. 6). These differ significantly from those compiled by McKerrow (1979) and Cocks *et al*. (2003). In the first instance, such curves plot the relative changes in depositional depth that occurred at any given location through time. However, each Llandovery area prograde appears to have been accompanied by the progressive erosion of its proximal portions, with the depth of erosion increasing in a landward direction. This suggests that these progrades do not simply record the cyclical infilling of accommodation space created by subsidence beneath a static or slowly rising base level, but periods when base level fell. It implies they were the product, at least in part, of forced regressions (e.g. Posamentier *et al*., 1992; Hunt and Gawthorpe, 2000). The deeper, more distal facies that closely overlie flooding surfaces provide a record of deposition during periods of rising and elevated relative base level within transgressive and high-stand system tracts. In contrast, each transition into shallower, more proximal facies signalled the onset of deposition within regressive/falling stage followed by low-stand system tracts (e.g. Catuneanu *et al*., 2011).

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Compiled from data beyond the limits of erosion, Figure 6 identifies the main Llandovery area base level events. The numbers used on this figure to identify sequence-defining flooding surfaces and the letters for periods of maximum flooding and shallowing are those cited throughout the remainder of the text. The first post-glacial maximum flooding surface (1), present in rocks barren of graptolites, underlies the first appearance in Wales of *taugourdeaui* Biozone chitinozoans (see Fig 5 [12, 20]). A second flooding level (2) coincides with the FAD of *persculptus* Biozone graptolites in Wales, but which is now

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thought to be later than elsewhere (see Vandenbroucke *et al*. 2008; Davies *et al*., 2013; Challands *et al*. 2014; and Supplementary Data). A third intra-Hirnantian event (3) is succeeded by Llandovery flooding surfaces that coincide with the local FADs of *revolutus* (4), *magnus* (6), middle and upper *convolutus* (7, 8) and lower *sedgwickii* (9) graptolite biozone assemblages. A further intra-*revolutus* Biozone event (5) is also recognised. The higher order base level curve points to maximum deepening events during the deposition of the upper *persculptus, revolutus* and lower *sedgwickii* Biozones (A – C). A marked flooding event that coincides with the local FAD of *guerichi* Biozone graptolites (10) is seen on both the high and low order datasets.

To facilitate the wider correlation of these events, it is important also to place them in the context of the revised ranges for the key brachiopod lineages and microfossil assemblages used in Llandovery correlation (Fig. 5). Thus, flooding events 1 and 2 lie within the range of the Hirnantia Fauna (Davies *et al*., 2009) and event 3 is closely related to the first appearance of primitive forms of *Stricklandia lens*. Event 4 coincides with the FAD of the more evolved *S. lens intermedia* alongside *eoplanktonica* Biozone acritarchs. Flooding events 5 and 6 also fall within the range of *S. lens intermedia*, event 5 marking the appearance of *maennili* Biozone chitinozoans, and event 6 of a precursor of the chitinozoan *Eisenackitina dolioliformis* within the range of *tenuis* Biozone conodonts. The intra-*convolutus* Biozone transition between *S. lens intermedia* and *S. lens progressa*, well documented in the Welsh Borderland (Cocks and Rickards, 1968; Zeigler *et al*., 1968b), appears related to event 7, which also marks the entry of *microcladum* Biozone acritarchs. Fully evolved forms of *S. lens progressa* are first recorded above flooding level 8, coincident with the local FADs of *estillis* Biozone acritarchs and *dolioliformis* Biozone chitinozoans. The earliest records of *Eocoelia hemispherica* at Llandovery are also from above this flooding surface, though the

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species is believed to first appear in the *leptotheca* graptolite Biozone (e.g. Cocks *et al*., 1984; Bassett, 1989). Event 9 marks the entry of the more highly evolved *E. intermedia* alongside *S. laevis*, yet specimens from above this level identified as *E. hemispherica* and *S. lens progressa* (Williams, 1951; Cocks *et al*., 1984) confirm an interval of overlapping ranges within the lower parts of the *sedgwickii* graptolite Biozone and the *staurognathoides* conodont Biozone. The records of *E. curtisi* at Llandovery are from a slump deposit (Davies *et al*., 2010, 2011), but this more evolved taxon has elsewhere also been shown to have its FAD in rocks of *sedgwickii* Biozone age (Doyle *et al*., 1991). No in situ shelly assemblages have been recognised closely overlying event 10 at Llandovery. However, data from elsewhere appear to confirm that only *S. laevis* and *E. curtisi* survive into and beyond the *guerichi* Biozone (Bassett, 1989), within which *encantador* Biozone acritarchs first appear (Davies *et al*., 2013)

The fault-generated uplift and deep erosion of proximal parts of the succession preclude the construction of an onlap curve (e.g. Haq and Schutter, 2008). However, the lateral extent of each of the main progrades provides an arbitrary measure of the basinward shift of facies belts associated with each relative lowering of base level (Fig. 6). The three composite sequences reached their progradational acmes (D, E and F) during the *acinaces*, lower *convolutus* and upper *sedgwickii-halli* graptolite biozones. Significant lower order progradations occurred during the *revolutus*, *triangulatus* and in the middle and upper *convolutus* biozones.

Was the forcing mechanism for these Llandovery area progrades regional isostasy, tectonism, or global eustasy and, if the latter, was this glacioeustasy, and did these factors operate in concert or separately at different times? Regional base level movement curves differ

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conceptually from true sea level movement curves (e.g. Grabau, 1940; Artyushkov and Chekhovich, 2001; Miall, 2004). The latter seek to provide a record of changes in sea level elevation through geological time relative to a fixed global datum, nominally taken to be modern sea level (e.g. Vail *et al*., 1977; Haq and Schutter, 2008). Such changes, if properly identified, must be eustatic (i.e. of global reach), even though their impacts might be rendered unrecognisable by local isostatic and/or tectonic effects. In reality, local and regional variations in rates of subsidence, source area uplift and sediment supply, all of which are linked to ambient epeirogenesis, must play a role in fashioning the detailed shape of such curves (e.g. Artyushkov and Chekhovich, 2001, 2003; Zhang *et al*., 2006) and can be the dominant factors, as during the Telychian in Wales (e.g. Schofield *et al*., 2009). These same factors make it unlikely that the base level history and hierarchy recognised in one area will be fully replicated in another.

When seeking to discern whether regional base level movements record a global (eustatic) signal, it is therefore gross trends, major flooding surfaces and peak events that offer the best potential for testing. For this reason, the Llandovery area base level history depicted on Figures 7 to 14 is divided into broad intervals of deepening and elevated base level (coloured blue) and of shallowing and lowered base level (coloured red) rather than simply into transgressive and regressive components. Parasequence-scale movements (Fig. 6) have been ignored. Where the boundaries between these sectors coincide with flooding surfaces, their location is precise, but where they are located on the regressive portions of the curves their placement is more arbitrary. Nevertheless, in providing a single template for comparison, this approach emerges as a practical means of gauging the broad similarities and differences displayed by a range of datasets (see Section 8).

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## 5 Regional and UK comparisons (Fig. 7)

Comparisons with other successions appear to confirm that many of the late Hirnantian-early Telychian base level events recognised in the type area occur widely throughout the UK (Fig. 7). To the east of Llandovery, in a palaeo-landward direction, the coeval rocks of the Welsh Borderland, notably in the Church Stretton area, testify to the pulsed transgression of a dissected topography (Johnson *et al*., 1998). Rhuddanian rocks were either largely excluded or subsequently eroded from much of this region. The work of Zeigler *et al*. (1968b; also Cocks and Rickards, 1968), reinterpreted in the light of the Type Llandovery findings, point to an initial inundation of more deeply incised settings around the Rhuddanian-Aeronian boundary (B), with evidence for subsequent pre- and intra-*convolutus* Biozone flooding episodes (6 and 7). Transgressive *Pentamerus*-bearing sandstones of *sedgwickii* Biozone age bear testimony to a more extensive inundation (9 and C), and the subsequent deepening that widely introduced *Clorinda* Community benthic assemblages can be matched to the *guerichi* Biozone flooding event at Llandovery (10).

Further west, in the contiguous, graptolitic, deep water Welsh Basin succession, many of the events documented in the type area are mirrored by the alternation of oxic and anoxic mudstones facies and by evolving patterns of coarse clastic deposition (e.g. Woodcock *et al*., 1996; Davies *et al*., 1997; Schofield *et al*., 2009) (Fig. 7). Periods of falling base level are argued to have promoted the better mixing of surface and deep water layers. The introduction of oxygenated waters then allowed a burrowing fauna to colonise the basin floor (e.g. Page *et al*., 2007; Challands *et al*., 2008). The resulting mudstone facies are, accordingly, strongly burrow-mottled. The coincident rejuvenation of sediment source areas and increased clastic

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input is recorded by the expansion and migration of sand-dominated turbidite lobes locally present on the basin floor (e.g. Cave and Hains, 1986; Davies and Waters, 1995). In contrast, episodes of rising base level have been linked to the establishment of a strongly stratified basin water column, the imposition of anoxic (anaerobic) bottom waters and, due to the exclusion of burrowing organisms, the accumulation of laminated, organic-rich mudstones (e.g. Leggett, 1978). The coeval drowning of source areas and the decline in sediment supply is reflected in the synchronous contraction of the basin’s deep water sandy systems (e.g. Schofield *et al*., 2009).

This level of linkage between the successions of the Welsh Basin and its contiguous margin is to be expected. Closely comparable oxic/anoxic alternations are recognised in Llandovery successions that also formed along the southern seaboard of Iapetus at Llanystumdwy and Conway (North Wales) and in the English Lake District (e.g. Baker, 1981; Rickards and Woodcock, 2005) (Fig. 2). Their presence in the Llandovery succession at Dob’s Linn in the Scottish Southern Uplands is more telling. There, in Aeronian strata, units that are barren of graptolites, with quasi-oxic mudstone beds, alternate with richly graptolitic, anoxic intervals (Toghill, 1968) in a pattern that can be matched to that in the Welsh Basin (Baker, 1981; Loydell, 1998; Page *et al*., 2007) and, by extrapolation, to many Type Llandovery events. This is significant since the succession in Scotland has been interpreted as an accretionary prism of Iapetus ocean floor sediments accreted during subduction along the southern edge of Laurentia (e.g. Leggett *et al*., 1979; Woodcock and Strachan, 2012; but see Stone *et al*., 1987). Hence, it offers evidence that many of the base level events recognised in the Llandovery area can be linked to changes in sea water chemistry that affected both intra-cratonic and oceanic settings alike. Only in the mid Rhuddanian do these successions fail to provide clear evidence of correlatable changes in facies and base level.

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## 6 Llandovery eustasy

Whether it is feasible to discern a eustatic signal in ancient sedimentary successions is widely questioned by those who argue that the ‘noise’ of regional factors is always likely to ‘drown out’ the impacts of all but the largest and most rapid global sea level movements (e.g. Miall, 2010) (see Section 8). Those who have published on Silurian eustasy take care to acknowledge and to counter such concerns (e.g. Witzke, 1992; Johnson, 2010). They point to facies, faunal and, increasingly, isotopic shifts that can be linked to changes in bathymetry, and appear to be widely correlatable, as evidence of global movements in marine base level. Johnson *et al*. (1991b) labelled this empirical approach the pursuit of ‘practical eustasy’ and, utilising regional datasets, many have since attempted to construct curves that purport to chart changing Silurian sea levels (Fig. 8).

The varied methods used in the construction of Silurian sea level curves and the concepts that underpin them have been reviewed by Johnson (2006, 2010). In shallow shelfal settings, systematic changes in brachiopod (e.g. Johnson, 1987, 1996 and *et al*., 1991a) and conodont (e.g. Zhang and Barnes, 2002b) benthic assemblages have proved effective in identifying gross trends and peak events, despite the misgivings of some (e.g. Aldridge *et al*., 1993; Loydell, 1998). Johnson *et al*. (1985; also Rong *et al*., 1984) suggest that variations in graptolite diversity may similarly reveal the impact of sea level changes in otherwise uniform deep water mudstones. Linked changes in lithofacies and biofacies have been used in both shallow water carbonate (e.g. Witzke, 1992; Copper and Long, 1998) and siliciclastic successions (e.g. Brett *et al*., 1998; Melchin and Holmden, 2006), and, in a variant of this

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approach, Baarli (1988, 1998; also Baarli *et al*. 1992) and Long (2007) chart changes in the frequency and thickness of storm beds (tempestites). Johnson *et al*. (1998) gauged the onlap of palaeotopography. Many of these studies deliberately target the successions of cratonic interiors on the assumption that tectonically stable regions are those most likely to preserve the imprint of eustatic events (e.g. Johnson *et al*., 1991b). Evidence of regional epeirogenesis within and along the margins of intra-cratonic basins in which many of the most extensively studied Llandovery successions accumulated tells a different story (e.g. Artyushkov and Chekhovich, 2001, 2003; Baarli *et al*., 2003; Davies *et al*., 1997).

The ‘graptolitic approach’ of Loydell (1998) benefits from the precise dating achievable for graptolite-bearing intervals, which, when shown to be widely correlatable, are argued to record global flooding events and, as a consequence, widespread anoxia (e.g. Leggett, 1980; Davies *et al*., 1997; see Section 5). Other explanations for anoxic events, however, such as basin restriction and/or locally elevated levels of organic productivity, suggest that the link between widespread anoxia and eustasy may be more complex (e.g. Challands *et al*., 2008). This is illustrated in recent studies documenting redox control on faunal (Vandenbroucke *et al.*, 2015) and facies variations (McLaughlin *et al*., 2012) that have previously been used to infer changes in Silurian sea level. Regional sequence analysis, used in tandem with these other methods, is widely seen as a prerequisite to curve construction (e.g. Harris *et al*., 1998; Brett *et al*., 1998 and 2009; Haq and Schutter, 2008) and is the approach adopted here.

### 6.1 Methodology

This study replicates the approach applied to North American datasets by Johnson (1987) and first attempted on a global scale by McKerrow (1979), prior to the influential studies of Johnson *et al*. (1991b), Johnson and McKerrow (1991) and Johnson (1996). Figures 8 to 12

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present a range of published curves that purport to chart either regional or global movements in late Hirnantian to early Telychian marine base level. Many of their authors label them ‘sea level curves’. These are compared with the base level trends and events recognised at Llandovery in an effort to gauge the levels of similarity. The implicit assumption is that trends and events that can be shown to be widely correlatable are those most likely to be eustatic (see Section 8).

For many regions, more than one curve is included. This reflects the availability of datasets compiled using different methods to gauge bathymetry. Some of these reveal a coincidence of trends and events, as for example on Anticosti Island (e.g. Zhang and Barnes, 2002b; Long, 2007). However, intra-regional curves that display marked differences and may reveal the impacts of local tectonism and/or isostasy, notably in Siberia and on the Yangtze Platform of China (e.g. Johnson *et al*., 1985; Yolkin *et al*., 2003), are also utilized for purposes of objectivity. Other Llandovery datasets (Figs 13, 14) argued to provide a proxy record of sea level change, based on physical evidence of glacial advance and retreat and the flux of stable isotope ratios, faunas and ocean states are assessed in Section 7.

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### 6.2 Curve construction and alignment

Given the current paucity of radiometric dates and stable isotope profiles, the correlation of many Llandovery successions necessarily remains reliant on biostratigraphical methods. To facilitate this, all the curves presented in Figures 8 to 13 have been recalibrated to align with the UK Llandovery graptolite biozonation (Fig 5), and this has required the vertical warping of many. In recalibrating each curve, the dating criteria provided by their authors have largely been relied upon. The justification for any amendments is provided via the numbered references [in square brackets] to Supplementary Data. The use of FADs and LADs has been

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a common theme in such re-evaluations and brings the virtue of consistency to the datasets. Nevertheless, the roles of facies control, provincialism, diachronous and divergent patterns of dispersal and cryptic omission, as well as collecting bias, all introduce uncertainty (e.g. Zalasiewicz *et al*., 2009;; Miall, 2004). Sadler (2004; also Sadler *et al*., 2009) shows that FAD and LAD-based biozonal boundaries when correlated on a global scale can rarely be viewed as truly isochronous and Cramer *et al*. (2015) suggest that, by using multiple high resolution datasets, it may soon be possible evaluate these levels of uncertainty. As it is, Silurian chronostratigraphy remains predicated on the assumption that such uncertainties fall within geologically acceptable limits (e.g. Cramer *et al*., 2011a; Melchin *et al*., 2012) and, as Witzke (1992) argues, that in the pursuit of ‘practical eustasy’, “parallel changes in relative sea level coincident with biozonal boundaries are most reasonably interpreted as synchronous.”

The horizontal axes of the curves are as used by their authors and reflect the different criteria they employed for calibration. Very few claim to chart changes in absolute bathymetric value, those of Ross and Ross (1996), Johnson *et al*. (1998), Artyushkov and Chekhovich (2001) and Haq and Schutter (2008) being notable exceptions. This use of varied criteria emphasises the need, when seeking to identify correlatable events, to focus on abrupt changes and gross trends rather than to compare precise profiles.

Before drawing conclusions from curve comparisons it is also important to consider the relative orders of movement and the relationships between the events that such curves portray. That different orders of sea level movement, superimposed upon one another, can be discerned in the stratigraphical record and that these record not just differences in vertical scale and duration, but ultimately in causative mechanism is a concept that has evolved (e.g.

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Vail *et al*., 1977; Duval *et al*., 1992; Embry, 1995; Schlager, 2004; Miller *et al*., 2005). Catuneanu *et al*. (2011) point to inconsistencies in this approach and highlight the misuse of numerical (1st, 2nd, 3rd, etc) and comparative (high, low) hierarchies. In this account, high order refers to sea level curves that purport to record vertical movements of many 10s or 100s of metres that took place over time periods that can range up to several millions of years. Lower order curves depict more frequent, lower amplitude events. The concept is valuable in enabling different levels of comparison between published datasets and offering a potentially broader insight into the origins of the base level movements recorded, but the distinction is not always straightforward (e.g. Embry, 1995; Schlager, 2004) and can result in the arbitrary inclusion of lower order events on high order curves.

Periods of high order global deepening may be interrupted at the local level by prograde events that record the impact of either low order eustatic regressions and/or local influences on sediment supply and accommodation space. In the same way, low order flooding events can be expected to punctuate episodes of high order global shallowing. The offset between high order, global maxima and regional, lower order oscillations accounts, arguably, for many of the marked discrepancies in the shapes of published curves and the problems encountered when attempting to match events. It follows that modest perturbations on high order curves may reflect the impact of lower order events that, at the local level and in the field, can appear every bit as significant as those associated with high order peaks. Conversely, detailed dating can show that what appears to be a minor event in the field – a mudstone on mudstone contact for example – conceals a more significant base level history, as with the contact between the Lower and Upper Sodus Shale in New York State (Brett *et al*., 1998) (see Supplementary Data). It is against these difficulties that the correlations presented on Figures 8 to 12 should be viewed.

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### 6.3 Analysis: Global sea level curves (Fig. 8)

In Figure 8, a selection of some of the most widely cited global sea level curves for the late Hirnantian to early Telychian interval are compared with the inferred base level movements recognised in the Llandovery area. Informed by the plots of McKerrow (1979), the curve of Johnson et al. (1991b) established what many came to view as the 'standard' for Silurian sea level movements, and the ages it established for key high-stand events remain essentially unmodified in all Johnson's subsequent reviews (1996, 2006, 2010). Yet, from a comparison of some of the most recent and authoritative examples of global sea level curves by Haq and Schutter (2008) and Johnson (2010), it is clear that a consensus is some way off. The suspicion also emerges (see below) that some of the most commonly used curves are over reliant on the data from a single region (e.g. Ross and Ross, 1996) and/or are a conflation of higher and lower order base level events, but are fully representative of neither.

In the first instance it is worth comparing the late Rhuddanian to early Telychian portion of the high order Type Llandovery curve with the same part of many of the other curves. The broad alignment of independently constructed peaks appears to offer support for a global signal within the Type Llandovery data. Several recognise a high order Rhuddanian transgression that peaked in the *revolutus* Biozone (B) (e.g. Ross and Ross, 1996; Page *et al*., 2007) or close to the *revolutus-triangulatus* biozonal boundary (e.g. Johnson, 1996, 2010). Loydell (1998) and Haq and Schutter (2008) delay the culmination of this event until the *magnus* Biozone and it is not inconsistent to suggest that flooding levels 4, 5 and 6 seen at Llandovery were lower order increments that contributed to this global high-stand.

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The lower *sedgwickii* Biozone is also widely seen as a period of elevated sea levels (C). Some see this as the peak of a prolonged deepening episode that spanned much of the preceding *convolutus* Biozone (e.g. Johnson, 2010), and to which lower order events (7, 8, and 9) may again have contributed. Others, by showing it as a pronounced, but short-lived deepening event (e.g. Ross and Ross, 1996), imply a wider significance for the basal *sedgwickii* Biozone flooding surface (9). The late *sedgwickii-halli* biozonal interval is widely recognised as a period of falling sea levels, shown by Johnson (1996), Ross and Ross (1996) and Page *et al*. (2007) to have reached its acme close to the base of the *guerichi* Biozone (F). Loydell's (1998) curve is notably at odds with the majority in its depiction of late Aeronian sea level movements.

Many curves acknowledge the presence of a pre-*sedgwickii* Biozone Aeronian low-stand, but opinions differ as to its scale and timing. Ross and Ross (1996; also Page *et al*., 2007) restrict it to the *convolutus* Biozone. Others, by recognising its peak in the mid Aeronian *leptotheca* Biozone (e.g. Loydell, 1998, 2007; Johnson, 1996, 2010), imply a link with at least part of shoaling episode E. The depiction of a discrete early Aeronian lowering of sea level by Ross and Ross (1996) is replicated in the subsequent curves of Page *et al*. (2007) and Haq and Schutter (2008). It compares with a lower order progradation (Ceg$^0$) seen at Llandovery, but the biostratigraphical dating of this global event is suspect (see Fig. 9 and Supplementary Data). Evidence of other lower order events, including both mid (7) and upper (8) *convolutus* Biozone flooding levels is provided by the curves of Loydell (1998, 2007).

In marked contrast to the Type Llandovery data, most global curves show the early-mid Rhuddanian as a period of steadily rising sea levels. There is no indication of a discrete *persculptus* Biozone deepening maximum (A), or of a subsequent shallowing event on the

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scale seen at Llandovery (D). Ross and Ross (1996) and Page *et al*. (2007) depict what appears to be a low order pre-*revolutus* Biozone regression, but the dating and global credentials of this event are again questionable (see below and Supplementary Data). The marked *guerichi* Biozone deepening at Llandovery (10) appears to show the abrupt termination of the preceding progradation (F) and the rapid onset of deep and distal sedimentation. This is consistent with the onset of regional subsidence (Davies *et al*., 2013) and of a period when contemporary orogenesis became the dominant influence on sedimentation within the Welsh Basin (e.g. Woodcock *et al*., 1996; Davies *et al*., 1997). A broadly coeval event widely recognised in the global datasets suggests that there was a coincidence of local and global forcing mechanisms, although the curves of Haq and Schutter (2008) and Johnson (2010) are inconsistent with this.

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### 6.4 Analysis: Regional curves from circum-Iapetus provinces (Figs 9, 10)

Following the studies of Johnson (e.g. 1979, 1987; Johnson *et al*., 1985; Johnson *et al*., 1991b) and Witzke (1992; Witzke and Bunker, 1996), Johnson (1996) recognised Laurentian-based eastern Iowa as the ‘type district’ for his four Llandovery high-stand events. The adjacent, closely comparable succession in Illinois appears to have influenced Ross and Ross (1996, fig. 2) in the construction of their sea level curve published in the same volume. Thus, the dating and interpretation of these mid USA successions has been critical in the evolution and application of the eustatic concept to the early Silurian in North America and globally. This is significant as the dating of many of the key events recognised in Iowa and Illinois is open to question (see Supplementary Data) and has implications for their wider correlation. Despite this, recalibrated regional curves mainly from Laurentian North America and from Baltica (e.g. Baarli *et al*., 2003) offer insights into the number and scale of lower order base level events in these areas (Figs 9,10).

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The *revolutus* Biozone deepening maximum (B) and the *sedgwickii* Biozone transgression (9), deepening maximum (C) and subsequent progradation (F) appear to be widely recorded in many of the recalibrated Laurentian datasets. A deepening during the *guerichi* Biozone (10) is also acknowledged where rocks of this age have escaped intra-Telychian erosion (Kluessendorf and Mikulic, 1996), as on Anticosti Island and in Arctic Canada (e.g. Zhang and Barnes, 2002b; Melchin and Holmden, 2006). In contrast to the global datasets, several North American curves (Figs 9, 10) suggest the presence of both early and mid Aeronian shallowing events, though, with the exception of the curve for Iowa (Fig. 9, curve 1), few endorse the scale and duration of prograde E seen at Llandovery. In addition to the base *magnus* Biozone transgression (6), multiple flooding events in strata believed to span the *leptotheca* and *convolutus* biozones (e.g. Harris *et al*., 1998; Long, 2007) raise the possibility that flooding surfaces matching those that define parasequences at Llandovery may be present, as well as those that define Llandovery area sequences (7 and 8). On the other hand, it is clear that significant non-sequences interrupt many of these successions and, whilst offering evidence of shallowing and subaerial erosion, these may also account for the non-preservation of key flooding levels (see Section 8). Zhang and Barnes (2002b) recorded a marked lowstand on Anticosti Island that matches closely the upper *convolutus* Biozone prograde at Llandovery. It succeeds a pre-*sedgwickii* Biozone deepening episode (8) and underlies a flooding surface that marks the local FAD of *sedgwickii* Biozone graptolites (9). The recalibrated curves for Iowa and Illinois offer evidence for a comparable shoaling between the regional FADs of *S. lens progressa* and *S. laevis* (Johnson, 1975; Witzke, 1992).

The data from Baltica (Norway, Sweden, Estonia and Russia) are more varied (Fig. 10), consistent with deposition in tectonically active basins (e.g. Baarli *et al*., 2003; Dahlqvist and

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Bergström, 2005). In northern Estonia, Nestor and Einasto (1997) recognised flooding levels consistent with events 4, 5 and 6 at Llandovery. This level of detail is not replicated by other Baltic datasets, although most show a *revolutus* Biozone deepening episode (B) (e.g. Johnson *et al*., 1991; Baarli *et al*., 2003). Many of the recalibrated Baltic curves also indicate a period of sustained Aeronian shallowing. In the Russian Timan-Petchora Basin, this peaked during the *leptotheca* Biozone, but it is shown elsewhere to have extended into the *convolutus* Biozone (E). The impact of a deepening that spanned the late *convolutus* to early *sedgwickii* biozonal interval, consistent with the conflation of flooding events 7, 8 and 9 and high-stand C, is seen throughout the Baltic region. Also widely acknowledged are a late Aeronian shallowing (F) and a subsequent *guerichi* Biozone deepening (10), the latter marked in Estonia by the transgressive base of the Rumba Formation (e.g. Nestor and Nestor, 2002; but see Supplementary Data).

Strata of *persculptus* Biozone age are absent from many circum-Iapetus sections (see Section 7.a), but where preserved in Iowa and Illinois, on Anticosti Island and in Arctic Canada, there is evidence of a deepening maximum (A) (e.g. Witzke and Bunker, 1996; Dewing, 1999; Zhang and Barnes, 2002b; Melchin and Holmden, 2006; Long, 2007). Other curves show a deepening episode extending from the Hirnantian that peaked at different times during the early Rhuddanian (Johnson *et al*., 1991; Harris et al., 1998; Copper and Long, 1999). Nonetheless, several regional base level curves, notably from North America, record a subsequent high-order regression that, in common with the Llandovery area (D), peaked prior to the *revolutus* Biozone and was followed by a deepening episode (4).

The Cornwallis Island (Arctic Canada) curve of Melchin and Holmden (2006) differs significantly from other Laurentian, ‘Avalonian’ and Baltic datasets (Fig. 10). It shows the

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early–mid Aeronian as a period of slowly rising base level that culminated in an early *convolutus* Biozone high-stand, and the early *sedgwickii* Biozone as a time of falling base level that peaked well below the base of the *guerichi* Biozone. From a comparison of depth-controlled conodont assemblages, Zhang *et al*. (2006) concluded that Anticosti Island and Cornwallis Island experienced very different tectonic and base level movement histories.

### 6.5 Analysis: Curves from other palaeoplates (Figs 11, 12)

Interpreting base level curves compiled for Llandovery successions that accumulated on other early Silurian palaeoplates is more challenging. Many of these curves appear to focus on high order events and very few extend down into the Hirnantian. An exception is the well-dated, high southern palaeolatitude Gondwanan succession examined by Underwood *et al*. (1998). This (Fig. 12, curve 21) provides evidence of a late Hirnantian flooding episode (2) that, in common with the Llandovery area, culminated in an upper *persculptus* Biozone high-stand (A). A subsequent shoaling into the *atavus* to *acinaces* biozonal interval (commonly also referred to as the *vesiculosus* graptolite Biozone) is also recognised in the Murzuq Basin of Saharan North Africa (Legrand, 2003) (Fig. 12, curve 22), where Loydell *et al.* (2009; also Loydell *et al*., 2013) view it as evidence for a glacioeustatic sea-level fall. However, the likely impact of glacioisostasy in this region persuaded Johnson (2010) that the local record of base level movements may not accurately reflect global events (see also Berry and Boucot, 1973). Certainly, curves for more northerly Gondwanan successions, which typically show the Rhuddanian as a time of generally rising and elevated base levels, more closely resemble many global datasets (Fig. 8). The Gondwanan curves for Australia (Jell and Talent, 1989; Talent, Mawson and Simpson, 2003) and the Himalayas (Talent and Bhargava, 2003) (Fig. 12, curves 23, 24), and for parts of Cathaysia (South China) (Johnson *et al*., 1985; also Rong

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*et al*., 2003) and Siberia (Artyushkov and Checkhovich, 2001; Yolkin *et al*., 2003) (Fig. 11) offer some support for a high order, *revolutus* Biozone flooding maximum (B).

Many curves, including that for the Peri-Gondwanan Prague Basin (Fig. 12, curve 18), mirror the Llandovery data in their depiction of the early-mid Aeronian as a time of falling or lowered base levels. There is evidence locally of a shoaling peak close to the base of the *convolutus* Biozone (E) followed by a high-stand event that could be viewed as a conflation of flooding episodes 7, 8 and 9. However, a majority of the curves presented by Koren *et al*. (2003) for Kazakhstan (Fig. 11) show only a base *sedgwickii* Biozone transgression (9). Siberian datasets, though they record Aeronian base level movements on a range of scales, are significant for the lateral variability in base level histories that they imply. Artyushkov and Chekhovich (2001) viewed this as evidence that regional isostasy was more influential than eustasy. Many curves associate the *sedgwickii-halli* biozonal interval with a period of shoal deposition (F) and, though the form of the subsequent deepening episode differs markedly on curves for Cathaysia, Siberia, Peri-Gondwana and Gondwanan North Africa and Australia, the *guerichi* Biozone is shown overlapping a period of elevated base levels in all these areas. In contrast, the records of base level change during this latter interval in other parts of Gondwana, in India and in Kazakhstan for example, show this as a period of base level lowering.

## 7 Glacioeustatic credentials

Davies *et al*. (2009) assessed the latest Hirnantian facies present in the Type Llandovery area that encompass events 1–3 of Figure 6. These record the pulsed early progress in Wales of

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the global transgression that immediately followed the period of maximum Gondwanan ice sheet expansion (e.g. Hambrey, 1985; Ghienne, 2003). They suggested that, following the deep erosion associated with the Hirnantian glacial maximum, it was only in basin margin settings, or where there was deeply incised palaeotopography, that the earliest phases of the late Hirnantian transgression were likely to be felt and its deposits preserved. Such palaeotopography was locally effective in excluding much of the late Hirnantian (*persculptus* Biozone) to Rhuddanian succession from the Laurentian interior (e.g. Witzke, 1992; Ross and Ross, 1996; Johnson and Baarli, 2007), Baltica (e.g. Nestor, 1997) and Africa (e.g. Underwood *et al*., 1998). Such exclusion may account for the poor and inconsistent record of events within this interval (see Section 8).

However, it is now acknowledged that this global transgressive event marked only the partial collapse of the ice sheet (e.g. Le Heron and Craig, 2008). The discovery of Llandovery glacigenic deposits in South America (e.g. Caputo, 1998) suggested to Dias-Martinez and Grahn (2007) that the locus of the Gondwanan-based glaciation shifted over time, although facies of comparable age recently reported from Libya (e.g. Le Heron *et al*., 2013) confirm that a diminished ice mass continued to occupy parts of Africa. These findings support the widely held assumption that many Llandovery base level events, both high and low order, provide a record of sea level change linked to dynamic changes in the shape and extent of an extant South Polar Ice Sheet (e.g. Ross and Ross, 1996; Loydell, 1998, 2007; Nestor *et al*., 2003; Zhang and Barnes, 2002b; Page *et al*., 2007; Haq and Schutter, 2008; Johnson, 2010; Munnecke *et al*., 2010). It is argued that the changes in global climate and ocean state associated with these glacial events are reflected in plots of stable isotope ratios and faunal flux, fostering the belief that these too provide a proxy record of Llandovery glacioeustasy (e.g. Melchin and Holmden, 2006; Cramer *et al*., 2011a).

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The scale and duration of many Silurian base level events are also seen as consistent with glacioeustatic forcing (e.g. Johnson and McKerrow, 1991), vertical movements of 10s of metres over time periods of less than a million years generally being seen as too great for epeirogenic effects to achieve on their own (e.g. Miller *et al*., 2005; Csato and Catuneanu, 2012). However, this is not to say that glacioeustasy alone was instrumental, or was always dominant, particularly in tectonic settings such as the faulted margin of the Welsh Basin, where high rates of subsidence were likely to have been a significant factor (cf. Gawthorpe *et al*., 1994).

### 7.1 Analysis: known glacial events (Fig. 13)

The limited dating available for the South American glaciogenic successions,  reviewed by Kaljo *et al*. (2003),is based principally on chitinozoans recovered from interbedded marine sediments. These data suggest that an extensive South Polar ice mass continued to occupy that part of Gondwana during the early Rhuddanian. The late Rhuddanian deepening seen in most global and some regional curves appears to reflect the first major period of melting of the South American ice mass (e.g. Dias-Martinez and Grahn, 2007). Subsequently, according to Caputo’s (1998) log of glacigenic deposits (Fig. 13), a re-advance during the *triangulatus* Biozone established an extensive, slowly down-wasting ice mass that was sustained throughout much of the Aeronian, prior to an abrupt and marked retreat at or close to the base of the *sedgwickii* Biozone. This preceded a late Aeronian to early Telychian re-advance and there is evidence also for a discrete late Telychian glaciation. Periods of ice retreat (interglacials), it can be assumed, were also periods of sea level rise.

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Given the paucity and nature of the fossil evidence, the suspicion persists that the dating of these glacial events is based partly on their ‘best fit’ to the ‘standard’ Llandovery sea level curve and lacks both independent corroboration and precision. At face value, the findings from South America can be seen broadly to endorse glacioeustatic credentials of the late Rhuddanian (*revolutus* Biozone) base level events seen at Llandovery (4, 5, B). Waxing and waning of the Aeronian ice sheet may account for the base level movements noted at the base of the *magnus* Biozone (6) and within the *leptotheca-convolutus* biozonal interval (7, 8), though the limited data from South America offer nothing to confirm this and these are the events that many other datasets fail to depict (see Section 8). Evidence of a discrete mid Aeronian ice advance on the scale and duration implied by the prograde seen at Llandovery (E) is also lacking. However, episodes of interglacial deepening are seen to offer a ready explanation for the *sedgwickii* Biozone (9, C) and *guerichi* Biozone (10) deepening events.

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### 7.2 Analysis: proxy records of climate change (Figs 13, 14)

Key datasets include those compiled for a range of stable isotopes and for faunal events. Here, any alignment of trends and peaks with those shown by base level curves does not offer direct proof of glacially linked sea level movements, but does imply that there may have been a causative link (e.g. Munnecke *et al*., 2010).

#### 7.2.1 Isotopic trends and excursions

Curves showing temporal variations in $\delta^{18}$O and $\delta^{13}$C are thought to reflect changes in global temperature and ice volume, and organic productivity and carbon burial respectively (e.g. Azmy *et al*., 1998, 1999; Cooper and Sadler, 2004; Page *et al*., 2007; Munnecke *et al*., 2010; Cramer et al., 2011a; McLaughlin *et al*., 2012; Melchin *et al.*, 2013; Vandenbroucke *et al.*, 2013). A review of the causal relationships between environmental and isotopic flux is

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outside the scope of this paper (see Griffiths, 1998; Gradstein *et al*., 2012 and references therein). The mechanisms by which isotopic fractionation is achieved are hotly debated (e.g. Attendorn and Bowen, 1997; Melchin and Holmden, 2006; Stanley, 2010; Gouldey *et al*., 2010) and the patterns of flux in oxygen and carbon isotope values do not always match one another (e.g. Long, 1993). Nevertheless, as many of the positive excursions seen in these isotope datasets appear to be widely correlatable, such curves have been seen to offer a proxy record of Late Ordovician and Silurian climatic events and, by extension, associated glacioeustasy.

The abundant $\delta^{13}$C isotope data now available for the Hirnantian Series generally support linked climatic and sea level changes that facies and faunal variations appear to record, including a *persculptus* Biozone deepening maximum (A) (e.g. Underwood *et al*., 1997; Kaljo *et al*., 2008; Desrochers *et al*., 2010; Finnegan *et al*., 2011). Published curves for the Rhuddanian to early Telychian interval, including Cramer *et al*.'s (2011a) synthesis of published $\delta^{13}$C carb data, depict negative excursions consistent with the late Rhuddanian high-stand and its component events (4, 5 and B) (e.g. Melchin and Holmden, 2006; Gouldey *et al*., 2010). Support for the pronounced flooding surface (7) that terminated the *convolutus* Biozone Ceg$^1$ prograde, for an early *sedgwickii* Biozone deepening episode (9), and for a deepening event that spanned the Aeronian-Telychian boundary (10), is also provided. Positive $\delta^{13}$C excursions in the early and late Aeronian have been linked to periods of global cooling, glacial advance and sea level fall (Fig. 13). Cramer *et al*. (2011a) recognise their early Aeronian positive excursion as peaking during the *triangulatus* Biozone. This would endorse the glacioeustatic credentials of the Ceg$^0$ progradation and its defining flooding event (6), but it is unclear whether this level of precision is justified (e.g. Melchin and Holmden, 2006). The isotopic evidence for a *sedgwickii-halli* biozone shoaling event (F) is also

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ambiguous, both in terms of its timing and impact. The regional curves of Melchin and Holmden (2006) and Gouldey *et al*. (2010; based on Kaljo and Martma, 2000) differ from global sea level curves (Fig. 8) in providing support for a mid Rhuddanian shallowing as seen at Llandovery (D).

Isotope excursions on the brachiopod-derived $\delta^{18}O$ curve of Azmy *et al*. (1998) broadly align with the main $\delta^{13}C$ excursions and offer support for Llandovery highstands during the late Rhuddanian (B) and mid Aeronian and for early and late Aeronian glacially induced regressions (Fig. 13). In common with other datasets, support for a *leptotheca*-lower *convolutus* Biozone low-stand event (E) is lacking and the impacts of a base *sedgwickii* Biozone deepening are not seen. However, the processes that led to these excursions, particularly the role played by biodiagenesis, are debated, and many authors question the unambiguous relationship between sea levels and $\delta^{18}O$ values (see Munnecke *et al*., 2010).

7.2.2 Graptolite faunal flux

Many of the flooding surfaces that define the Llandovery area prograde sequences are associated with the local FADs of biozonal graptolite assemblages. This implies an empirical relationship between base level events and changes in contemporary graptolite assemblages. Melchin *et al*. (1998; also Storch, 1995) discussed the complex interplay of climatic, oceanic and ecological factors that likely contributed to the flux in Silurian graptolite populations. Cooper *et al*. (2014) pointed to an empirical relationship between Llandovery population dynamics and the global $\delta^{13}C$ curve, from which they too inferred climatic influence. It follows that the plots produced by these studies provide a further proxy means of assessing the impacts of glacioeustasy at Llandovery (Fig. 14).

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In general, these plots fail to endorse biozonal scale, low order base level events, but trends that match the high order, Type Llandovery curve are clearly apparent. Cooper *et al*. (2014) recorded patterns of reduced extinction and elevated origination for highstands that span the *persculptus–ascensus-acuminatus* (A) interval and the *revolutus–magnus* biozones (B). The flux in populations also mirror the mid Rhuddanian (D) and mid Aeronian (E) shoaling episodes and the rising base levels associated with the *convolutus-sedgwickii* biozonal boundary (C), though in these cases the relationships between diversity, extinction and putative sea level movements appear contrary to that proposed by Melchin *et al*. (1998). The impacts of a late *sedgwickii-halli* Biozone shoaling event (F) and subsequent *guerichi* Biozone transgression (10) are also evident in the graptolite plots.

### 7.2.3 Oceanic and climate models

It is pertinent briefly to discuss the influential, if controversial oceanic model of Jeppsson (1990, 1998). Based on empirical associations of sedimentary facies and faunas, particularly patterns of conodont extinction, Jepsson (1990, 1998) contended that the Silurian global ocean passed repeatedly between two distinct states: ‘primo episodes’ linked to periods of glacial advance; and ‘secundo episodes’ associated with times of ice retreat (see Johnson, 2006). It follows that glacially driven movements in sea level should closely mirror the pattern of primo and secundo states. Page *et al*. (2007), in their extension to this model, argued for a cyclical, self-regulating mechanism. They contended that the sequestration of carbon in deep water black shales and shallow water carbonates during periods of elevated global temperature led to cooling, glacial re-advance, and sea level fall. This, in turn, triggered the shutdown of mass sequestration, rising atmospheric $CO_2$ levels then promoting the next warming phase. Whether glacioeustasy was the cause or the effect is a moot point,

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but it is clear that there should be a close alignment of chemostratigraphical and sea level events.

Many dispute the universal applicability of the Jeppsson model and point to inconsistencies between its key events and those based on other sedimentary and fossil criteria (e.g. Johnson, 2006). Nevertheless, Jeppsson's (1998) schematic model of changing sea level elevations offers support for curves that show the Rhuddanian and early Aeronian as a period of elevated sea levels (e.g. Loydell, 1998) (Fig. 14). There is no evidence for a putative early Aeronian glacial advance, but there is evidence for mid-Aeronian shallowing linked to the *convolutus* Biozone (E). Jeppsson's (1998) Sandvika Event records a primo-secundo transition that is consistent with an early *sedgwickii* Biozone deepening (9 and C), but his model is at odds with many other datasets in suggesting that the resulting high-stand persisted throughout the remainder of the biozone and much of the early Telychian.

## 8 An index of Llandovery eustasy

In the pursuit of 'practical eustasy', there is always a temptation to invoke the periodic prevalence of local forces to explain discrepancies between regional and global trends, both in timing and scale. Subsidence is always on hand to account for regional deepening events that fall outside eustatic templates, just as tectonic uplift can be used to account for unexpected shoaling episodes. The assumption by critics of deep-time eustatic research is that it is for the exponents of eustasy to demonstrate the widespread correlatability of events (Miall, 2004). Yet, the absence of objective proof for one forcing factor does not of itself confirm the importance of others. For the relative roles played by tectonism and isostasy in

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fashioning local stratigraphies to be properly quantified, the relative impact of contemporary eustasy in creating and destroying accommodation space must also be evaluated (e.g. Ettensohn and Brett, 1998; Artyushkov and Chekhovich, 2001, 2003; Dahlqvist and Bergström, 2005). The need to calibrate the ambient eustatic signal is essential to both camps, particularly during 'icehouse' periods when ongoing glacioeustasy can be anticipated (e.g. Zecchin 2007; Csato and Catuneanu, 2012). The Eustasy Index methodology presented herein is intended as a possible first step towards untangling these conflicting factors at the regional level.

### 8.1 Eustasy Index methodology

The range of techniques used to compile the 62 datasets examined as part of this study, allied to their wide palaeogeographical distribution (Fig. 1; Table 1), supports their use in an attempt to quantify the role played by eustasy in shaping the Type Llandovery succession. Each of the twelve UK graptolite biozones that have been the focus for this study *(*upper *persculptus* to *guerichi* biozones) have been arbitrarily subdivided into three to create a matrix with 36 rows for scoring the levels of similarity (see Supplementary Data). For each of the studied datasets (Figs 7–14), every subdivision that displays a trend comparable to (or, for proxy datasets, inferred to be consistent with) the low order curve at Llandovery - and is coloured blue or red for 50% or more of its duration - has been given a score of 1.0 (see Eustasy Index scores in Supplementary Data). Segments displaying trends that compare more closely with the high order base level curve at Llandovery rather than the low order curve, indicated by the diagonal ornament on Figures 7 to 14, are given a score of 0.5.

Account is also taken of the incomplete nature of many datasets. Where this reflects limitations of outcrop or exposure, or, as for some proxy curves, the restricted range of the

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sampled interval (e.g. Underwood *et al*. 1997), the 'missing' subdivisions are omitted from the scoring process. More difficult to account for are gaps that record the local impacts of emergence and erosion. Those of short duration – a subdivision or less - are included since it is reasonable to infer that they record the impacts of a single, short lived episode of local base level lowering. However, where non-sequences span several subdivisions and record prolonged and/or multiple phases of emergence, it is likely that evidence of local base level movements has been lost. Therefore, with the exception of the final subdivision prior to the resumption of deposition, these too are omitted from the scoring mechanism. Analysis of the levels of representation (Fig. 15) confirms that late Hirnantian and early Rhuddanian deposits, which might otherwise record the early progress of the post-glacial maximum transgression, have been widely excluded from many of the areas for which Llandovery base level and proxy curves have been compiled.

The score for each subdivision across the complete range of datasets, expressed as a percentage of its level of representation, provides the Eustasy Index (EI) for that section of the Type Llandovery base level curve (Fig. 15 and Supplementary Data):

$$EI = (EIr/tR)\% \qquad \text{(Eq. 1)}$$

where EIr is the sum of the Eustasy Index raw scores for a subdivision and tR is the total number of datasets in which that subdivision is represented.

The scores obtained for each subdivision of the Llandovery curve should be viewed as providing an indication only of the likelihood that eustasy was a significant factor rather than a measure of the relative importance of sea level movements in any absolute sense. Since

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Llandovery area events that obtain the highest EI scores are those recognised on a majority of the other datasets, it follows that eustasy was likely a factor in shaping these events wherever they have been identified. Conversely, intervals with low EI values, for which matching events in other successions are least apparent, are more likely to have been periods when regional influences on the Llandovery succession were dominant. Importantly, this need not imply that eustasy was insignificant during low scoring events (see below), or was not the dominant factor in shaping other datasets.

### 8.2 Eustasy Index results (Fig. 15)

At first sight, the results of this analysis appear paradoxical. Their high eustasy indices show that the Type Llandovery highstands that peaked during the *persculptus* (A), *revolutus* (B) and early *sedgwickii* biozone (C) align with episodes of global deepening, as does the basal *guerichi* Biozone flooding event (10). Many of the lower order flooding events that contributed to these deepening episodes, in the early *revolutus* Biozone and linked to the appearance of *magnus* and mid and late *convolutus* biozonal assemblages, are also inferred to have had a strong eustatic component. However, the intervening lowstands are characterised by low Eustasy Index values, notably in the early–mid Rhuddanian and mid Aeronian intervals.

The low eustacy indices for the principal Llandovery area progrades perhaps testifies to their accumulation along the margins of a tectonically active basin, a setting where regional epeirogenesis operated alongside eustasy to rejuvenate source areas and create accommodation space. Widespread source area uplift coincident with the early stages of the Scandian Orogeny and reactivation of the Tornquist Zone in Europe (e.g. Johnson *et al*., 1991; Baarli, Johnson and Antoshkina, 2003), and with late stages of the Taconic Orogeny in

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North America (e.g. Ettensohn and Brett, 1998; also Brett *et al*., 1998), can be invoked as an alternative or enhancing mechanism for the marked early–mid Rhuddanian shallowing not widely seen outside the circum-Iapetus realm (but see below). It is principally the datasets from this same region that offer evidence of a *leptotheca* to lower *convolutus* Biozone shoaling episode on the scale observed at Llandovery. However, such analysis illustrates the difficulties of 'practical eustasy' as a thesis that requires us to focus on the similarities in the datasets. An alternative interpretation, consistent with its tectonic setting, is to see the influence of regional epeirogenesis on Type Llandovery base levels as normally dominant (cf. Gawthorpe *et al*., 1994). Periods with a high Eustasy Index can then be seen as episodes either of tectonic quiescence, during which global sea level movements were able preferentially to influence sedimentation, or when such movements were of sufficient magnitude and rate to overwhelm the regional signal. It may not be a coincidence that it is base level movements linked to interglacial high-stand events that are most clearly identified as eustatic at Llandovery (Fig. 13). The rapid and substantial rises in sea level associated with the disintegration and collapse of maritime ice sheets are those most likely to overwhelm regional epeirogenic processes, whereas the slowly falling sea levels that accompany periods of gradual ice sheet expansion are less able to outstrip regional effects as the most active forcing factors (e.g. Berry and Boucot, 1973; Morton and Suter, 1996). Yet, it remains curious that at least two of the major lowstand episodes seen at Llandovery overlap with known periods of ice sheet expansion seen in South America (Fig. 13) when glacioeustatic drawdown would be anticipated to have had an impact.

### 8.3 Significance of glacioeustatic, epeirogenic and orogenic interactions (Fig. 16)

EI scores, as obtained for the Type Llandovery succession, are a function of global and regional forcing factors, the detailed form of any regional base level curve reflecting the

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interplay between eustasy and near-field orogenesis, epeirogenesis and sediment supply. High levels of subsidence can serve locally to exaggerate the impacts of marine transgressions, in terms of both rate and reach, and to offset and mask the effects of falling sea levels (cf. Artyushkov and Chekhovich, 2003). Changes in sea level on at first drained and then flooded shelves are also accompanied by the removal and then the imposition of hydrostatic and sediment load (e.g. Long, 2007). Such changes in load will be accommodated either by isostasy or, in tectonically active settings, by the differential movement of faulted blocks (e.g. McGuire, 2012; Stammer *et al*., 2013; Steffen *et al*., 2014). Similar adjustments must have affected early Silurian source areas and depocentres, notably during periods of falling sea level when, it can be inferred, the deep erosion of a landscape supporting little vegetation (e.g. Wellman *et al*., 2013) resulted in the rapid transfer of sediment to marine shelves and basins (e.g. Davies and Gibling, 2010). Hence, glacioeustatic regressions and transgressions would themselves have been forcing factors in regional Silurian epeirogenesis.

Accordingly, low Eustasy Index scores should not be taken as evidence that changes in sea level were insignificant during the development of Llandovery area lowstands (Fig. 16). Coeval glacioeustasy likely contributed to these base level events, but, as sediment source areas were exposed, the rapid transfer of sediment to the subsidence-prone basin margin triggered a self-sustaining epeirogenic response that quickly outstripped eustasy as the dominant forcing factor. Local base level movements then diverged from global trends. Viewed in this way, Eustasy Index results can be seen not simply as offering a measure of when eustatic forcing was dominant, but also of changing rates of eustasy (or eustatic flux). Intervals with high eustasy indices appear to equate with periods of rapid and/or frequent sea level movement. Periods with lower scores may record times when sea levels changed more slowly and epeirogenic forcing was able to dominate. These may have been periods of slowly

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rising or static sea level, but can also be seen as consistent with the slow, but possibly substantial falls in sea level that accompanied episodes of sustained glacial advance.

Such analysis negates the need to invoke episodic tectonic events. It implies a self-regulating mechanism to account for why global and regional influences alternated in their impacts on local sedimentation, and it explains why the eustasy indices for parts of the Type Llandovery succession fail to track precisely the pronounced falls in sea level that must have accompanied known periods of ice sheet growth in South America (Caputo, 1998; Dias-Martinez and Grahn, 2007; Fig. 13). This model can be applied more widely. It is likely to have been interglacial flooding events that were most successful in drowning cratonic interiors and therefore these that are recorded preferentially by base level curves for cratonic successions. It is clear too that ‘practical eustasy’ as a methodology has tended to focus on the timing of flooding events rather than lowstands (e.g. Johnson *et al*., 1991b) and therefore unsurprising that Johnson’s (1996, 2006, 2010) ‘standard’ sea level curve for the early Silurian, based on a ‘type district’ in Laurentian Iowa, is also biased towards such events.

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Subsequently, in Wales, the Telychian onset of a more dynamic phase of regional tectonism, though it seems initially coincident with glacioeustatic deepening, signalled a long term departure from the far field influence of glacial activity on sedimentation. The erosion of upper Aeronian and lower Telychian strata across much of Laurentian and eastern Baltica suggests that broadly coeval effects were again widely felt throughout circum-Iapetus regions where, in Europe, they record an encroaching Scandian orogenic front (e.g. Kirkland *et al*., 2006).

### 8.4 Wider implications

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The Eustasy Index calculations for the Llandovery succession have implications for global sea level models. Contrary to Haq and Schutter (2008), these calculations strongly endorse the separate early and late Aeronian highstand events that the majority of global curves depict (Fig. 8). Johnson (2010) departed from previous models (e.g. Johnson, 1996) in showing the early Telychian as a lowstand, but the Llandovery area data offer support for curves that recognise this as a time of rising or elevated sea levels (e.g. Johnson *et al*., 1991b; Loydell, 2007; Page *et al*., 2007). Of particular interest is the high Eustasy Index obtained for a discrete late *persculptus* Biozone highstand seen at Llandovery (Fig. 15).

The Type Llandovery base level curve fails to offer support for the precise timing, duration and scale of glacial lowstands. Nevertheless, glaciogenic deposits in South America show that separate episodes of Gondwanan ice re-advance during the Aeronian (Fig. 13; see Section 7) overlap two of the main Llandovery area lowstands characterised by reduced rates of eustatic flux (see above). The Llandovery area findings challenge researchers to look for evidence of such activity during the comparable Rhuddanian interval also. The findings of Dias-Martinez and Grahn (2007) imply that an extensive ice mass was in place in South America at this time. The work in Africa of Underwood *et al*. (1998), Legrande (2003), Loydell (2009; also Loydel *et al*., 2013) suggests this may, in part, have been the product of a discrete intra-Rhuddanian re-advance (Fig. 12) for which some proxy datasets offer support (Figs 12, 13). Confirmation of such an event has implications for the interpretation of shallow and deep water Rhuddanian facies in Wales previously seen as unrelated to eustatic events (e.g. Davies and Waters, 1995; Schofield *et al*., 2009; Davies *et al*., 2013). It would also imply that all the most widely cited global curves (Fig. 8) may be in error in depicting the late Hirnantian to late Rhuddanian as a period of almost uninterrupted rising sea levels.

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It follows that the Eustasy Index methodology should now be applied more widely and that many of the datasets examined herein could be the focus of similar analysis. The results of such studies will serve to distinguish the impacts of local epeirogenesis and, when viewed collectively, allow the ‘standard sea level curve’ for the Llandovery to be refined. Moreover, this methodology has the potential to be used in assessing the base level credentials of correlatable marine successions of any age.

## 9 Conclusions

For the first time, a detailed and biostratigraphically well-constrained sequence stratigraphy is available for the Type Llandovery Series succession in mid Wales. The recognition of a series of prograde sequences with bounding flooding surfaces has enabled the construction of both high and low order relative base level movement curves for those parts of the succession that preceded the onset of Telychian tectonism in Wales. Qualified comparisons with widely cited sea level curves, isotope data, examples of facies and faunal flux and nascent climatic models allow the relative importance of global (eustatic) and regional (tectonic/isostatic) forcing to be evaluated, and the far field impacts of glacioeustasy to be tested.

The concept of a Eustasy Index emerges as a useful tool to evaluate the potentially complex interplay of local, regional and global forcing factors that shaped base level curves. Its application to the Llandovery succession suggests the presence of ‘eustatic windows’ linked to interglacial global highstands. In contrast, the glacioeustasy that accompanied the slow re-growth of contemporary ice sheets is suggested to have triggered regional epeirogenic responses that saw base level patterns during the main Llandovery area lowstands diverge from global trends, negating the need to invoke episodic tectonic events. Such an analysis

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invites speculation that a significant ice advance unrecognised by current global Silurian sea level models occurred during the mid Rhuddanian. Subsequently, the Telychian response to the Scandian Orogeny, though initially coincident with glacioeustatic deepening, signalled a long term departure from the far field influence of glacial activity on sedimentation in Wales.

It is anticipated that future application of the Eustasy Index methodology to other marine successions will similarly highlight the impacts of local epeirogenesis and, in so doing, allow a more precise history of global sea level activity to be elucidated, both during the Llandovery and for other time intervals.

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## Figure captions

**Figure 1.** Global Llandovery palaeogeography showing the distribution of tectonic plates and the locations of sections used in this study (numbers are those used on Figures 7-11). Note, according to Ladenberger *et al*. (2012), the collision between Laurentia and Baltica that initiated the northern Europe Scandian Orogeny was already in progress during earliest Llandovery times (but see Kirkland *et al*., 2006). Cathaysia is commonly referred to as South China.

**Figure 2.** a) Key areas of Llandovery aged rocks in the UK; b) Llandovery Series rocks in Wales; c) Type Llandovery area showing location of traverse lines used in the construction of Fig. 4 (after Davies *et al*, 2013). Abbreviations: BF, Bala Fault; CSFZ, Church Stretton Fault Zone; db, slump disturbed units; DD, Derwyddon Formation (shown schematically); ELD, English Lake District; LL, Llandovery town; LPWB, Lower Palaeozoic Welsh Basin; MfS, Mwmffri Sandstone Member; PL, Pontesford Lineament; SSU, Scottish Southern Uplands; TL, Tywi Lineament; WBFS, Welsh Borderland Fault System.

**Figure 3**. Facies model for Rhuddanian and Aeronian strata at Llandovery showing the sedimentary and faunal characteristics of the principal facies (after Davies *et al*. 2013). Benthic Communities are those of Zeigler *et al*, (1968a); BA refers to the broadly equivalent Benthic Associations of Boucot (1975); BI refers to the Bioturbation Index of Taylor and Goldring (1993). For other abbreviations see Figure 4.

**Figure 4.** Architectural models for the Type Llandovery succession (after Davies *et al*., 2013): a) lithostratigraphy and thickness; b) chronostratigraphy model calibrated using UK

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graptolite biozonation of Zalasiewicz *et al*. (2009); c) as b, but recast to show distribution of facies belts and progradational sequences (numbers refer to facies belts of Fig. 3). See Figure 2 for location of lines of traverse. Abbreviations for stratigraphical nomenclature: BrF, Bronydd Formation; CcF; Crychan Formation; Ceg, Cefngarreg Sandstone Formation; Cer, Cerig Formation; ChF, Chwefri Formation; db, slump disturbed units; DD, Derwyddon Formation; GHF, Garth House Formation; Gol, Goleugoed Formation; Rdg, Rhydings Formation; TfF, Trefawr Formation; Wow, Wormwood Formation; Ydw, Ydw Member; Yst, Ystradwalter Member. Note in b use of symbols Ceg$^0$, Ceg$^1$, etc. to distinguish separate prograde units within individual formations (see Fig. 4); and in b and c alternative base positions for the Aeronian and Telychian stages based either on current GSSPs (*) or internationally applied biozonal criteria (see Fig. 5 and Davies *et al*., 2013).

**Figure 5.** Compilation of selected biostratigraphical ranges and biozonal schemes in use for the late Hirnantian and Llandovery series. Principal sources for columns: A, Zalasiewicz *et al*. (2009) (subdivions of the *persculptus* Biozone are those of Blackett *et al*., 2009); B, Cocks *et al*. (1984), Baarli (1986; also Baarli and Johnson, 1988), Temple (1987) and Davies *et al*. (2013); C, Aldridge and Schönlaub (1989), Dahlqvist and Bergström (2005), Mannik (2007) and Cramer *et al*. (2011a,b); D, Verniers *et al.* (1995), Loydell *et al*. (2010), Nestor (2012) and Davies *et al*. (2013); E, Davies *et al*. (2013); F, Burgess (1991); G, Brett *et al*., (1998); H, Loydell (2011); I, Bergström *et al*. (2009) and Cramer *et al*. (2011a) with selected GTS 2012 (Spline) Ages of Melchin *et al*. (2012). Notes: 1, historic base of the Silurian System in Wales (see Davies *et al*., 2009; note that recent syntheses suggest that the FADs of both *taugourdeaui* Biozone chitinozoans (t) and *persculptus* Biozone graptolites (p) are significantly younger in Wales than in other parts of the world; see Supplementary Data); 2, base of former Idwian Stage; 3, base Aeronian according to internationally applied criteria

(Melchin *et al*., 2012); 4, approximate base of former Fronian Stage; 5, former base Telychian of Cocks *et al*. (1970); 6, base Telychian based on internationally applied criteria (Cocks, 1989; Melchin *et al*., 2012); 7, historic base Wenlock Series, but see discussion in Melchin *et al*. (2012); T = onset of post glacial maximum transgression in Wales (see Supplementary Data for discussion re revised age of this event); GSSP = positions of current stage stratotypes (see Davies *et al*., 2013). In Column B solid lines show known ranges of brachiopod taxa in the Type Llandovery area; dashed lines show known ranges in Wales and the Welsh Borderlands; and dotted lines show know ranges in other areas. In other columns horizontal dashed lines denote uncertainty. Note the *persculptus* and *convolutus* Biozone are expanded to allow FADs and LADs to be better illustrated; post-*guerichi* biozones are foreshortened; subdivisions 1-4 of the upper *persculptus* Biozone refer to the successive morphotypes of *Normalograptus*? *parvulus* recognised in Wales by Blackett *et al*. (2009). For additional sources and discussion see the notes and numbered links [in square brackets] to information submitted as Supplementary Data.

**Figure 6.** Generalised log of the late Hirnantian to early Telychian succession in the Type Llandovery area showing sequence stratigraphy and derived base level movement curves. UK graptolite biozone bases are taken at the first appearances (FADs) of diagnostic biozonal assemblages using the criteria of Zalasiewicz *et al.* (2009) (see also Fig. 5). GSSP$^{I}$ – relative position of Aeronian Stage GSSP; GSSP$^{II}$ – relative position of Telychian Stage GSSP (see text and Supplementary Data). See Figures 2 and 3 for lithostratigraphical abbreviations and explanation of facies belts. N.B. sequence stratigraphy has not been applied to Telychian strata and parasequence-scale base level movements within the *convolutus* Biozone have been omitted for clarity. *See Supplementary Data for usage of upper *persculptus* Biozone; numbers 1, 2 and 3, 4 show inferred ranges of Blackett *et al*.'s (2009) divisions (see Fig. 5).

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**Figure 7**. Comparison of the Type Llandovery relative base level curves with other UK Llandovery datasets. Coloured blocks identify trends in these datasets inferred to be consistent with the base level changes recognised at Llandovery (see text) without necessarily implying a causal relationship; diagonal ruling is used for segments of datasets consistent only with inferred high order base level movements at Llandovery. All datasets have been recalibrated to fit the standard UK graptolite biozonal scheme of Zalasiewicz *et al*. (2009); the biozones are not drawn to scale, and are divided into three or, in the case of the *atavus-acinaces* and *sedgwickii-halli* biozonal intervals, six arbitrary subdivisions to facilitate comparisons between the datasets (see Section 8). Numbers [in square brackets] refer to notes provided as Supplementary Data; dashed vertical lines on subsequent figures indicate the presence of putative non-sequences (see Section 8a)

**Figure 8.** Comparison of the Type Llandovery relative base level curves with a selection of published late Hirnantian to early Telychian global sea level curves showing levels of correspondence (see Fig. 7 for explanation).

**Figure 9**. Comparison of the Type Llandovery relative base level curves with a selection of published late Hirnantian to early Telychian regional base level curves for Laurentia showing levels of correspondence (see Fig. 7 for explanation). The curve of Zhang and Barnes (2002b) is simplified; that of Dewing (1999) shows the late Hirnantian-Rhuddanian portion only.

**Figure 10**. Comparison of the Type Llandovery relative base level curves with a selection of published late Hirnantian to early Telychian regional base level curves for Laurentia and Baltica showing levels of correspondence (see Fig. 7 for explanation).

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**Figure 11**. Comparison of the Type Llandovery relative base level curves with a selection of published late Hirnantian to early Telychian regional base level curves for Siberia, Kazakhstan and Cathaysia (South China) showing levels of correspondence (see Fig. 7 for explanation).

**Figure 12**. Comparison of the Type Llandovery relative base level curves with a selection of published late Hirnantian to early Telychian regional base level curves for Peri-Gondwana and Gondwana showing levels of correspondence (see Fig. 7 for explanation). Note, the curve for the Murzuq Basin is a conflation of two overlapping curves from different parts of the basin.

**Figure 13**. Comparison of the Type Llandovery relative base level curves with a selection of published proxy datasets (including distribution of South American glacial facies and isotope curves) for the late Hirnantian to early Telychian showing levels of correspondence (see Fig. 7 for explanation).

**Figure 14.** Comparison of the Type Llandovery relative base level curves with a selection of published datasets of trends in late Hirnantian to early Telychian graptolite populations and the oceanic events of Jeppsson (1998), showing levels of correspondence (see Fig. 7 for explanation).

**Figure 15.** Eustasy Index for late Hirnantian to early Telychian base level movements in the Type Llandovery area based on a comparison of the Type Llandovery relative base level curve with the 62* regional and global datasets presented in Figures 7-14 (see Supplementary

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Data for detailed breakdown of scores). Shaded areas indicate base level events that score incrementally higher than the mean EI value (see Supplementary Data) considered those most likely to include a dominant eustatic component. *The 62 datasets exclude the Type Llandovery relative base level curves, but include the part curve of Dewing (1999) used on Figure 9; the Welsh Basin turbidite sandbodies shown on Figure 6 are considered as a single dataset.

**Figure 16.** Matrix of global and regional forcing factors that interact to influence Eustasy Index scores (see text).

**Plate 1.** Coquina of adult and juvenile *Pentamerus oblongus* valves, solitary rugose corals and bivalves in topset sandstone facies, Derwyddon Formation, Crychan Forest track section, UK National Grid Reference [SN 853 385].

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Table 1. Range of palaeogeographical (see Fig. 1) and proxy datasets used in the calculation of the Eustasy Index for Type Llandovery base level movements as shown on Fig. 15 (see text and Supplementary Data). * Does not include Type Llandovery datasets excluded from the scoring process.

| **Palaeogeographical and/or proxy datasets** | | **Relevant text figure** | **Number of datasets** |
|---|---|---|---|
| UK (Avalonian & Iapetus)* | | 7 | 6 |
| Laurentia | | 9,10 | 13 |
| Baltica | | 10 | 6 |
| Siberia | | 11 | 5 |
| Kazakhstan | | 11 | 1 |
| Cathaysia (South China) | | 11 | 2 |
| Peri-Gondwana | | 12 | 3 |
| Gondwana | | 12 | 6 |
| Global | | 8 | 7 |
| Proxy datasets | Glacial deposits | 13 | 1 |
| | Isotopes | 13 | 5 |
| | Graptolite flux | 14 | 6 |
| | Oceanic model | 14 | 1 |
| **Total number of datasets** | | | 62 |

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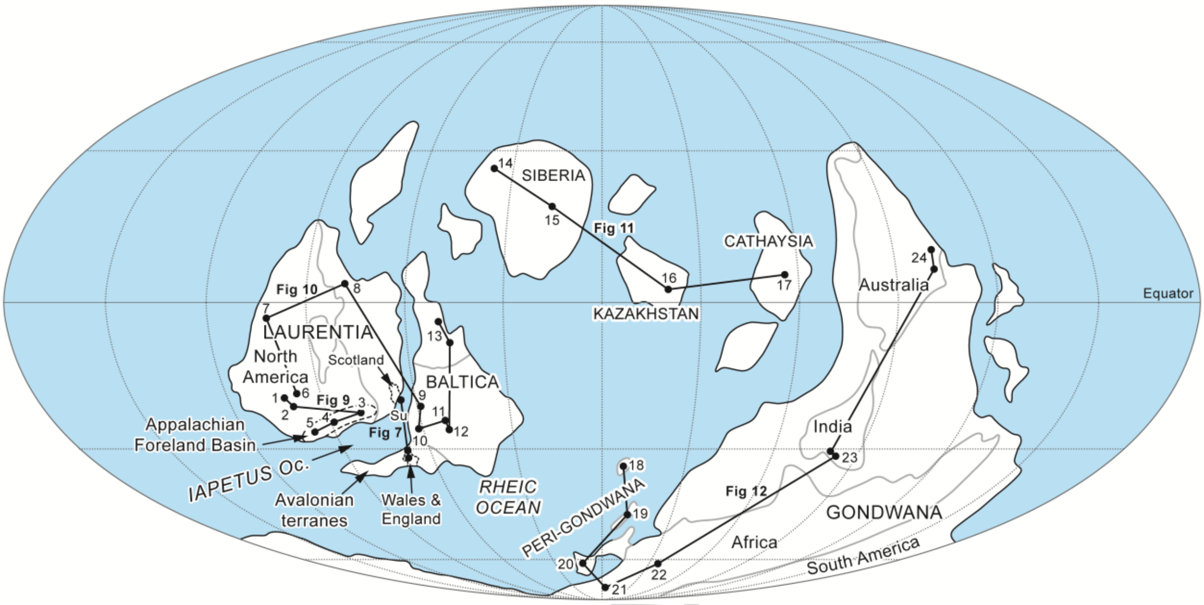

Figure 1

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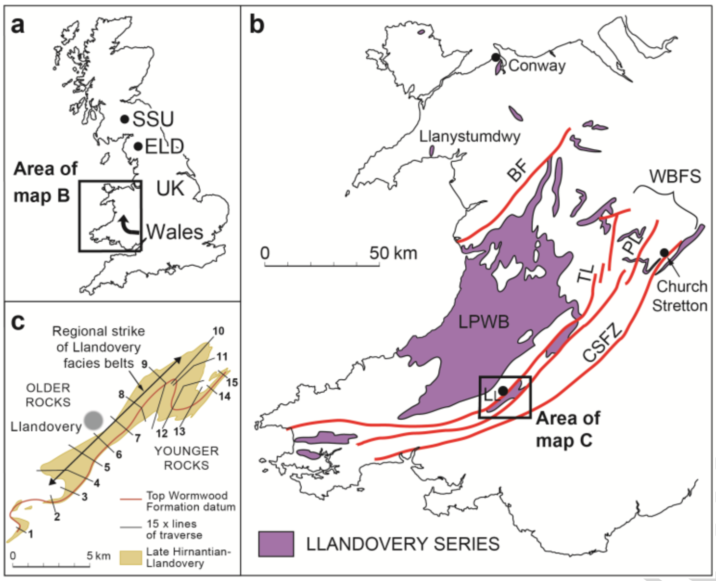

Figure 2

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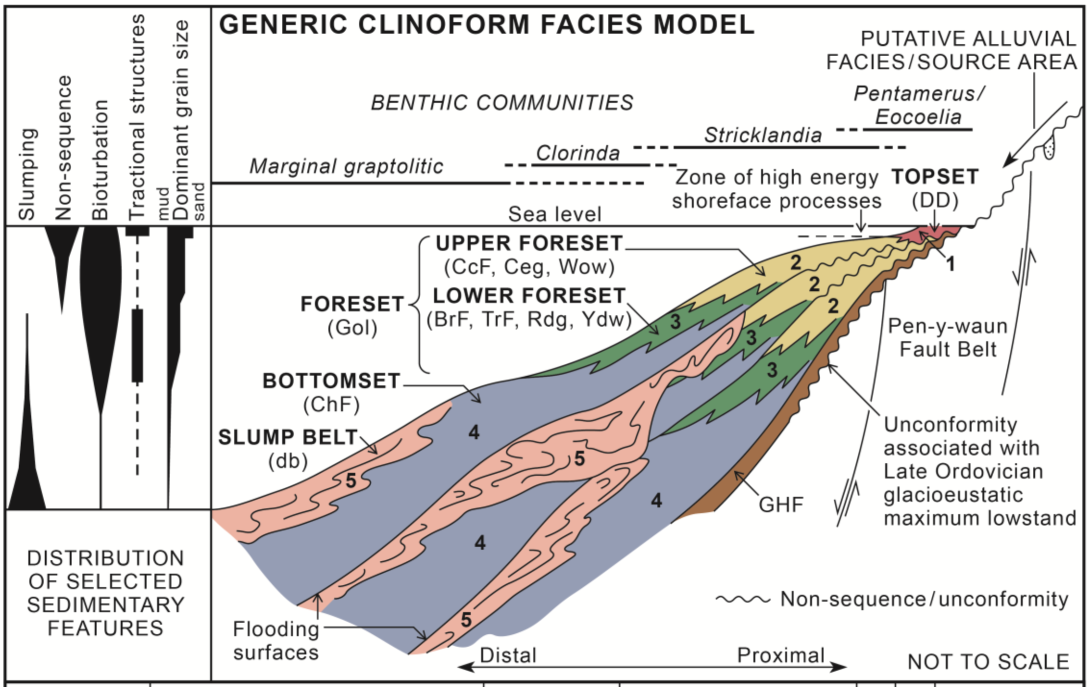

| Clinoform facies belts | Principal component lithologies (inc. typical relative percentages) | Formation/ member | Principal sedimentary structures | BA | BI | Selected trace fossils |
|---|---|---|---|---|---|---|
| **1 TOPSET** | Sandstone, medium-bedded, medium- to coarse-grained (95) | **DD, Wow** | Cross-stratification; pentamerid brachiopod coquinas; common burrow-mottling | 2/3 | 2-4 | *Skolithos, Diplocraterion* |
| | Pebble and granule conglomerate (2-5) | | | | | |
| **2 UPPER FORESET** | Sandstone, intensely bioturbated, thick-bedded, fine- to medium-grained, with dispersed granules and pebbles (20) | **CcF, Ceg, Wow, Gol** | Pervasive burrow-mottling; parallel- and cross-lamination only common in thin sandstone beds; pebble and granule lags | 3/4 | 4-5 | *Teichichnus, Palaeophycus, Planolites, Zoophycus, Chondrites* |
| | Muddy sandstone, intensely bioturbated, thick-bedded, fine- to medium-grained, with dispersed granules and pebbles (70) | | | | | |
| | Sandstone as thin, sharp-based beds and laminae with bioturbated tops (2-10) | | | | | |
| **3 LOWER FORESET** | Sandy mudstone, strongly bioturbated, medium bedded, with dispersed coarse sand grains and granules (85) | **BrF, TrF, Rdg, Gol, Yst, Ydw** | Pervasive burrow-mottling (sparse in Ydw); parallel- and cross-lamination only common in thin sandstone and siltstone beds | 5 | 3-4 | *Thalassinoides, Planolites, Zoophycus, Chondrites* |
| | Sandstone as thin, sharp-based beds and laminae with bioturbated tops (2-10) | | | | | |
| | Silty mudstone with thin, weakly bioturbated sandstone and siltstone beds and laminae (5) | **Ydw** | | | 2-3 | *Zoophycus, Chondrites* |
| **4 BOTTOMSET** | Mudstone, silty, thin-bedded with diffuse colour banding (90) | **ChF** | Poorly preserved hemipelagic lamination; sparse burrow-mottling; minor slump-related convolutions | 6 | 1-2 | *Chondrites* (small diameter) |
| | Thin, unbioturbated beds and laminae of sandstone and siltstone (2-10) | | | | | |
| **5 SLUMP BELT** | Disturbed bottomset mudstone (75-95) | **db (locally affects most formations)** | Slump folds and convolute bedding; listric surfaces; basal and internal slide planes | Not applicable | | |
| | Mélange/debrite – mudstone with ill-sorted angular and rounded clasts (5-20) | | | | | |
| | Large displaced rafts of other facies belt lithologies (dominant in some slump complexes) | | | | | |

Figure 3

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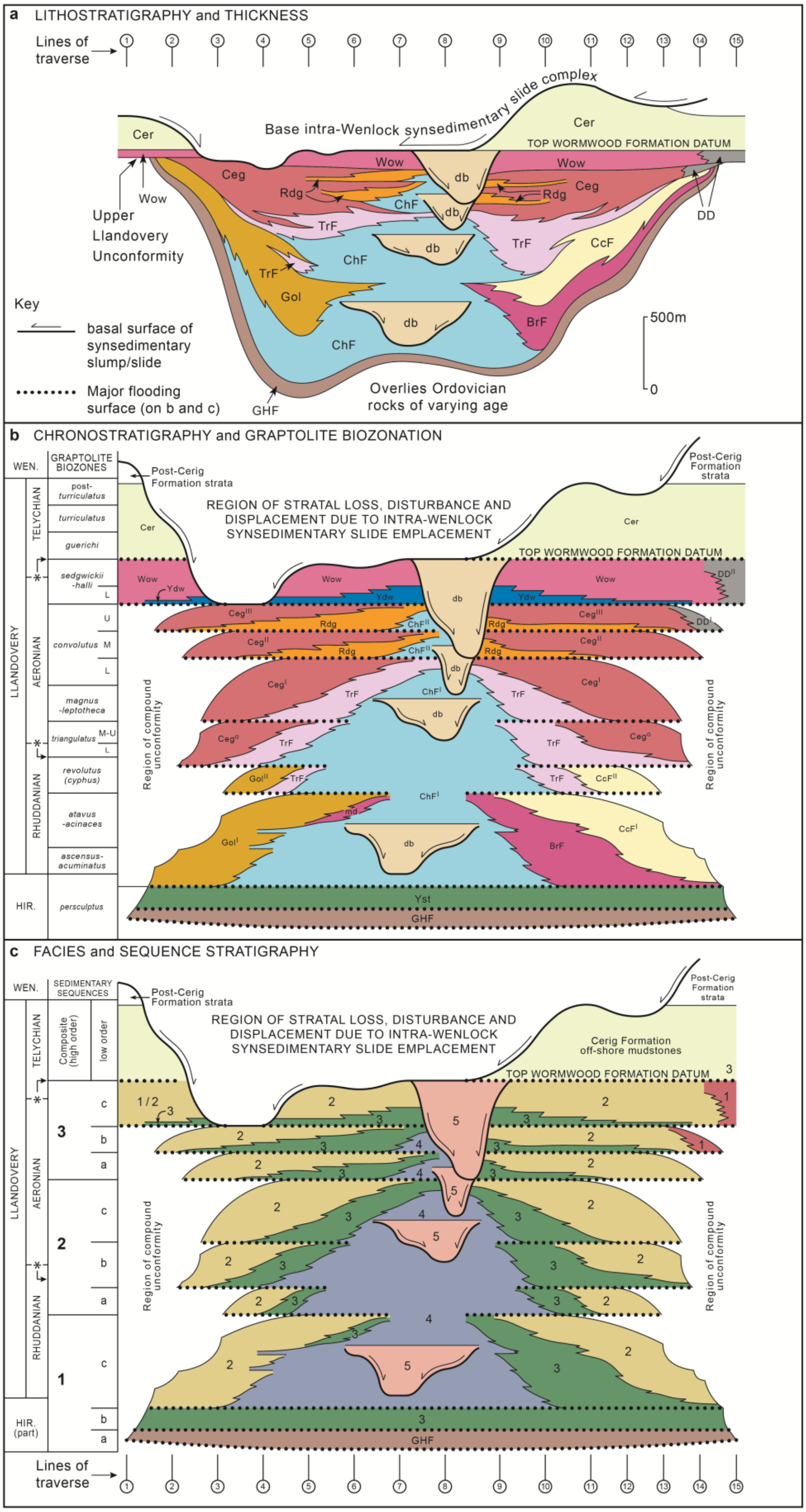

Figure 4

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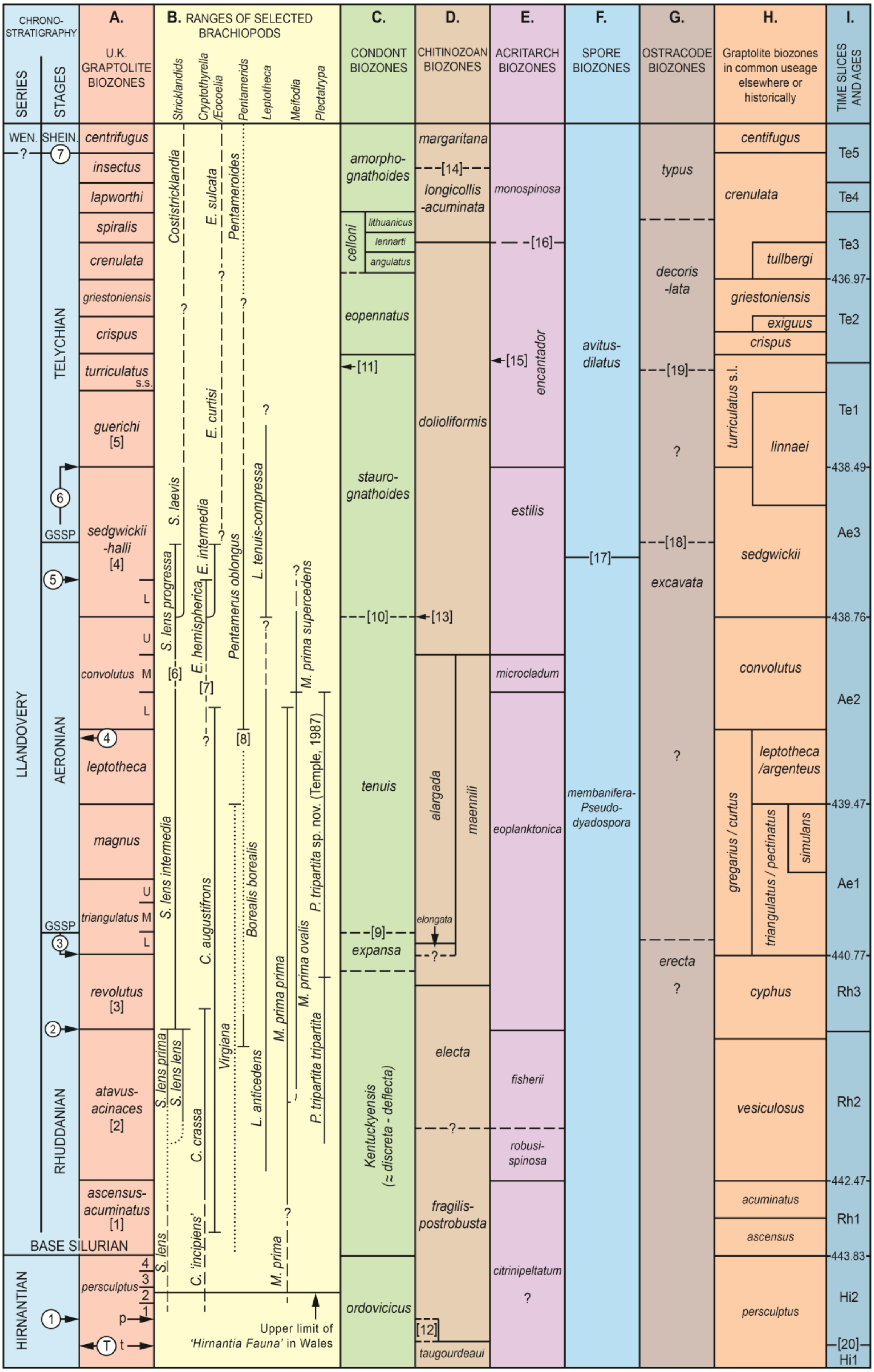

Figure 5

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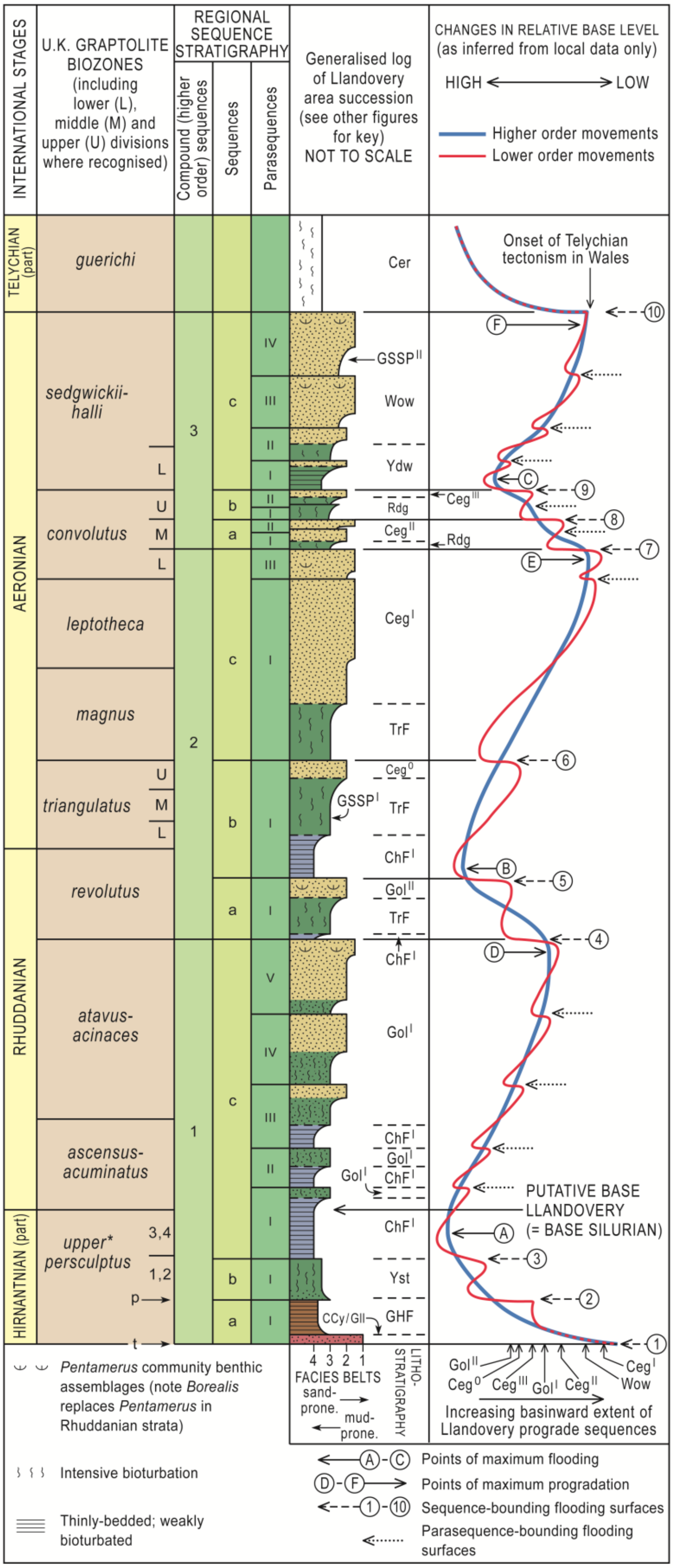

Figure 6

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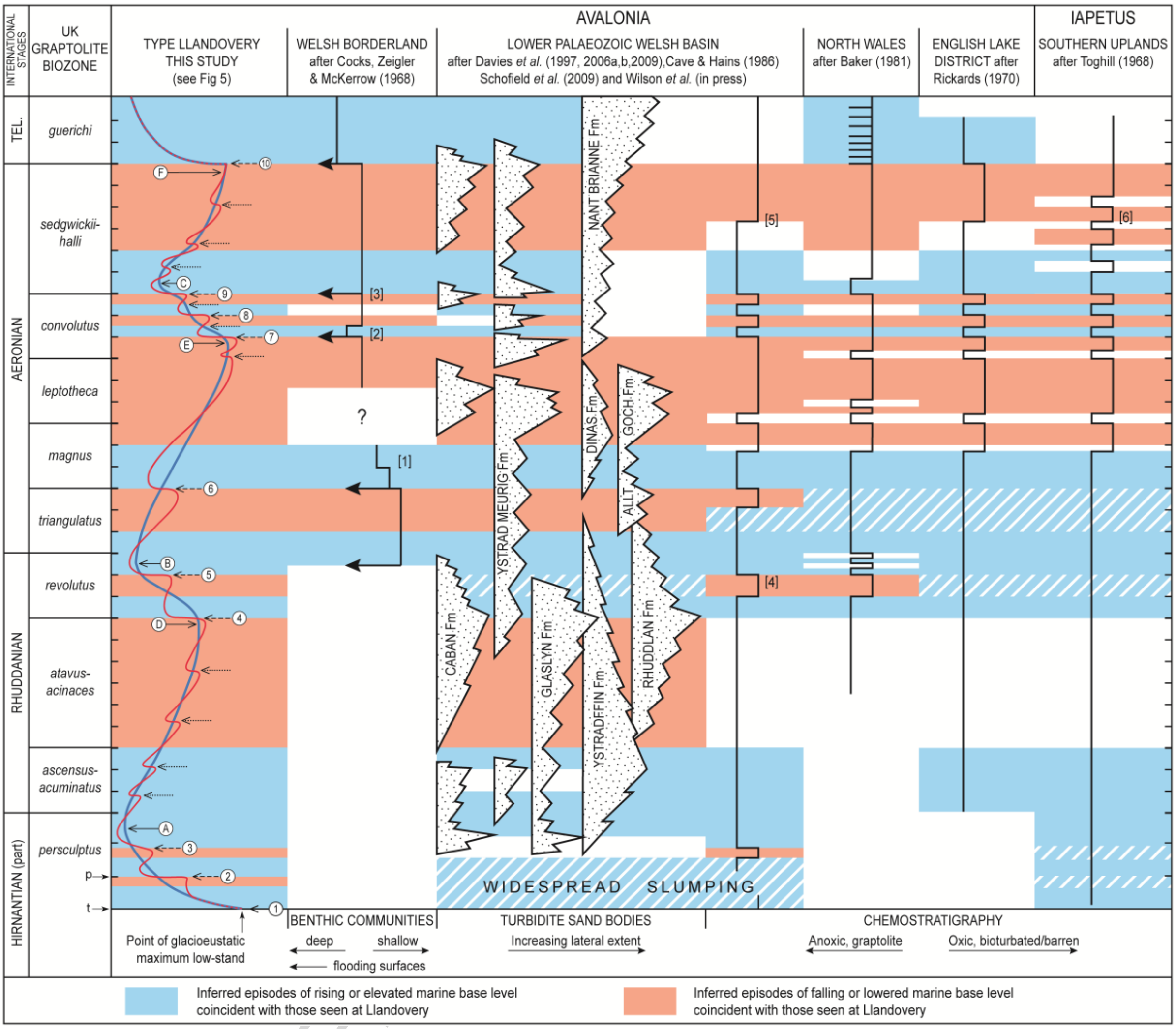

Figure 7

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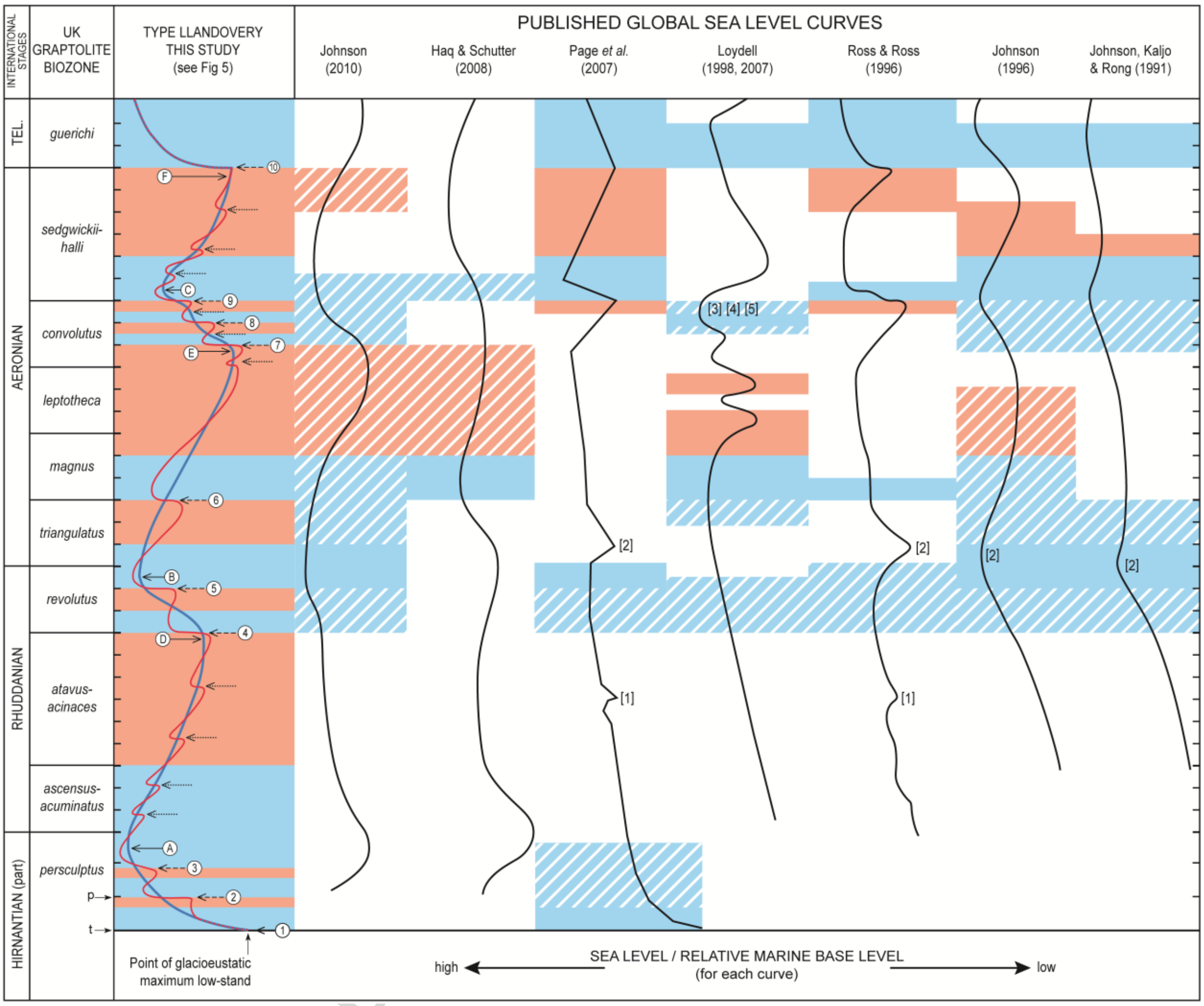

Figure 8

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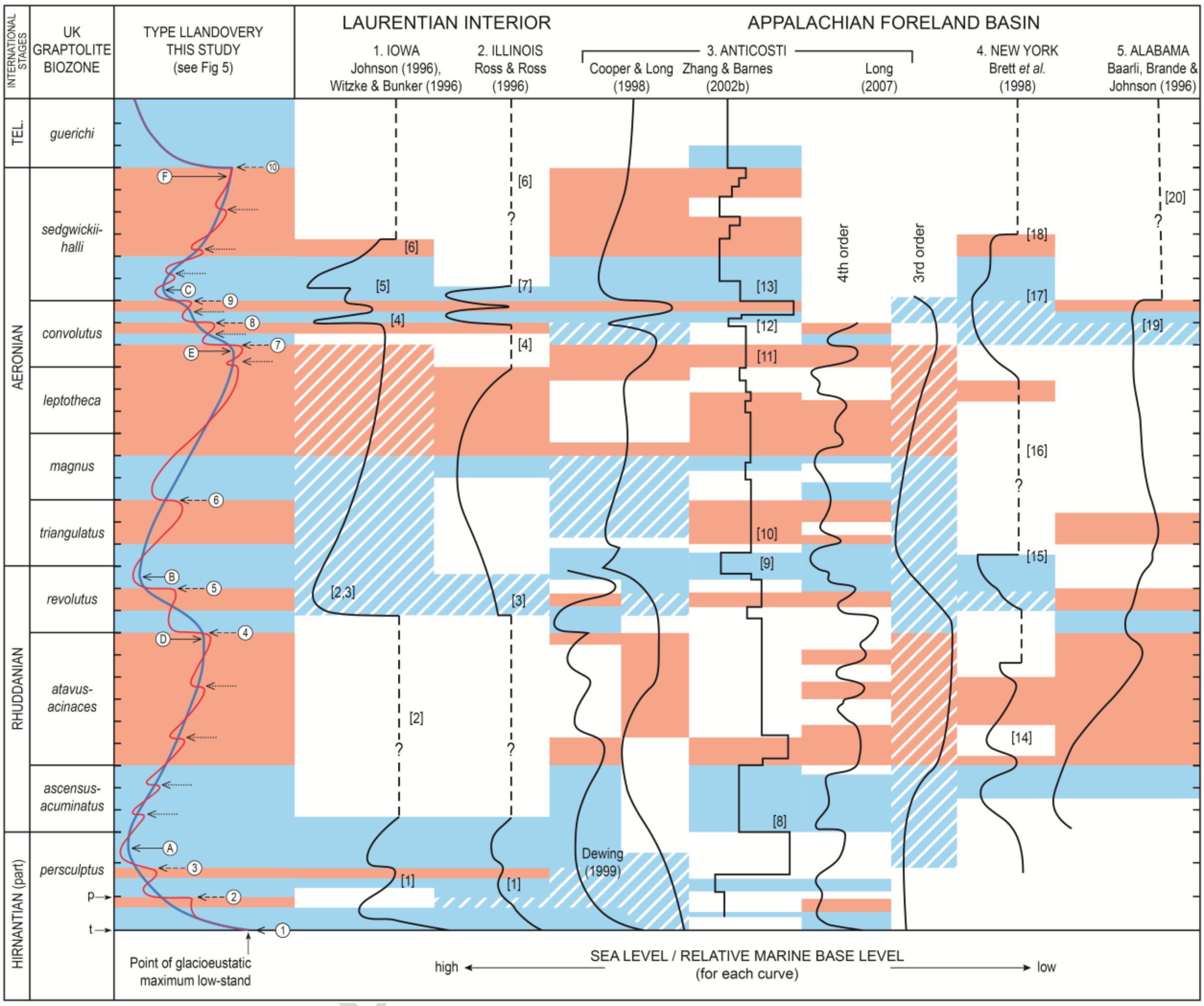

Figure 9

ACCEPTED

ACCEPTED MANUSCRIPT

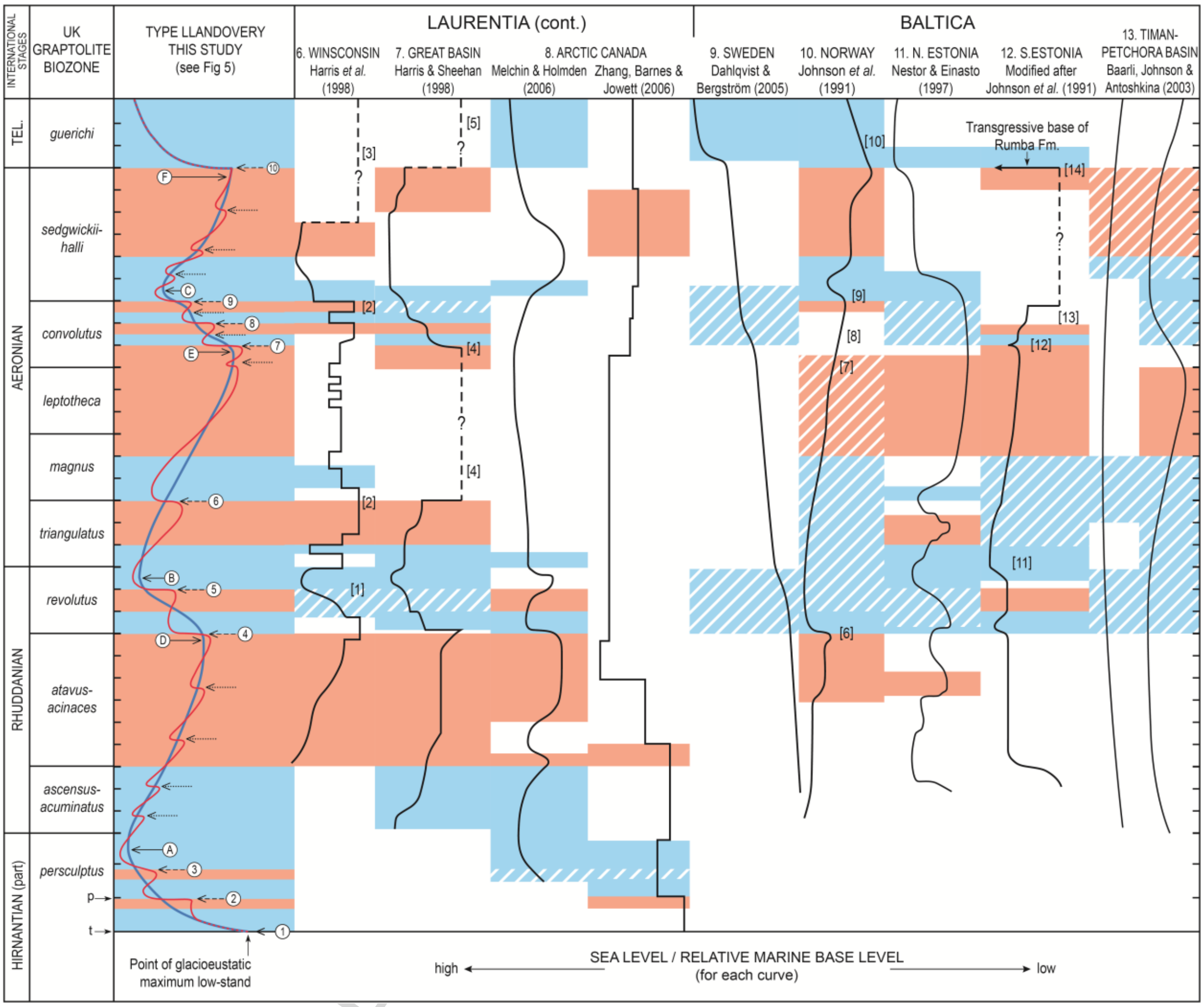

Figure 10

ACCEPTED MANUSCRIPT

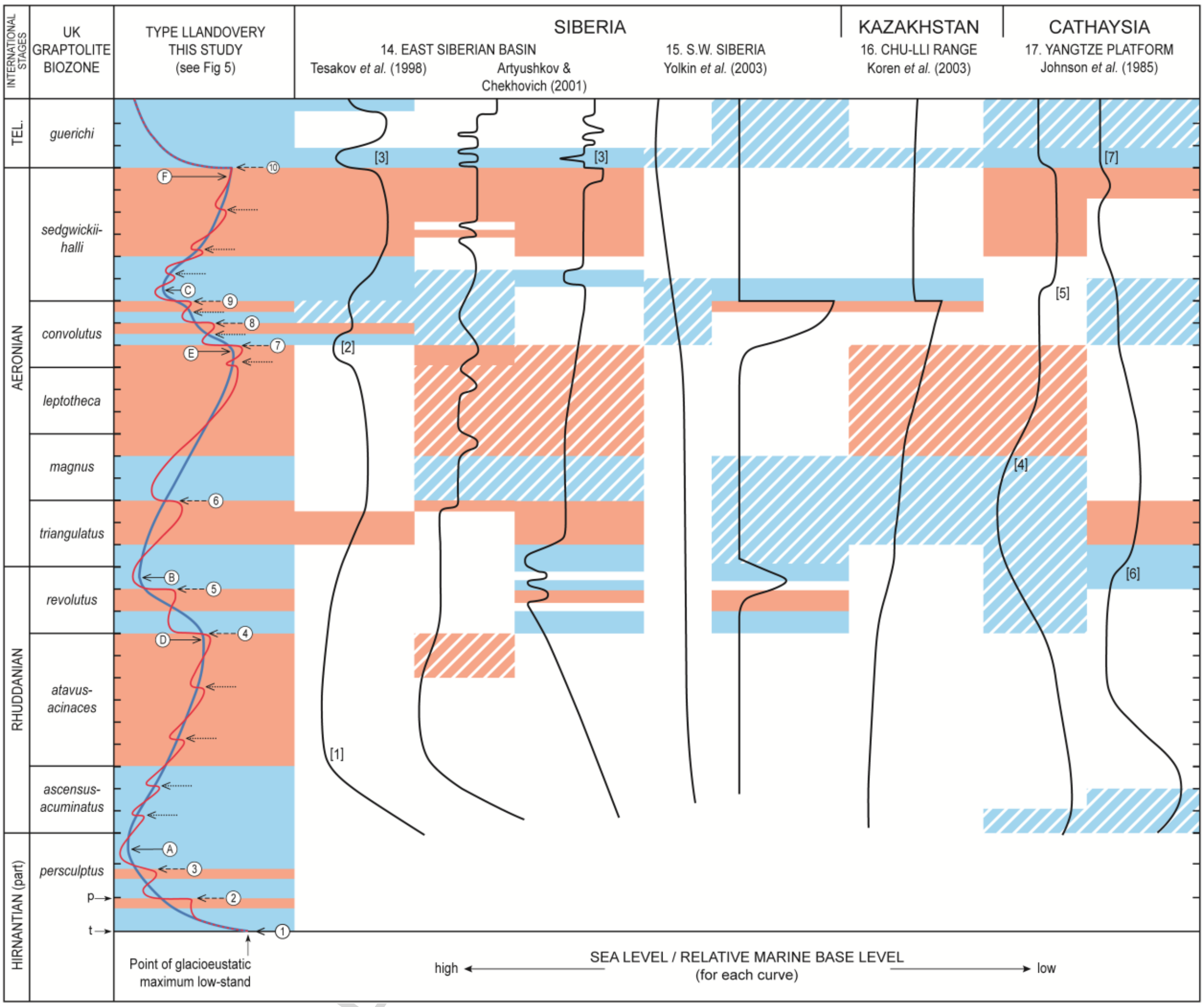

Figure 11

ACCEPTED

ACCEPTED MANUSCRIPT

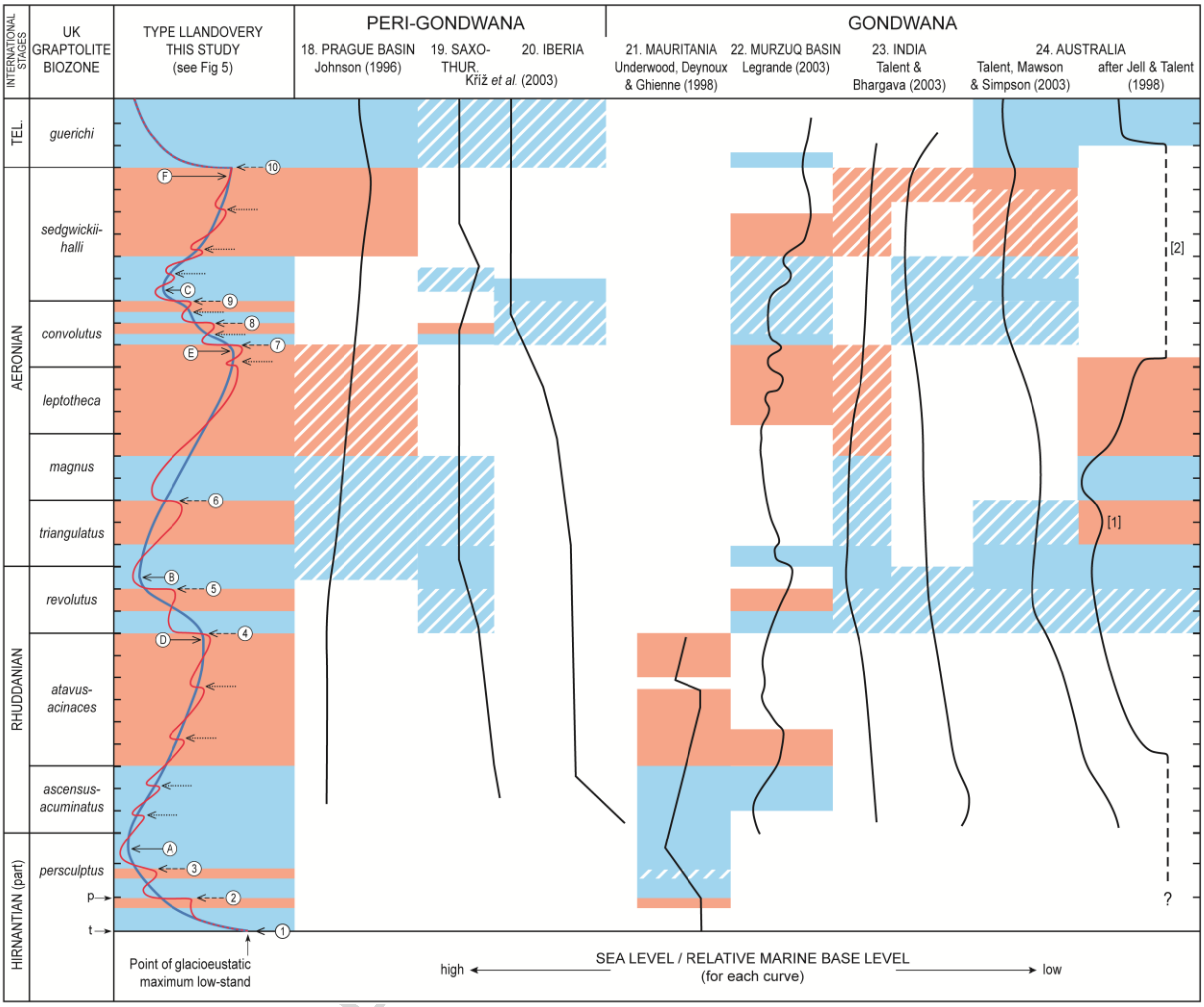

Figure 12

ACCEPTED

ACCEPTED MANUSCRIPT

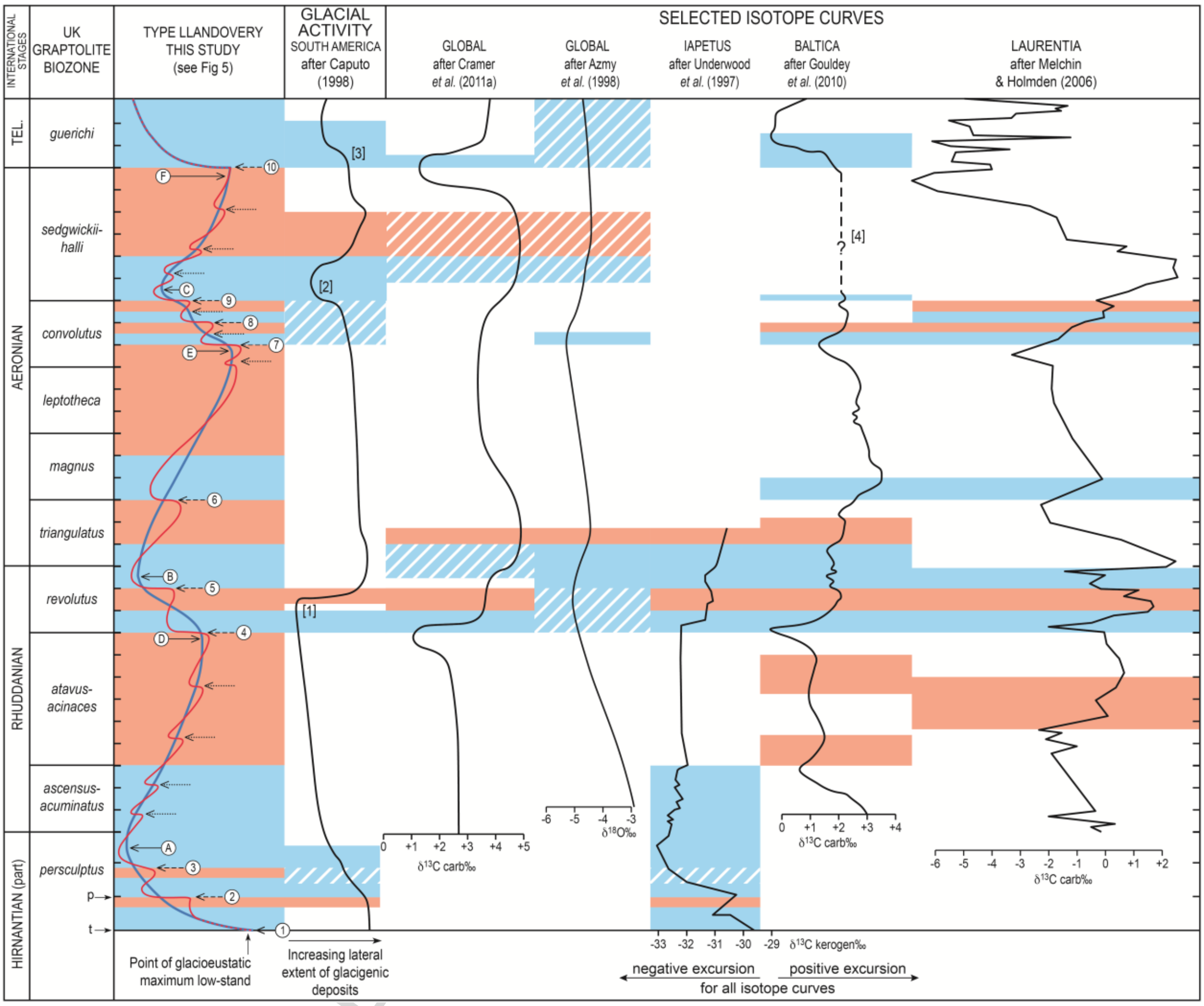

Figure 13

ACCEPTED

ACCEPTED MANUSCRIPT

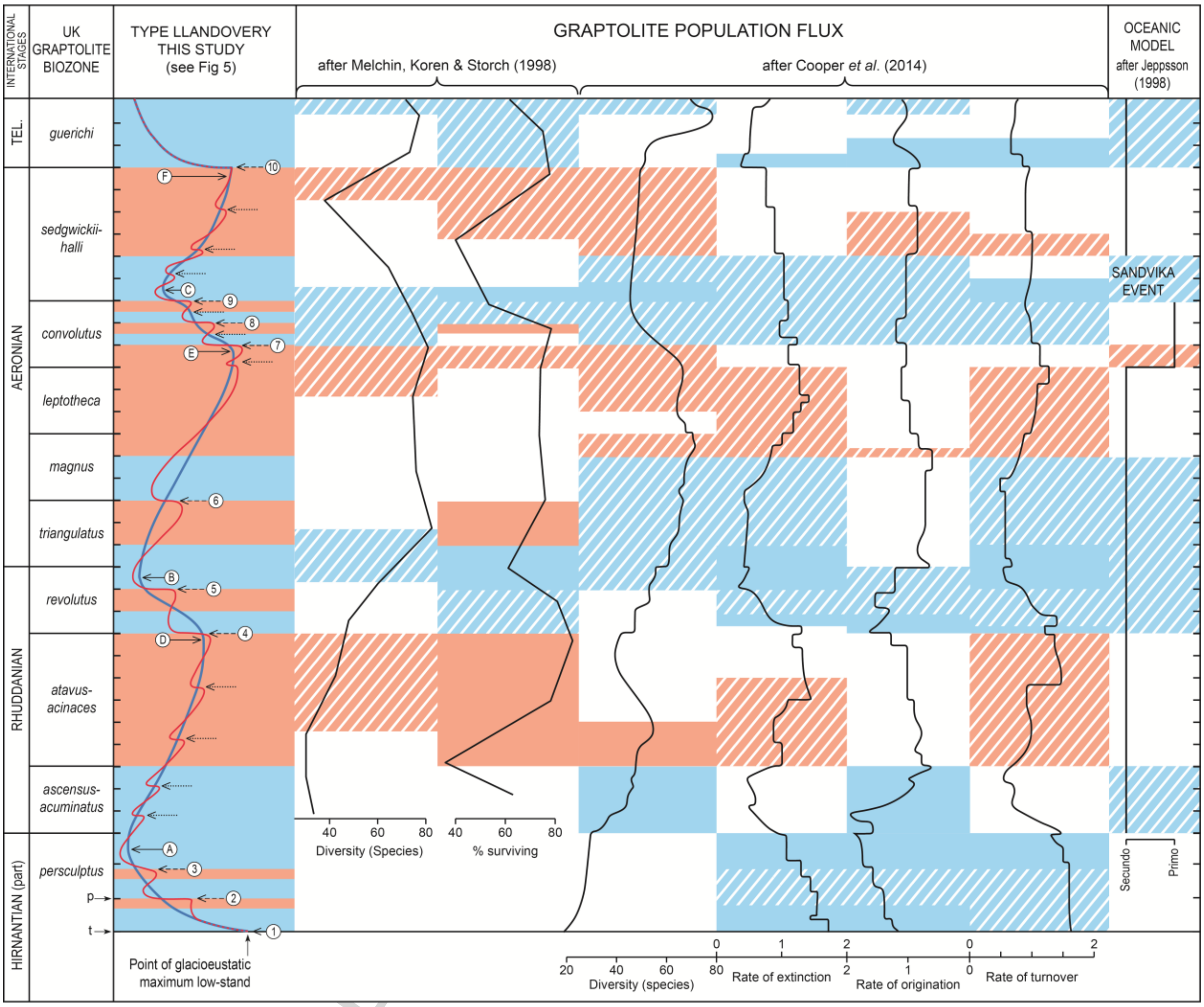

Figure 14

ACCEPTED

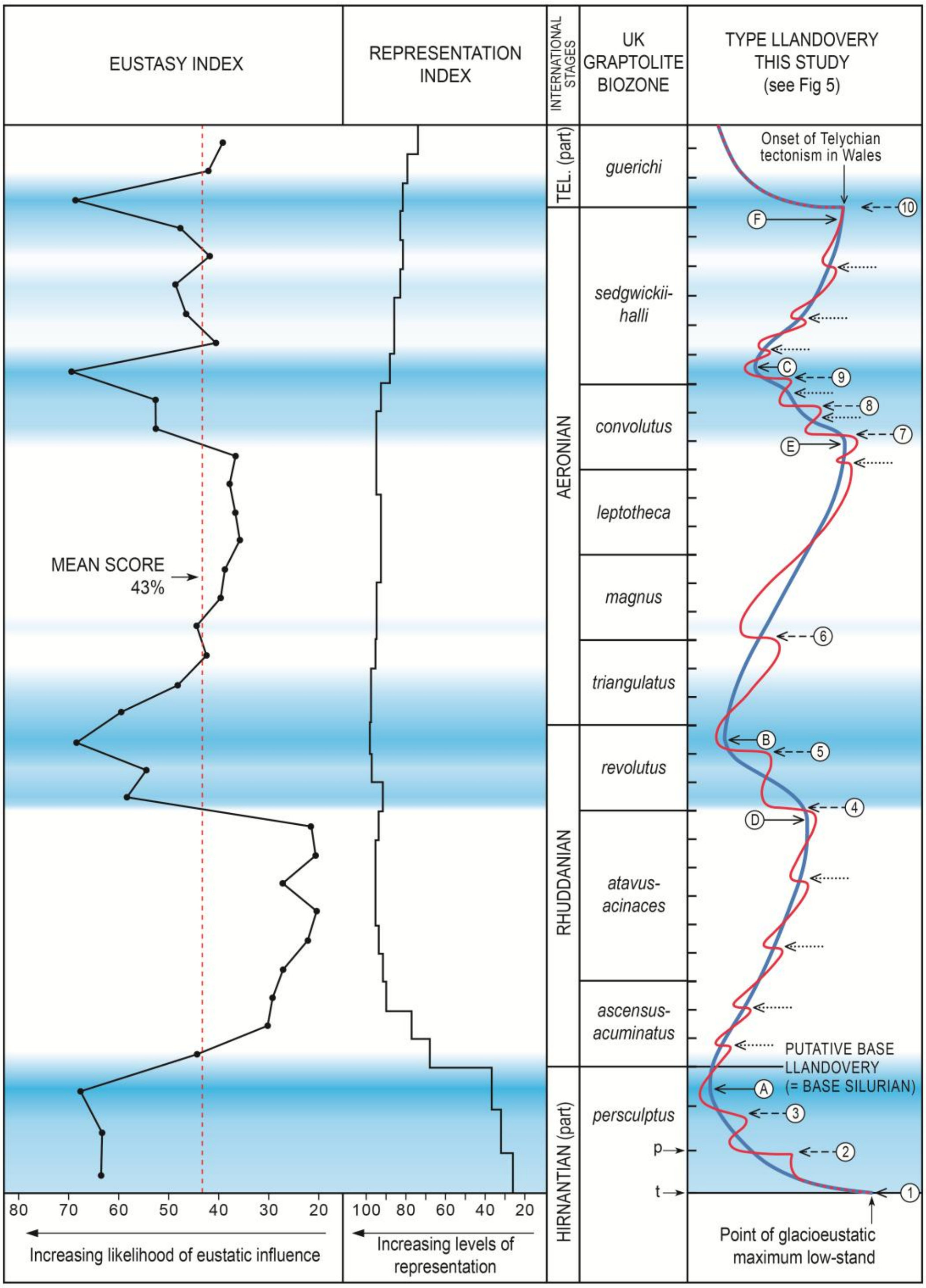
EUSTASY INDEX
REPRESENTATION INDEX
INTERNATIONAL STAGES
UK GRAPTOLITE BIOZONE
TYPE LLANDOVERY THIS STUDY (see Fig 5)
TEL. (part)
AERONIAN
RHUDDANIAN
HIRNANTIAN (part)
guerichi
sedgwickii-halli
convolutus
leptotheca
magnus
triangulatus
revolutus
atavus-acinaces
ascensus-acuminatus
persculptus
p
t
MEAN SCORE 43%
Onset of Telychian tectonism in Wales
PUTATIVE BASE LLANDOVERY (= BASE SILURIAN)
Point of glacioeustatic maximum low-stand
A
B
C
D
E
F
1
2
3
4
5
6
7
8
9
10
80 70 60 50 40 30 20
Increasing likelihood of eustatic influence
100 80 60 40 20
Increasing levels of representation

Figure 15

ACCEPTED MANUSCRIPT

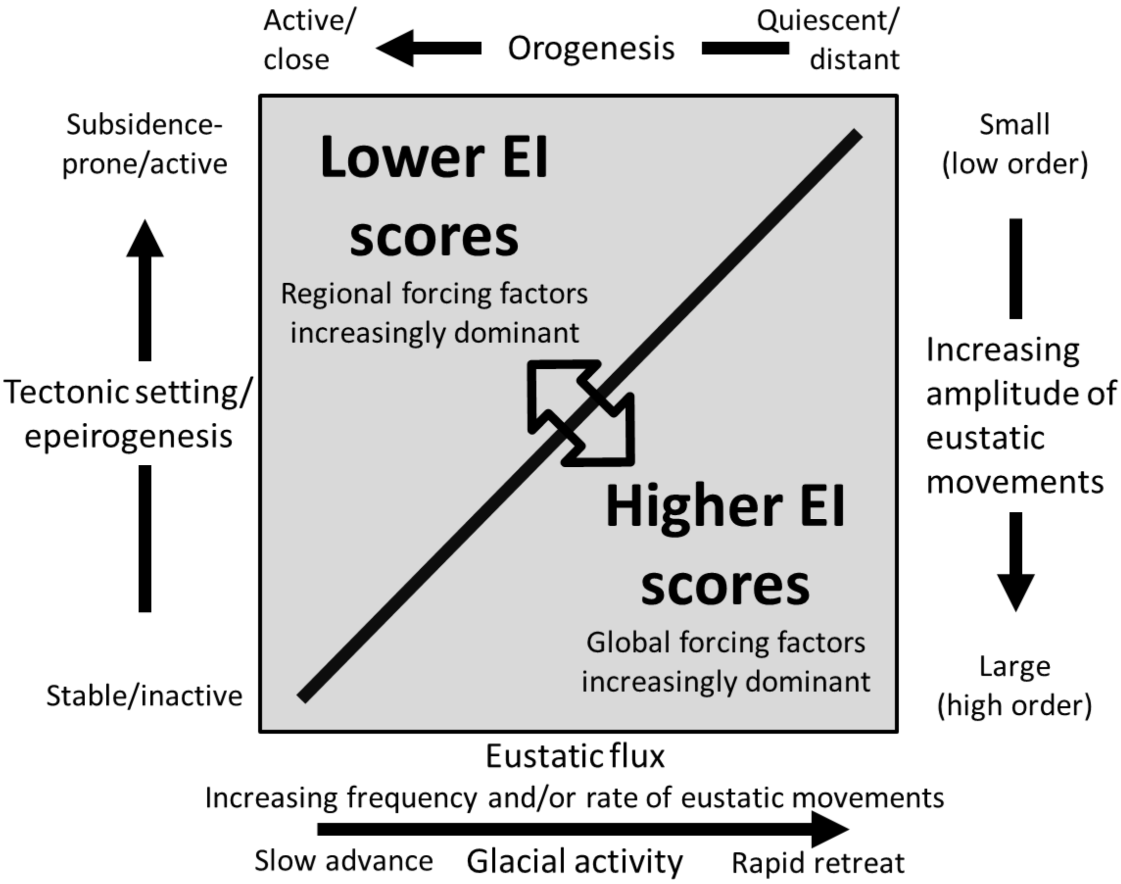

Figure 16

ACCEPT

ACCEPTED MANUSCRIPT

Plates 1

ACCEPTED