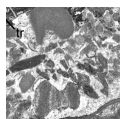


The Homeric (Silurian) stratigraphy of the Usk Inlier of Wales, UK: integration of carbon isotope data and sequence stratigraphy

DAVID C. RAY, LISA OOSTRA & EMILIA JAROCHOWSKA



The globally recognised Homeric (Silurian) carbon isotope excursion (CIE) is reported for the first time from the Usk Inlier of the southern part of the Midland Platform (Avalonia), Wales. There the first and second peaks of the Homeric CIE are documented from the limestone lithofacies of the Ton Siltstone (Trostre Limestone Member) and Usk Limestone formations. The magnitudes of the CIE peaks are strongly influenced by the lithofacies with the relatively offshore nodular limestones of the Trostre Limestone Member containing a diminutive first peak (0.6‰), when compared with the second peak (2.3‰) that is developed in the nearshore Usk Limestone Formation. A sequence stratigraphic interpretation has been facilitated by the occurrence of competing siliciclastic and carbonate sedimentary systems, which result from the proximity of the Usk Inlier to the landmass of Pretannia. Notably, the onset of the Homeric CIE is well expressed, and is associated with regressive wave-rippled sandy siltstones within the Ton Siltstone Formation, with the overlying first peak of the CIE within nodular limestones (Trostre Limestone Member) that are representative of the early transgressive systems tract. Based upon the integration of carbon isotope data and sequence stratigraphy the Usk Inlier succession can be correlated with the Much Wenlock Limestone Formation of the wider Midland Platform, as well as key successions upon Baltica. • Key words: Silurian, Wenlock, carbon isotope, stratigraphy, Usk Inlier, Midland Platform, Avalonia.

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The Usk Inlier (Monmouthshire, Wales) is the result of a periclinal fold that exposes some 600 m of Silurian rocks, the oldest of which belong to the Wenlock Series (Walmsley 1982). The inlier contains a shelf succession, which, being at the confluence of competing sedimentary systems, comprises skeletal carbonates and sandstones. During Homeric times (late Wenlock Epoch) the Usk study area was located near the northern margin of the landmass of Pretannia, and was within a sub-basin (Usk-Woolhope Basin) developed on the south-westerly margin of the Midland Platform; an area of gently subsiding shallow marine shelf, which occupied south Wales, the Welsh Borders and much of central England (Bassett *et al.* 1992, Butler *et al.* 1997) (Fig. 1). From a global viewpoint, the Midland Platform formed part of the eastern Avalonia microcontinent and was situated somewhere between 30° and 13° S of the equator (Torsvik *et al.* 1993, Golonka *et al.* 2023). The Homeric was a time of considerable global environmental change, associated with climate shifts, glacio-eustatic sea-level fluctuations, marine biodiversity

crises impacting conodonts and graptolites (*i.e.* Mulde Extinction Event, *lundgreni* Event or Big Crisis), and carbon isotope excursions (Jeppsson *et al.* 1995, Johnson 2006, Calner 2008, Cramer *et al.* 2012, Trotter *et al.* 2016). Many of these changes have been used as a means of correlation and allow for the development of a high-resolution stratigraphy for rocks of this age (Cramer *et al.* 2015). In particular, the positive double-peaked Homeric carbon isotope excursion (CIE) is recognised from Avalonia (*e.g.* Corfield *et al.* 1992; Fry *et al.* 2017; Ray *et al.* 2020, 2025) and other palaeocontinents including Baltica, Laurentia and peri-Gondwana (*e.g.* Porębska *et al.* 2004, Cramer *et al.* 2006, Calner *et al.* 2012, Frýda & Frýdová 2014, Jarochowska *et al.* 2016, Manda *et al.* 2019, Klock *et al.* 2025). The Homeric CIE and associated sea-level changes are constrained within multiple sections by age diagnostic graptolite and conodont occurrences, and accordingly can be correlated to the globally recognised Homeric stage slices (Ho1, Ho2 and Ho3) and the geologic time-scale (Fig. 2) (Cramer *et al.* 2011, Melchin *et al.* 2020).

The succession under investigation here consists of the Ton Siltstone Formation, including its middle subdivision, the Trostre Limestone Member, and the Usk Limestone Formation. The lithostratigraphy, age constraints, and correlation of this succession have been hindered by limited exposure and a scarcity of age-diagnostic fossils. Notably, the thickness and lateral extent of lithofacies are difficult to determine, and this has contributed to miscorrelation between the Trostre Limestone Member and the Usk Limestone Formation, resulting in anomalous thickness variations quoted for the Usk Limestone Formation (Walmsley 1958, Barclay 1989). Similarly, a debate regarding the correlation of the limestones at Usk with those developed elsewhere on the Midland Platform (Hurst 1975, Bassett 1976), has contributed to the estab-

lishment of competing lithostratigraphic schemes. Consequently, the Ton Siltstone and Usk Limestone formations are reflective of lithostratigraphic divisions unique to the Usk Inlier (Hurst 1975, Barclay 1989), while the alternative divisions (Wenlock Shale or Coalbrookdale Formation = Ton Siltstone Formation and underlying Glascoed Mudstone Formation; Wenlock Limestone or Much Wenlock Limestone Formation = Usk Limestone Formation) infer lithostratigraphic correlation with successions developed elsewhere on the Midland Platform (Walmsley 1958, Bassett 1974, Sheridan 2002). Herein we follow the lithostratigraphic subdivisions used by the British Geological Survey (Barclay 1989, Davies 2025) (Fig. 2), but note that this scheme has not been universally adopted (*e.g.* Cocks *et al.* 1992).

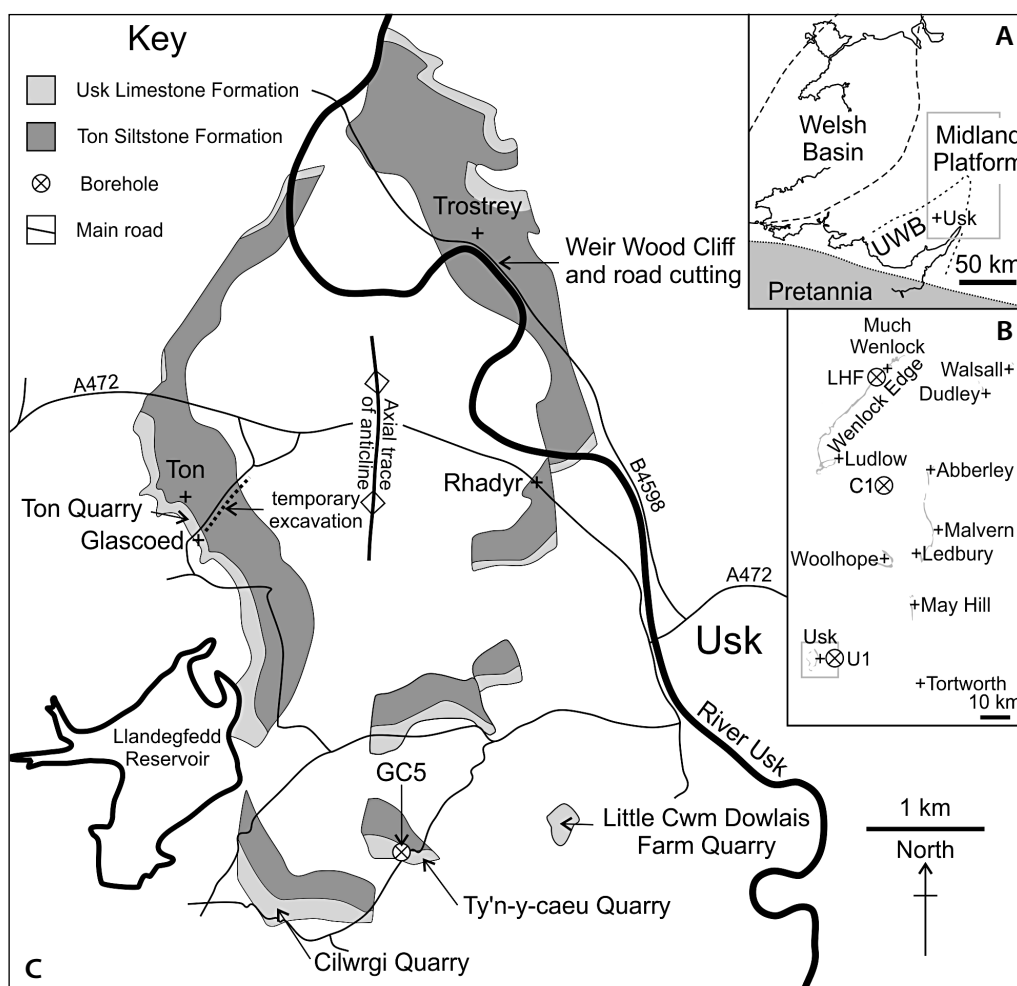


Figure 1. Palaeogeography and location maps for the mid-Silurian succession in Wales and central England. • A – generalised palaeogeography showing the location of the landmass of Pretannia, the shallow marine shelf of the Midland Platform, including the Usk-Woolhope Basin (UWB), and the deeper waters of the Welsh Basin. The area containing the Welsh Borders and central England are highlighted by a rectangular box. • B – outcrops of Much Wenlock Limestone and Usk Limestone formations (grey) upon the Midland Platform, with the study area highlighted by a square box. Abbreviations: C1 – Collington-1 Borehole (SO 6460 6100); LHF – Lower Hill Farm Borehole (SO 5817 9788); U1 – Usk-1 Borehole (SO 4020 0085). • C – outcrops of the Ton Siltstone and Usk Limestone formations situated around the Usk Inlier (modified from Walmsley 1958; Barclay 1989), showing the locations given in the text. Abbreviation: GC5 – Gas Council 5 Borehole (ST 3513 9883).

The biostratigraphic framework for the Ton Siltstone and Usk Limestone formations is based upon conodonts. Our re-evaluation of the conodonts from the upper Ton Siltstone Formation (Weir Wood Cliff; Austin & Bassett 1967) identifies the conodont *Ozarkodina bohémica* (Austin & Bassett 1967, pl.14, figs 19, 20), and questionably *Ozarkodina sagitta sagitta* (Austin & Bassett 1967, pl. 14, fig. 16); originally reported as the form taxa *Spathognathodus edithae* and *Spathognathodus sagitta rhenanus*, the latter corresponding to the biological taxon *Ozarkodina sagitta rhenana* (see Aldridge 1975, p. 326). In addition, the conodonts *Ozarkodina bohémica* and *Wurmiella* (*Ozarkodina* in the original text) *excavata* have been reported from the Usk Limestone Formation (Cilwrgi Quarry; Aldridge *et al.* 2000, p. 208). These conodonts,

along with shelly faunas, are considered indicative of a late Wenlock (Homerian) age (Bassett 1974; Aldridge *et al.* 2000, p. 209; Märss & Miller 2004, fig. 3). They occur above a record of the long-ranging Wenlock graptolite *Monograptus flemingii flemingii* from the underlying Glascoed Mudstone Formation (Bassett 1974, Barclay 1989), and below graptolite records indicative of the lower Ludlow (Gorstian) from within the overlying Lower Forest Beds (Walmsley 1958, Squirrell & Downing 1969, Bassett 1976).

Although the consensus view is that the Ton Siltstone and Usk Limestone formations are of late Wenlock age (Walmsley 1982, Barclay 1989, Cocks *et al.* 1992), uncertainty in biostratigraphic constraint may accommodate all or part of the Usk Limestone Formation

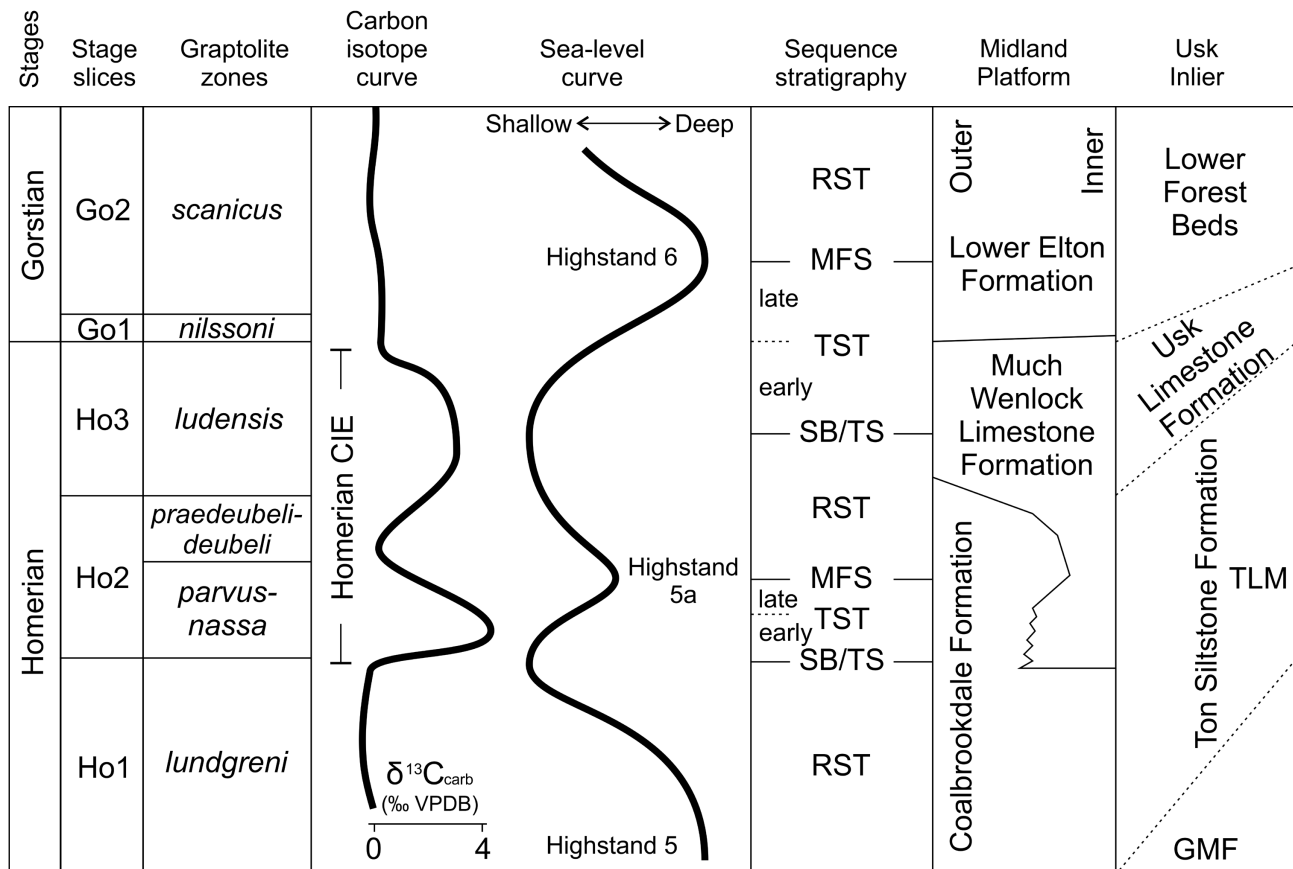


Figure 2. The relationship between the stages, stage slices and graptolite zones of the geologic timescale (Melchin *et al.* 2020), carbon isotope trends, global sea-level change (eustasy), regional sequence stratigraphy and lithostratigraphy. The carbon isotope curve, showing the Homerian carbon isotope excursion (CIE), is schematic and based upon regional and global curves (Cramer *et al.* 2012, Fry *et al.* 2017, Melchin *et al.* 2020, Ray *et al.* 2020), the sea-level curve and associated highstands follow Johnson (2006), and the sequence stratigraphy reflects regional interpretations (Ray *et al.* 2020, 2025). Across the Midland Platform the following systems tracts and their bounding surfaces are recognised (after Ray *et al.* 2020, 2025): SB/TS – sequence boundary and combined transgressive surface; TST – transgressive systems tract; MFS – maximum flooding surface; RST – regressive systems tract. The transgressive systems tract can be divided into early (slow) and late (fast) phases of sea-level change. The Midland Platform lithostratigraphy shows age differences in the Much Wenlock Limestone Formation between the inner and outer parts of the platform. Successions representative of the outer platform include southern Wenlock Edge and Ludlow, while the inner platform is representative of Dudley, Walsall, Abberley, Malvern and May Hill (Fig. 1). The Usk Inlier lithostratigraphy shows the uncertainty in the age constraint and correlation prior to our study. Abbreviations: GMF – Glascoed Mudstone Formation; TLM – Trostre Limestone Member.

within the Gorstian, as has been previously proposed. Notably, based on a study of brachiopod ecology and sea-level change it has been argued that the Usk Limestone Formation occurred above a widely recognizable end-Wenlock transgressive event, and is therefore of early Ludlow age (Hurst 1975) (Fig. 2).

In the last few decades the majority of Homerician outcrop belts and inliers on the Midland Platform have been re-investigated, with the nearby May Hill Inlier (*c.* 40 km northeast of the Usk Inlier) being the most recently studied (Ray *et al.* 2025). These investigations have resulted in a high-resolution stratigraphic framework based on correlation using the Homerician CIE, sequence stratigraphy, lithofacies, and bentonite horizons, and include sections containing age-diagnostic fossils and a radioisotope date, thereby allowing correlation with the geologic timescale (Ratcliffe & Thomas 1999; Ray *et al.* 2010, 2013, 2020; Cramer *et al.* 2012; Blain *et al.* 2016; Fry *et al.* 2017).

This study identifies the globally recognised Homerician CIE, and associated eustatic sea-level changes, which have facilitated correlations with the geologic timescale, the rest of the Midland Platform of eastern Avalonia, as well as other palaeocontinents.

Representative sections and previous studies

Identification of representative sections

Fieldwork within the study area investigated exposures of the Ton Siltstone and Usk Limestone formations over an area approximately 8 km north to south and 4 km wide. The formations are exposed in a roughly elliptical outcrop belt, which encircles the Glascoed Mudstone Formation, is broken by numerous faults, and is situated to the immediate west of the town of Usk (Fig. 1). The aim was to identify extensive exposures representative of the succession, which were suitable for carbon isotope

analysis, sedimentary logging, lithofacies determination, and sequence stratigraphic interpretation. In particular, we visited the sites described in the Geological Conservation Review of British Silurian Stratigraphy (Aldridge *et al.* 2000, pp. 205–209), alongside key sections described in the mapping of the area (Walmsley 1958, Squirrell & Downing 1969, Barclay 1989), in sedimentary studies (Ratcliffe & Thomas 1999, Sheridan 2002) and within field guides (Walmsley 1982, White 1992, Sheridan *et al.* 2012, Cherns 2019). As a sequence stratigraphic interpretation is dependent upon traceable variations in lithofacies, and carbonate carbon isotope analysis requires the presence of carbonate rock, the monotonous and only sporadically calcareous argillaceous rocks of most of the Ton Siltstone Formation were avoided. Rather, our focus was on the upper Ton Siltstone Formation, with its calcareous subdivision the Trostre Limestone Member and associated sandy siltstone and sandstone horizons, as well as the Usk Limestone Formation and its lower and upper divisions (Figs 1, 3). Having identified the most suitable sites, data collection was undertaken with the aim of creating a composite section, and, in doing so, improving correlation and age constraint. These sites can be located using the Ordnance Survey National Grid reference system and include: Weir Wood Cliff (SO 3593 0416) – which contains the type section of the Trostre Limestone Member (Fig. 3A, B); Little Cwm Dowlais Farm Quarry (ST 3662 9903 and ST 3658 9902) – which contains the lower boundary of the Usk Limestone Formation, and the transition from the lower division into a near complete upper division (Fig. 3C, E); Cilwrgi Quarry (ST 3394 9835) – which contains the lower division of the Usk Limestone Formation (Fig. 3D); Ty'n-y-caeu Quarry (ST 3530 9876) – which contains much of the lower division of the Usk Limestone Formation and its transition with the upper division; Ton Quarry (SO 3326 0177) – which contains the transition from the Usk Limestone Formation into the Lower Forest Beds (Fig. 3F). It is stressed that the permission of landowners' must be sought to access most of these localities.

Figure 3. Measured sections within the Ton Siltstone and Usk Limestone formations. The hammer is 30 cm long (A, B, and highlighted in D, E). • A – Weir Wood Cliff showing the sandy siltstones developed within the upper Ton Siltstone Formation. The wave rippled surface (wr) is near the top of an upward coarsening succession (fine sandstone), which is below the base of the Trostre Limestone Member. The head of the hammer marks the base of an upward fining succession. An articulated crinoid stem (cs) occurs near the base of the exposure (see also Fig. 7A). • B – Weir Wood Cliff showing nodular limestones and silty mudstones from the middle of the Trostre Limestone Member, immediately above a minor gap in the succession. • C – Lower Little Cwm Dowlais Farm Quarry showing the boundary between the Ton Siltstone Formation and the lower division of the Usk Limestone Formation. The arrow marks the erosive boundary between the formations. • D – Cilwrgi Quarry showing the lower division of the Usk Limestone Formation. The arrow marks the boundary between bedded and biohermal limestones (flooding surface). • E – Upper Little Cwm Dowlais Farm Quarry with the arrow marking the boundary and flooding surface between the lower and upper divisions of the Usk Limestone Formation. Massive wave rippled grainstones developed near the top of the upper division are exposed at the top of the section. • F – Ton Quarry cave entrance, showing the boundary between the Usk Limestone Formation (ULF) and the Lower Forest Beds (LFB). The lower part of the succession shows alternations between grainstone-rudstone and silty marl beds (gr) (see Fig. 7F). A large (0.7 m across) coral colony (co) occurs near the top of the Usk Limestone Formation. The rock face is *c.* 4.5 m high.



Previous studies of the Ton Siltstone Formation

Exposures of the Ton Siltstone Formation are limited to cliffs along the River Usk, and road cuttings around Trostrey and Ton. The Ton Siltstone Formation is estimated to be 100 m thick, and consists mostly of sandy siltstones, siltstones, and silty mudstones, with lesser horizons of sandstone, and nodular limestones (Barclay 1989). In 1964, a temporary excavation across the central part of the inlier (Fig. 1) allowed for the most detailed description of the succession. There, alongside silty deposits, this succession contained rippled, coarse-grained micaceous sandstone beds at 4.5 m, 37.5 m and 45 m below a level considered to coincide with the base of the Usk Limestone Formation, as well as nodular limestones (Trostrey Limestone Member) at 15 m below this level (Bassett 1974, fig. 3). To the northwest of this excavation is the hamlet of Ton, near to which are the type sections of the Ton Siltstone Formation (SO 3294 0247 to SO 3324 0255). These contain intermittent lane-side exposures in the upper half of the formation (Barclay 1989), but are without exposures of nodular limestones and are lacking in distinctive sandstone beds. The nodular limestones of the Trostrey Limestone Member are < 10 m thick, correspond to the nodular limestone lithofacies of Ratcliffe and Thomas (1999), and occur near the top of the Ton Siltstone Formation. The type section occurs at Weir Wood Cliff (SO 3593 0416) (Fig. 3A, B), near the hamlet of Trostrey (Barclay 1989). There, the type Trostrey Limestone Member is under- and overlain by beds typical of the Ton Siltstone Formation, most of which are no longer accessible but are referred to in published descriptions (*i.e.* Weir Wood Cliff (Walmsley 1958, fig. 2) and Weir Wood Road Cutting (Sheridan 2002, fig. 169a–c). These descriptions provide an account of the estimated 15–20 m of Ton Siltstone Formation that occurs between the top of the Trostrey Limestone Member and base of the Usk Limestone Formation (Barclay 1989), as well as the 5 cm thick conodont-bearing crinoidal limestone that occurs between 4 and 5 m below the base of the Trostrey Limestone Member (Austin & Bassett 1967). A final section of historic note is the disused railway cutting near Rhadyr (SO 3642 0184 to SO 3650 0176), which has previously been used to provide evidence of thickness variations within the limestones (Walmsley 1958). There a thin limestone (< 1 m), has been correlated with the entirety of the Usk Limestone Formation by Walmsley (1958) and the entirety of the Trostrey Limestone Member by Barclay (1989). Both authors commented on poor exposure, and our investigations suggest that this has further deteriorated (we were unable to find the limestone described, and instead found patchy exposures of siltstone with very occasional thin beds of nodular and crinoidal

limestone). More broadly, it would seem that neither author was particularly confident in the interpretation and thickness of this limestone, as Walmsley (1958, p. 487) states that the junction between the Ton Siltstone and Usk Limestone formations cannot be seen within the Usk Inlier, presumably including at Rhadyr, and Barclay (1989, p. 7) states that the thickness of the Trostrey Limestone Member ranges between 2 to 8 m, thereby excluding Rhadyr. Accordingly, as neither author fully included this section in their summation of the succession, it is apparent that significant thinning of either limestone division cannot be inferred with confidence from this section.

Previous studies of the Usk Limestone Formation

The Usk Limestone Formation has been used for building and the production of lime, and is exposed in disused quarries and mines to the south of the River Usk; the succession north of the River Usk being mostly covered by superficial deposits. Previous authors have variably included or excluded nodular limestones within silty mudstones from the uppermost part of the formation, while the lower boundary of the formation has not been described (Walmsley 1958, Squirrell & Downing 1969, Bassett 1974); although digital borehole records made accessible by the British Geological Survey (Gas Council 5 Borehole, ID: 385366) do document this boundary. Furthermore, as many disused quarries expose only 3 to 4 m of the succession it can be difficult to place these sections into the broader stratigraphy of the formation. Accordingly, the thickness of the Usk Limestone Formation is uncertain and is typically given to range from < 1 to 14 m (*e.g.* Walmsley 1982, Cocks *et al.* 1992); excluding the disused railway cutting near Rhadyr 10 to 14 m (*e.g.* Gardiner 1916, Squirrell & Downing 1969, Barclay 1989). In detail, the Usk Limestone Formation can be subdivided based on the identification of a lower, massive to thick-bedded division, and an upper, nodular division (Crosfield & Johnston 1914, p. 212; Squirrell & Downing 1969). Using the lithofacies of Ratcliffe & Thomas (1999, fig. 3), the lower division mostly consists of the crinoidal grainstone lithofacies with a localised reef lithofacies, while the upper division consists of three lithofacies: the nodular limestone, interbedded limestone and silty mudstone, and crinoidal grainstone lithofacies. Based upon the subdivision of the Usk Limestone Formation, and the minimum and maximum estimates provided by Squirrell & Downing (1969, pp. 9, 10) the lower division may range between 5.8 m and 8.8 m thick, and the upper division between 4.2 m and 11.6 m, suggesting a potential thickness range of 10.0 to 20.4 m

for the Usk Limestone Formation. To further complicate matters, a thickness of *c.* 30 m for the Usk Limestone Formation is documented from digital records of the Usk-1 Borehole, situated *c.* 2.5 km east of Usk (Butler *et al.* 1997, fig. 2).

Field and laboratory methods

For each section we investigated, a sedimentary log and sequence stratigraphic interpretation were created (Figs 4, 5). Samples were collected from suitable sections for carbon isotope analysis (Figs 4–6), alongside a lesser number of samples for thin section investigations into sedimentology (Fig. 7). In sections where the lithology was highly variable (*i.e.* Weir Wood Cliff; Little Cwm Dowlais Farm Quarry; Ton Quarry) samples for carbon

isotope analysis were collected at 0.2 m intervals, whereas within more uniform successions the sampling interval was focused on collecting from each dm scale bed (*i.e.* Cilwrgi Quarry). Carbon isotope analysis was not undertaken at Ty'n-y-caeu Quarry owing to significant secondary deposits of limestone tufa on the accessible quarry faces, and the investigation of the Weir Wood Road Cutting was limited to a visual inspection of the rockface, owing to the proximity of the fast-flowing traffic on the B4598 road adjacent to this section.

The method of analysing bulk rock for stable isotopes, which inevitably contains some skeletal material, has been shown to provide reliable results in other Silurian studies (*e.g.* Cramer *et al.* 2006, Calner *et al.* 2012, Jarochowska *et al.* 2016). Furthermore, it has been shown that $\delta^{13}\text{C}_{\text{carb}}$ values from biohermal mounds are very similar to those derived from the surrounding bedded strata (Ray *et al.* 2025). Isotope values were measured at GeoZentrum Nordbayern, Friedrich-Alexander-Universität Erlangen-Nürnberg (Little Cwm Dowlais Farm Quarry) and Utrecht University (all other sections). Rock samples were cleaned and cut using a rock saw. The fresh surfaces were sampled for carbonate powder using a hand drill. From Little Cwm Dowlais Farm Quarry samples, 100 μg were weighed and reacted with 100% phosphoric acid at 70 °C. The resulting CO_2 was measured using a Gasbench II connected to a ThermoFinnigan Five Plus mass spectrometer. Reproducibility and accuracy were monitored by replicate analysis of laboratory standards calibrated to NBS19 and LSVEC. At Utrecht University, between 60 and 110 μg of powdered sample were weighed into vials. Samples from argillaceous intervals, particularly the Ton Siltstone Formation and the Lower Forest Beds, required repeated attempts to obtain sufficient material for analyses due initially to low ion beam intensity, which negatively impacted measurement precision and accuracy. Each analytical run consisted of the samples, along with 11 NAXOS standards and 4 EAEA-603 standards that weighed between 50 and 100 μg . Prior to the run, the vials were flushed with helium for 5 minutes at a flow rate of 20–30 mL/min per vial to ensure a clean environment. Then the samples were introduced in the Gasbench II Delta V Advantage IRMS. Here, phosphoric acid was injected into each vial, reacting with the carbonate samples to produce (CO_2). The resulting CO_2 was introduced into a continuous-flow mass spectrometer, where ion beam intensity was measured to determine $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values. All values are reported in per mill relative to Vienna Pee Dee Belemnite (VPDB) by assigning $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values +1.95‰ and –2.20‰ to international standard National Bureau of Standards 19 (NBS19) and –46.6‰ and –26.7‰ to international standard LSVEC, respectively. All data are reported for calcite.

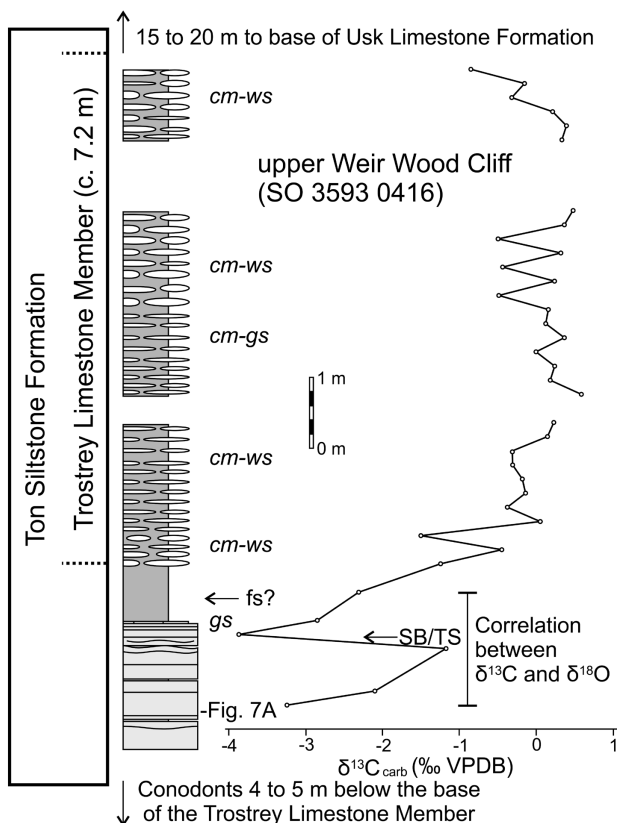


Figure 4. Sedimentary log and $\delta^{13}\text{C}_{\text{carb}}$ values from Weir Wood Cliff. See Fig. 5 for lithology key. Carbonate textures are: cm – carbonate mudstone; ws – wackestone; gs – grainstone. Sequence stratigraphic surface: fs? – flooding surface observed in only one section; SB/TS – sequence boundary and combined transgressive surface. Conodont records are reported by Austin & Bassett (1967) and can be stratigraphically placed below the logged succession using figure 2 of Walmsley (1958). Six samples with $\delta^{13}\text{C}$ values correlating with $\delta^{18}\text{O}$ values are highlighted (see Fig. 6 and text). These samples should be treated with caution, and may not be stratigraphically useful.

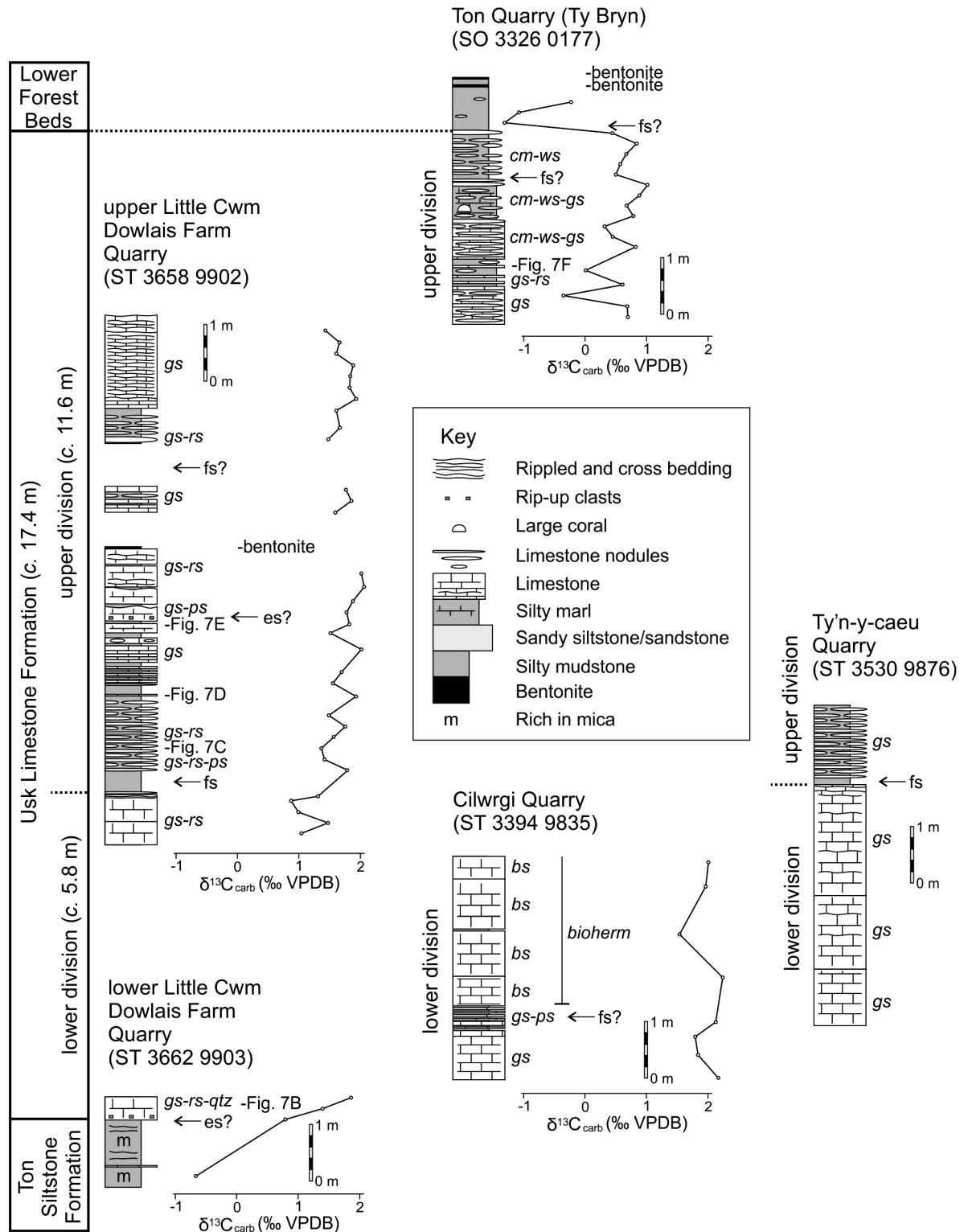


Figure 5. Sedimentary logs and $\delta^{13}\text{C}_{\text{carb}}$ values from Little Cwm Dowlais Farm Quarry, Cilwrgi Quarry, Ty'n-y-caeu Quarry and Ton Quarry. The relative position of the logs is based upon the correlation of the lower and upper divisions of the Usk Limestone Formation, the minimum and maximum thickness estimates of these divisions according to Squirrell & Downing (1969, pp. 9, 10), and the assumption that markedly different $\delta^{13}\text{C}_{\text{carb}}$ values should not overlap. Carbonate textures are: cm – carbonate mudstone; ws – wackestone; ps – packstone; gs – grainstone; rs – rudstone; bs – boundstone; qtz – limestone containing abundant quartz grains. Sequence stratigraphic surface: fs? – flooding surface observed in only one section; fs – flooding surface observed in two or more sections; es? – erosive surface observed in only one section (the stratigraphically higher erosive surface may correspond to a regional sequence boundary and combined transgressive surface).

The precision for $\delta^{13}\text{C}$ was 0.06‰ and 0.04‰ for $\delta^{18}\text{O}$. In total, 103 samples provided results and carbon isotope curves have been produced, alongside sedimentary logs, for Weir Wood Cliff, Little Cwm Dowlais Farm Quarry, Cilwrgi Quarry and Ton Quarry (Figs 4, 5; Tab. 1). Cross-plots between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values were examined visually to assess the potential for diagenetic overprinting (Fig. 6).

Carbon isotope results

At Weir Wood Cliff (Fig. 4) $\delta^{13}\text{C}_{\text{carb}}$ values range between -3.9‰ and 0.6‰ . Initially, there is a minor positive excursion, as values rise from -3.2‰ to -1.2‰ and then undergo a marked fall to -3.9‰ . This interval spans the lowermost six samples, which stand out from the others due to their distinctly more negative $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values compared to the rest of the dataset, with $\delta^{18}\text{O}_{\text{carb}}$ reaching -10.9‰ (Fig. 6). Above, values show a progressive rise, beyond which most values plateau between -0.5‰ and 0.5‰ . The minor positive excursion corresponds to the siliciclastics of the Ton Siltstone For-

mation, while the plateau and the relatively high values correspond to the overlying Trostre Limestone Member. The plateau in values is reached by a progressive rise in values of $+3.4\text{‰}$ (from -3.9‰ to -0.5‰), above which there is a sawtooth rise in values to a peak of 0.6‰ . Towards the top of the section, and near the inferred upper boundary of the Trostre Limestone Member, values begin to fall.

Little Cwm Dowlais Farm Quarry (Fig. 5) can be divided into lower and upper sections. The lower section contains the boundary between the Ton Siltstone and Usk Limestone formations. Insufficient carbonate content in the Ton Siltstone Formation prevented the acquisition of $\delta^{13}\text{C}_{\text{carb}}$ values from four out of five samples taken. Nonetheless, based upon the available data, the transition between the formations is associated with a progressive increase in values from -0.7‰ to 1.9‰ . Within the upper section values range between 0.8‰ and 2.1‰ , and show a gentle sawtooth rise to a maximum halfway through the section, above which is a gentle decline. The lowest values are associated with the base of the section and correspond to the transition between the lower and upper divisions of the Usk Limestone Formation.

At Cilwrgi Quarry (Fig. 5) $\delta^{13}\text{C}_{\text{carb}}$ values range between 1.6‰ and 2.3‰ . The section belongs to the lower division of the Usk Limestone Formation and contains biohermal mounds and bedded flanking deposits, both of which give similar $\delta^{13}\text{C}_{\text{carb}}$ values.

At Ton Quarry (Fig. 5) $\delta^{13}\text{C}_{\text{carb}}$ values range between -1.3‰ and 1.0‰ . Within the upper division of the Usk Limestone Formation values show a sawtooth increase to near its top. The overlying Lower Forest Beds are notable for a significant fall in values (below -1.0‰), but also included samples with an insufficient carbonate content for analysis.

Correlation and regional differences in the Homeric Carbon Isotope Excursion

The Homeric CIE is constrained within multiple sections by age-diagnostic graptolite and conodont occurrences, and can be correlated to the globally recognised Homeric stage slices (Ho1 to Ho3) and the geologic timescale (Fig. 2) (Melchin *et al.* 2020). In particular, the first peak of the double-peaked Homeric CIE typically begins near the Ho1–Ho2 stage slice boundary and is restricted to Ho2, while the second peak begins in Ho2 and ends near to the Homeric–Gorstian boundary (Ho3–Go1) (Cramer *et al.* 2011, Fry *et al.* 2017, Melchin *et al.* 2020). On the Midland Platform the Homeric CIE has been documented from a variety of depositional settings ranging from the shallow-marine biohermal successions of the Much Wenlock Limestone Formation of Dudley,

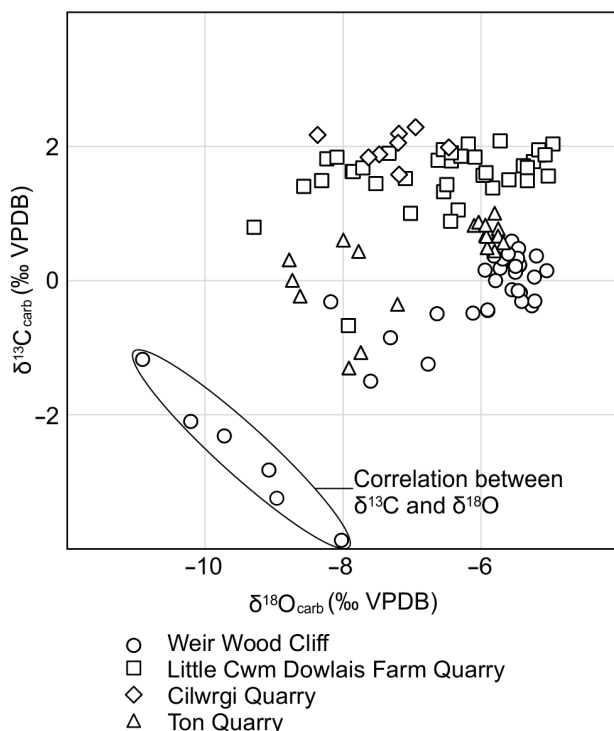


Figure 6. A cross-plot of bulk carbonate oxygen and carbon isotope values of samples from all localities ($n = 103$). All values reported with respect to the VPDB standard. The samples showing correlation between oxygen and carbon isotope values should be treated with caution, and may not be stratigraphically useful. These samples are from the base of Weir Wood Cliff (Fig. 4).

Table 1. $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values from Weir Wood Cliff, Little Cwm Dowlais Farm Quarry, Cilwrgi Quarry and Ton Quarry. Samples with no values reported contained insufficient carbonate content for analysis.

Sample code	Position from base of section (m)	$\delta^{13}\text{C}_{\text{carb}}$	$\delta^{18}\text{O}_{\text{carb}}$
Weir Wood Cliff			
WW1	0		
WW2	0.2		
WW3	0.4		
WW4	0.6	-3.24	-8.96
WW5	0.8	-2.10	-10.21
WW6	1		
WW7	1.2		
WW8	1.4	-1.17	-10.91
WW9	1.6	-3.87	-8.02
WW10	1.8	-2.82	-9.08
WW11	2		
WW12	2.2	-2.31	-9.72
WW13	2.4		
WW14	2.6	-1.24	-6.77
WW15	2.8	-0.45	-5.90
WW16	3	-1.50	-7.60
WW17	3.2	0.06	-5.23
WW18	3.4	-0.37	-5.26
WW19	3.6	-0.14	-5.55
WW20	3.8	-0.18	-5.43
WW21	4	-0.30	-5.22
WW22	4.2	-0.31	-5.41
WW23	4.4	0.15	-5.05
WW24	4.6	0.23	-5.44
GAP			
WW25	5	0.59	-5.55
WW26	5.2	0.19	-5.72
WW27	5.4	0.24	-5.52
WW28	5.6	0.00	-5.79
WW29	5.8	0.37	-5.20
WW30	6	0.13	-5.50
WW31	6.2	0.16	-5.94
WW32	6.4	-0.48	-6.12
WW33	6.6	0.24	-5.44
WW34	6.8	-0.43	-5.91
WW35	7	0.32	-5.69
WW36A	7.2	-0.49	-6.64
WW36B	7.4	0.37	-5.81
WW37	7.6	0.48	-5.46
GAP			
WW38	8.6	0.34	-5.47
WW39	8.8	0.40	-5.61
WW40	9	0.22	-5.50
WW41	9.2	-0.32	-8.18
WW42	9.4	-0.15	-5.46
WW43	9.6	-0.85	-7.31
Cilwrgi Quarry			
LO-2025-003	0	2.19	-7.19
LO-2025-004	0.4	1.88	-7.48
LO-2025-005	0.8	1.84	-7.63
LO-2025-006	1	2.17	-8.37
LO-2025-007	1.8	2.29	-6.95
LO-2025-008	2.5	1.58	-7.19
LO-2025-009	3.4	1.99	-6.47
LO-2025-010	3.8	2.05	-7.20
Ton Quarry			
T22	0	0.69	-5.76
T21	0.2	0.68	-5.93
T20	0.4	-0.35	-7.21
T19	0.6	0.61	-7.99
T18	0.8	0.00	-8.73
T17	1.2	0.82	-6.10

T16	1.4	0.44	-5.80
T15	1.6	0.31	-8.78
T14	1.8	0.77	-5.75
T13	2	0.67	-5.75
T12	2.2	0.87	-6.03
T11	2.4	1.01	-5.80
T10	2.6	0.49	-5.91
T9	2.8	0.56	-5.67
T8	3	0.66	-5.92
T7	3.2	0.83	-5.94
T6	3.4	0.44	-7.77
T5	3.6	-1.30	-7.92
T4	3.8	-1.07	-7.74
T3	4	-0.23	-8.62
T2	4.2		
T1	4.4		

Sample code and identification of lower and upper sections	Position from base of section (m)	$\delta^{13}\text{C}_{\text{carb}}$	$\delta^{18}\text{O}_{\text{carb}}$
Little Cwm Dowlais Farm Quarry			
lower LCDF1	0.2	-0.67	-7.92
lower LCDF2	0.4		
lower LCDF3	0.6		
lower LCDF4	0.8		
lower LCDF5	1		
lower LCDF6	1.2	0.80	-9.29
lower LCDF7	1.4	1.41	-8.57
lower LCDF8	1.6	1.87	-5.17
GAP			
upper LCDF9	6.2	1.05	-6.33
upper LCDF10	6.4	1.49	-8.31
upper LCDF11	6.6	1.01	-7.02
upper LCDF12	6.8	0.89	-6.44
upper LCDF13	6.9	1.33	-6.54
upper LCDF14	7.1		
upper LCDF15	7.3	1.82	-8.24
upper LCDF16	7.5	1.43	-6.50
upper LCDF17	7.7	1.38	-5.83
upper LCDF18	7.9	1.56	-5.03
upper LCDF19	8.1	1.78	-5.24
upper LCDF20	8.3	1.50	-5.60
upper LCDF21	8.6	1.95	-5.16
upper LCDF22	8.8	1.57	-5.97
upper LCDF23	9	1.71	-5.39
upper LCDF24	9.2		
upper LCDF25	9.4	2.04	-4.96
upper LCDF26	9.7	1.53	-7.10
upper LCDF27	9.9	1.84	-8.09
upper LCDF28	10.1	1.80	-6.62
upper LCDF29	10.3	1.90	-7.33
upper LCDF30	10.5	2.08	-5.72
upper LCDF31	10.8	2.04	-6.19
upper LCDF32	11.1		
GAP			
upper LCDF33	11.9	1.61	-5.93
upper LCDF34	12.1	1.88	-5.07
upper LCDF35	12.3	1.79	-6.43
GAP			
upper LCDF36	13.1	1.49	-5.33
upper LCDF37	13.3	1.69	-5.33
upper LCDF38	13.7	1.63	-7.87
upper LCDF39	13.9	1.95	-6.55
upper LCDF40	14.1	1.85	-6.09
upper LCDF41	14.3	1.86	-6.29
upper LCDF42	14.4	1.90	-6.43
upper LCDF43	14.7	1.63	-7.86
upper LCDF44	14.9	1.68	-7.71
upper LCDF45	15.1	1.45	-7.53

northern Wenlock Edge, Malvern, and May Hill, to the deeper-marine platform marginal limestones and silty mudstones of the Much Wenlock Limestone Formation and underlying Coalbrookdale Formation of southern Wenlock Edge and Ludlow (Blain *et al.* 2016; Fry *et al.* 2017; Ray *et al.* 2020, 2025). A comparison of $\delta^{13}\text{C}_{\text{carb}}$ values shows clear spatial variations, with lighter values recorded from more distal settings and heavier values from shallower settings (Blain *et al.* 2016). Furthermore, it has been shown that regional differences in the rate of palaeobathymetric change and the nature of the associated carbonates could control and offset the broad trend in isotopic values (Ray *et al.* 2020). For example, the first peak of the Homerian CIE varies from 5.5‰ to 4.8‰ to c. 2.8‰, as you move from the shallow-water biohermal carbonates of the Much Wenlock Limestone Formation (Lower Quarried Limestone Member) at Dudley and Malvern, westwards to the distal nodular limestones and silty mudstones of the Coalbrookdale Formation (Farley Member) near Much Wenlock (Fry *et al.* 2017, Ray *et al.* 2020) (Fig. 1). Values for the second peak at Dudley and Much Wenlock are within similar biohermal carbonates (Much Wenlock Limestone Formation) and have similar values (3.8‰ to 3.9‰) (Marshall *et al.* 2012, Ray *et al.* 2020), while a north-south transect between Dudley, Malvern, and May Hill shows a reduction in values from 3.8‰ to 3.0‰ to c. 1.6‰, which is accompanied by a loss of bioherms and changes in lithofacies (Ray *et al.* 2013, 2020, 2025).

Correlation of the Ton Siltstone and Usk Limestone formations based upon carbon isotope values

Within the investigated succession of the Usk Inlier, the double peaks of the Homerian CIE are readily identifiable as progressive rises and falls in values above and below the pre-excursion levels, which are typically below 0‰ $\delta^{13}\text{C}_{\text{carb}}$ within the Wenlock of the Midland Platform (Hughes & Ray 2016). Based upon these criteria, and the creation of a composite section, the carbon isotope trends and values derived from Weir Wood Cliff, Little Cwm Dowlais Farm Quarry, Cilwrgi Quarry and Ton Quarry all correspond to intervals within the Homerian CIE (Figs 4, 5, 8). Notably $\delta^{13}\text{C}_{\text{carb}}$ values rise above pre-excursion levels within the Trostre Limestone Member and Usk Limestone Formation, and show progressive rises from the siliciclastics of the Ton Siltstone Formation, and a marked decline into the overlying Lower Forest Beds.

Within the Usk Inlier the first peak of the Homerian CIE is smaller than the second peak, and when compared to values obtained elsewhere on the Midland Platform (*e.g.* 5.5‰ to c. 2.8‰) it is unusually small (0.6‰). In

globally distributed studies, the first peak of the Homerian CIE is typically slightly larger than the second peak (Jarochowska & Munnecke 2016, Manda *et al.* 2019), but there are exceptions documented from Lithuania and Arctic Canada (Martma *et al.* 2005, Noble *et al.* 2012). Within the Usk Inlier the difference in values between the first and second peaks of the Homerian CIE may reflect differences in depositional setting, with the lighter $\delta^{13}\text{C}_{\text{carb}}$ values reflecting the more distal setting. Accordingly, the differences in peak values, in part, reflect the difference between the distal setting of the Trostre Limestone Member (first peak), and the significantly shallower setting of the Usk Limestone Formation (second peak). Notably, in the lower Wenlock of the Midland Platform and Welsh Basin, similar differences in peak $\delta^{13}\text{C}_{\text{carb}}$ values have been documented from the Early Sheinwoodian positive Carbon Isotope Excursion (ESCIE). There, the limestones of the shallowest setting (Eastnor Park Borehole) have a peak value of 4.3‰ (Hughes & Ray 2016), whilst the graptolitic hemipelagites and mudstones of the deepest setting (Banwy River Section) have a peak value of just 0.2‰; above pre-excursion lows of –2‰ within the Wenlock and –7‰ in the uppermost Telychian (Cramer *et al.* 2010). However, at Weir Wood Cliff (Usk Inlier), the onset of the first peak of the Homerian CIE corresponds to six samples with $\delta^{13}\text{C}$ values correlating with $\delta^{18}\text{O}$ values, whereas this correlation is absent from the remaining samples and the majority of the first peak (Figs 4, 6). Concurrent negative shifts in both values are commonly associated with meteoric diagenesis, which may not necessarily eliminate the original relative shifts in seawater $\delta^{13}\text{C}$, but make them more negative than the original signal (*e.g.* Knauth & Kennedy 2009). Without controlling for temperature and carbonate cement composition, it is not possible to separate syndepositional and diagenetic changes to the isotope values (Swart & Oehlert 2018). Accordingly, the correlation of these lowermost six samples should be treated with caution. Nonetheless, whilst the Homerian CIE of the Usk Inlier is unusual in terms of the size of the first peak and its relationship with the second peak, such differences are not without precedence nor explanation. Furthermore, comparison between the onset of the first peak of the Homerian CIE at Weir Wood Cliff (Usk Inlier), and those at Malvern and Dudley show broad similarities in the variability of values, and the amount and rate of change (Fig. 8). This suggests correlation between the uppermost Ton Siltstone and the immediately overlying Trostre Limestone Member and the transition between the Coalbrookdale and Much Wenlock Limestone formations of the inner Midland Platform; a correlation that would still be made with the exclusion of the lower six samples at Weir Wood Cliff, and is further supported by regional sequence stratigraphy.

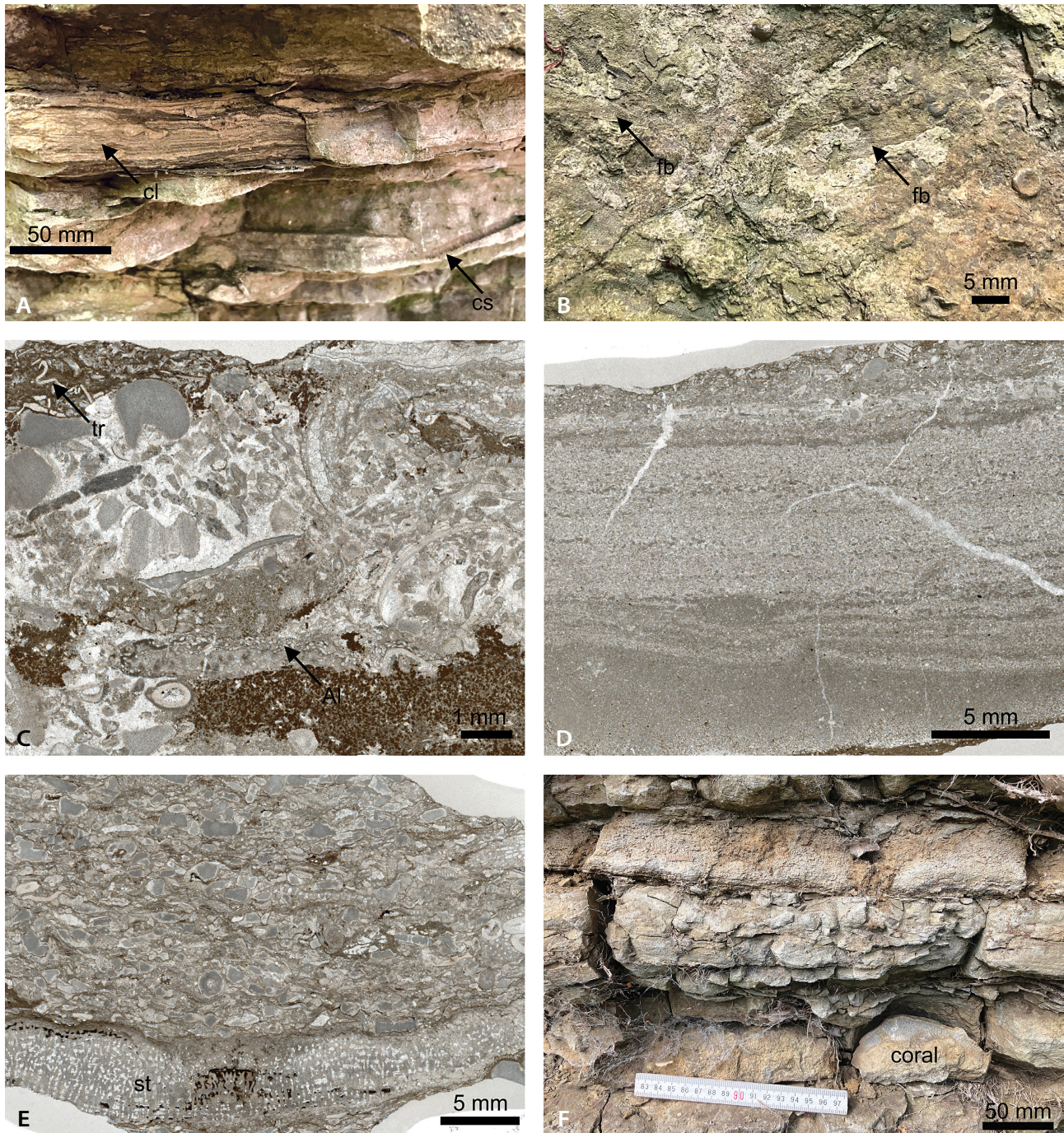


Figure 7. Detailed outcrop and thin section photographs from the Ton Siltstone and Usk Limestone formations (see Figs 4 and 5 for stratigraphic positions). • A – articulated crinoid stem (cs), and burrowed carbonaceous laminae (cl) within the upper Ton Siltstone Formation, near the base of Weir Wood Cliff (Fig. 3A). • B – current-aligned *Fenestella* bryozoans (fb) from a loose block of the lower division of the Usk Limestone Formation at Little Cwm Dowlais Farm Quarry. • C – a nodular crinoidal grainstone from the Usk Limestone Formation at Little Cwm Dowlais Farm Quarry, showing poorly sorted crinoid ossicles, alongside brachiopods, bryozoans, corals, and ostracods. Many grains are coated with the encrusting problematicum *Allonema* (Al) and the calcareous cyanobacterium *Rothpletzella*. The nodule is surrounded by a clay and iron oxide-rich matrix containing bryozoan and trilobite (tr) fragments. • D – laminated bed of mudstone to packstone from the Usk Limestone Formation at Little Cwm Dowlais Farm Quarry. The base of the bed is composed of clay- to fine silt-sized micritic grains with quartz admixture, which grade upwards into a fine sand-sized peloidal packstone with mica. The top of the bed is a bioclastic grainstone composed of disarticulated crinoid ossicles, fragments of tabulate corals and ostracods. • E – stromatoporoid framestone-crinoidal packstone-grainstone with a fitted fabric from the Usk Limestone Formation at Little Cwm Dowlais Farm Quarry. The stromatoporoid (st) is sheet-like, in situ, and surrounded by poorly sorted crinoid ossicles with fragments of the tabulate corals *Coenites* sp. and halysitids. • F – alternation between grainstone-rudstone storm beds with coral (*Heliolites* sp.), and silty marls, from the upper Usk Limestone Formation at Ton Quarry (Fig. 3F).

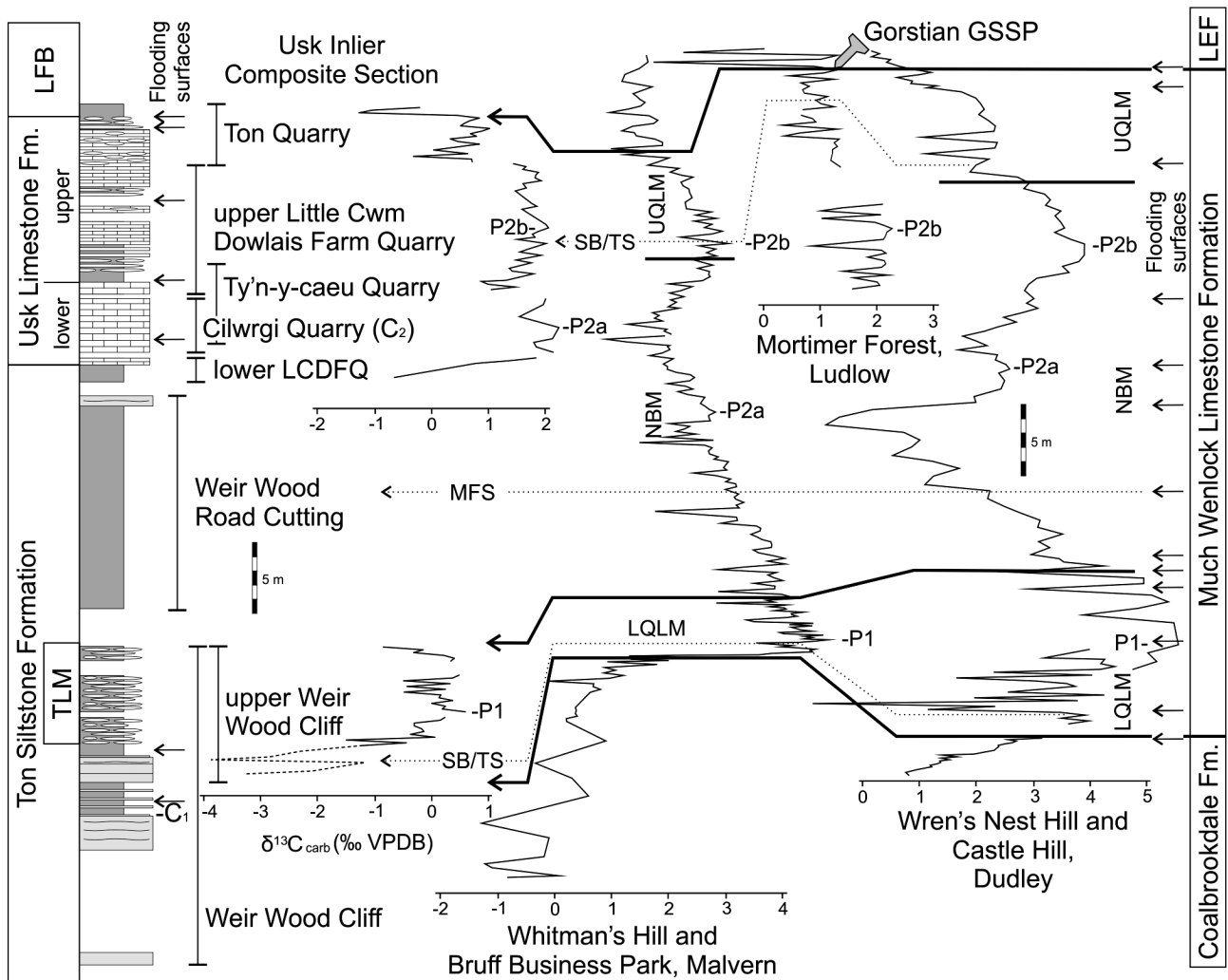


Figure 8. An Usk Inlier composite section, comparing carbon isotope curves from the Usk Inlier with curves from elsewhere on the Midland Platform (all values are $\delta^{13}\text{C}_{\text{carb}} \text{‰ VPDB}$). The carbon isotope comparative curves, by increasing distance from the Usk Inlier, are from Whitman's Hill Quarry (SO 7487 4826) and Bruff Business Park (SO 7365 5065) near Malvern (Ray *et al.* 2020), Mortimer Forest (Stops 1 to 3, SO 4716 7303 to SO 4723 7298) near Ludlow (Davies *et al.* 2011, fig. 29; Fry *et al.* 2017), and Wren's Nest Hill (SO 9373 9189) and Castle Hill (SO 9454 9164) near Dudley (Ray *et al.* 2020). The maximum values of the first (P1) and second (P2a/b) peaks of the Homerian CIE are shown on each of the carbon isotope curves. Note that the second peak can be subdivided into lower (P2a) and upper (P2b) subpeaks (see Ray *et al.* 2020, fig. 6). Lithostratigraphic boundaries and sequence stratigraphic surfaces are shown against the curves, and the flooding surfaces (arrows) described in the text are shown against the Usk Inlier Composite Section and the curve at Dudley. Note that Mortimer Forest Stop 3 (Pitch Coppice) contains the Gorstian GSSP, which coincides with the boundary between the Much Wenlock Limestone Formation and the Lower Elton Formation (LEF). In addition, the Much Wenlock Limestone Formation near Malvern and Dudley can be divided into the following members: LQLM – Lower Quarried Limestone Member; NBM – Nodular Beds Member; UQLM – Upper Quarried Limestone Member. The following sequence stratigraphic surfaces are shown: SB/TS – sequence boundary and combined transgressive surface; MFS – maximum flooding surface. The Usk Inlier composite section is based upon the relative position of measured sections. The Ton Siltstone Formation part of the composite is based upon the estimated position of the Trostre Limestone Member (TLM) below the base of the Usk Limestone Formation (see Bassett 1974, Barclay 1989), our log of the upper part of Weir Wood Cliff, and published sections from Weir Wood Cliff and Weir Wood Road Cutting (Walmsley 1958, fig. 2; Sheridan 2002, fig. 169a–c). The Usk Limestone Formation composite is based upon the correlation of the lower and upper divisions of the formation, the minimum and maximum thickness estimates of these divisions according to Squirrell & Downing (1969, pp. 9, 10), and the assumption that markedly different $\delta^{13}\text{C}_{\text{carb}}$ values should not overlap. The six samples with $\delta^{13}\text{C}$ values correlating with $\delta^{18}\text{O}$ values from the upper part of Weir Wood Cliff are highlighted by a dashed line (see Figs 4, 6 and text). These samples should be treated with caution, and may not be stratigraphically useful. Abbreviations: LFB – Lower Forest Beds; LCDFQ – lower Little Cwm Dowlais Farm Quarry; C₁ – position of the conodonts described by Austin & Bassett (1967); C₂ – position of the conodonts from within Cilwrgi Quarry, described by Aldridge *et al.* (2000, p. 208).

The second peak is the most obvious carbon isotopic feature of the studied succession, and is also of most stratigraphic significance, in that it places the Usk Limestone Formation within the upper Homerian, rather than the Gorstian (Fig. 2). This confirms the consensus view that the Usk Limestone Formation is age-equivalent to the Much Wenlock Limestone Formation of the Welsh Borders (Cocks *et al.* 1992). In particular, the maximum value of 2.3‰ within the Usk Limestone Formation is similar to values documented from the second peak of the Much Wenlock Limestone Formation at Malvern, Ludlow, and May Hill (3.0‰, 2.3‰, *c.* 1.6‰) (Fry *et al.* 2017; Ray *et al.* 2020, 2025). At Usk and Ludlow the matching peak values likely reflect similar outer platform depositional settings along the western margin of the Midland Platform. Furthermore, peaks and troughs associated with the lower and upper divisions of the Usk Limestone Formation appear to have clear equivalence upon the curves from the upper half of the Much Wenlock Limestone Formation at Malvern and Dudley (Fig. 8), and allow for finer-scale correlation based upon the P2a/b subpeaks of the Homerian CIE.

Sedimentology, lithofacies and sea-level change within the Ton Siltstone and Usk Limestone formations

Long-term sea-level changes within the Wenlock

Broad eustatic sea-level changes within the Wenlock are well documented and frequently show a mid-Wenlock sea-level high under- and over-lain by early and late Wenlock sea-level lows (Johnson *et al.* 1991, fig. 5; Johnson 2006). These sea-level changes are expressed across the Midland Platform, in that the Wenlock succession consists of shallow marine lower and upper limestone divisions (Dolyhir and Nash Scar Limestone, Woolhope Limestone, Buildwas, and Barr Limestone formations, and the Much Wenlock Limestone Formation, respectively), separated by a significant thickness of deeper marine argillaceous rocks (Coalbrookdale Formation) (see Cherns & Bassett 1999).

Based upon the Usk-1 Borehole (Butler *et al.* 1997, fig. 2) the Wenlock succession of the Usk Inlier is like that of the adjoining Midland Platform. It begins with *c.* 35 m of limestone (Woolhope Limestone Formation) overlain by *c.* 350 m of mudstones and siltstones with occasional sandstones and limestones that are subdivided into the Glascoed Mudstone Formation (*c.* 250 m) and the overlying Ton Siltstone Formation (*c.* 100 m) (Barclay 1989), above which is *c.* 30 m of limestone (Usk Limestone Formation). The most distal setting within the succession

is considered to occur within the occasionally graptolitic mudstones of the Glascoed Mudstone Formation, above which the Ton Siltstone and Usk Limestone formations are considered to reflect a period of overall shallowing (Calef & Hancock 1974, Barclay 1989).

Short-term sea-level changes within the Ton Siltstone and Usk Limestone formations

Within the Usk Inlier the long-term regression shown by the Ton Siltstone and Usk Limestone formations can be subdivided into short-term transgressive-regressive cycles. These cycles are identifiable at a range of scales, from broad lithostratigraphic alternations between siliciclastic and carbonate divisions, to parasequences. A key consideration in the interpretation of these cycles is an attribution of water depth to sedimentary and faunal characteristics. For example, the nodular limestone, interbedded limestone and silty mudstone, and crinoidal grainstone lithofacies of Ratcliffe & Thomas (1999, figs 3, 5) are identifiable from the Usk Limestone Formation and represent an overall shallowing from around storm wave-base to above fair-weather wave-base, with their reef lithofacies overlapping with the two shallowest lithofacies. More broadly, the silty mudstones of the Ton Siltstone Formation and Lower Forest Beds are commonly associated with *Isorthis clivosa* and *Dicelospira* brachiopod-dominated benthic communities and are considered reflective of a low energy offshore setting, while the sandstones and limestones of the Ton Siltstone Formation and limestones of the Usk Limestone Formation are considered reflective of a higher energy nearshore setting, and are associated with *Homoeospira*, *Sphaerirhynchia* and *Salopina* communities (Calef & Hancock 1974, Hurst 1975, Bassett 1976).

The division of the succession into offshore and nearshore settings can be further refined based upon the evidence for storm sedimentation, which can be used to assess the position of the sea floor relative to storm wave-base (Brett *et al.* 1993, Ratcliffe & Thomas 1999). The silty mudstones typically show little evidence of current reworking and suggest a low energy offshore setting mostly below storm wave-base, while deposition between storm and fair-weather wave-base is evidenced by coarser-grained sedimentary rocks (*e.g.* sandstones, grainstones and rudstones), cross-bedding, wave-ripples, amalgamated beds and evidence of erosion (*e.g.* rip-up clasts and scours). In general, the limestones of the Usk Limestone Formation are coarser-grained and form thicker packages of amalgamated beds than the sandstones of the Ton Siltstone Formation, and by this measure the limestones represent the higher energy and shallower setting. This is supported also by the presence of

bioherms exposed at Cilwrgi Quarry, where they contain a large proportion of tabulate corals and crinoids, filter-feeding organisms requiring agitated water. Furthermore, sandstones and sandy beds are described from transitional successions both below and above the Usk Limestone Formation (Walmsley 1958, Bassett 1974), suggesting that sands were deposited outboard of the carbonate sediments, as implied by Calef & Hancock (1974, fig. 5).

Given the dominance of silty mudstones within an offshore setting and the proximity of the Usk Inlier to the landmass of Pretannia, it seems that siliciclastic sediments were transported through the carbonate depositional setting; as evidenced by quartz sand grains, silty mudstone rip-up clasts, and silty mudstone beds within the Usk Limestone Formation. Moreover, storm and fair-weather waves would have influenced siliciclastic sedimentation rates and turbidity, and in doing so controlled carbonate productivity by influencing factors such as the depth of the photic zone and the availability of hard substrates for colonisation. Accordingly, sandstone deposition seems to have taken place within a setting characterised by storm-induced turbidity and high rates of siliciclastic sedimentation, while the deposition of the Usk Limestone Formation occurred closer to fair-weather wave base in a setting where siliciclastic sediments were less able to settle and carbonates could proliferate. A possible exception to the arrangement outlined above is the nodular limestone lithofacies of the Trostre Limestone Member, where storms are evidenced by concentrations of skeletal debris preserved in some nodules, suggesting a setting close to the lower limit of storm wave-base (see Ratcliffe & Thomas 1999), and in a more offshore setting than that attributable to the rippled sandstone beds of the Ton Siltstone Formation. A possible explanation for this may be variations in the input of siliciclastics, owing to the retreat and advance of nearby coastal sediments. Such variations in the input of siliciclastic sediments may result from short-term climate change and/or transgressions and regressions, which alongside water depth and the impact of wave action, would have been important in determining the nature of the succession.

Having established the water depths attributable to the sedimentology and faunas of the Ton Siltstone and Usk Limestone formations, a broad pattern of sea-level change can be determined. Using the changes evident from the composite section (Fig. 8) it is apparent that the rippled sandy siltstone beds of the Ton Siltstone Formation represent a nearshore setting, overlain by a deeper-water transgressive succession that begins with a thin silty mudstone horizon followed by the Trostre Limestone Member, and continues into the overlying silty mudstones of the uppermost Ton Siltstone Formation. Regression is evidenced near the top of the Ton Siltstone Formation by the occurrence of rippled sandstones, which are overlain

by the limestones of the Usk Limestone Formation. Within the Usk Limestone Formation, massive, bedded, and nodular limestones in association with silty mudstones indicate both small scale sea-level variations, and a deepening trend into the overlying Lower Forest Beds. The correlation of these broad sea-level changes with the Homerian CIE identifies similarities with the high-resolution stratigraphic framework of the Midland Platform, as well as that of other palaeocontinents. Accordingly, the development of a sequence stratigraphic model based upon the identification of systems tracts and their bounding surfaces should further facilitate correlations and age constraint.

Integration of carbon isotope data and sequence stratigraphy

Global comparisons between Homerian carbon isotope trends and sequence stratigraphy

The Homerian CIE has been widely associated with sea-level changes upon Avalonia (*e.g.* Ray *et al.* 2020), Baltica (*e.g.* Calner 2008) and Laurentia (*e.g.* Danielsen *et al.* 2019), and such studies provide a template of carbon isotopic change and sequence stratigraphy for comparison with the Usk Inlier (Fig. 2). These studies show that prior to the Homerian CIE, there was a broad regression from a sea-level high near the Sheinwoodian-Homerian boundary (Highstand 5 of Johnson, 2006). The peak of this regression coincides with the onset of the Homerian CIE and is associated with a sequence boundary and combined transgressive surface near the Ho1–Ho2 stage slice boundary. The overlying early transgressive systems tract contains the first peak of the Homerian CIE. The maximum flooding surface and overlying highstand (Highstand 5a of Johnson 2006) contains falling carbon isotope values from the first peak (within Ho2), while the second peak is typically associated with the next phase of regression. The end of the Homerian CIE occurs within the overlying early transgressive systems tract and approximates to the Ho3–Go1 stage slice boundary, with the next maximum flooding surface occurring well within the Gorstian (Go2 stage slice; Highstand 6 of Johnson, 2006).

Integration of carbon isotope data and sequence stratigraphy within the Ton Siltstone Formation

Within the Usk Inlier the onset of regression that replaced the Glascoed Mudstone Formation with the Ton Siltstone

Formation may be correlated with, and age constrained by, shallowing identified elsewhere on the Midland Platform (Fig. 1). The Collington-1 Borehole, Herefordshire (65 km north-northeast of the Usk Inlier), contains c. 340 m of silty mudstones (Coalbrookdale Formation), the upper c. 80 m of which are accompanied by nodular limestones, suggestive of shallowing (Penn 1987, Dorning & Harvey 1999). Similarly, the Lower Hill Farm Borehole, Wenlock Edge (100 km north of the Usk Inlier), contains 197 m of silty mudstones (the lower two-thirds of the Coalbrookdale Formation) the upper 50 m of which contains siltstone beds, suggestive of shallowing (Ray & Butcher 2010, Hughes & Ray 2016). In both cases the onset of shallowing within the Coalbrookdale Formation is considered to have commenced in the earliest Homerian (Dorning & Harvey 1999, Hughes & Ray 2016). Based upon the available biostratigraphic data and the position of the overlying Homerian CIE, a similar age is assumed for the onset of shallowing within the Usk Inlier and for the base of the Ton Siltstone Formation (lower Ho1). Accordingly, the base of the Ton Siltstone Formation approximates to the onset of shallowing following eustatic Highstand 5 of Johnson (2006) (Fig. 2).

In detail, regression within the Ton Siltstone Formation is indicated by rippled coarse-grained micaceous sandstone beds containing *Sphaerirhynchia* and *Salopina* communities at 30 m and 22.5 m below the base of the Trostre Limestone Member (Bassett 1974, 1976). In addition, micaceous sandy siltstones and fine sandstones occur immediately below the Trostre Limestone Member at Weir Wood Cliff (Figs 3A, 4, 8) (Walmsley 1958, Barclay 1989). There, symmetrical wave ripples, scours, and the preservation of an articulated crinoid stem suggest high energy storm events, while carbonaceous laminae and plant debris indicate a proximity to the coastline (Fig. 7A). This succession is of a similar age, and bears a striking resemblance to the Rhymney Grit (Cae Castell Formation) of the Rumney Inlier (30 km southwest of Usk) (Walmsley 1958, p. 488). The Rhymney Grit, 6 to 20 m thick, is interpreted as a subtidal sand bar, developed due to rapid shallowing to within a nearshore high-energy environment (Waters & Lawrence 1987; Aldridge *et al.* 2000, pp. 221–224), and as such may indicate rapid regression near the Ho1–Ho2 stage slice boundary. The exposure at the base of Weir Wood Cliff (Figs 3A, 4) also contains evidence of small-scale cyclicity (parasequences). Over a thickness of 1.59 m the sandy siltstones coarsen upwards to form prominent rippled and planar laminated sandstone beds, and indicate upward shallowing. Above, the beds rapidly (over 0.19 m) become siltier, are capped by a thin (3 cm) crinoidal grainstone bed that is in turn overlain by 0.76 m of silty mudstones, and indicate a rapid deepening event, with the crinoidal grainstone bed reflecting a transgressive lag deposit, prior to the development of

the most offshore setting and a flooding surface. This parasequence occurs immediately below the Trostre Limestone Member, but a further thin (5 cm) conodont-bearing crinoidal grainstone bed overlying a similar sandy succession is described from below the present exposure (Figs 4, 8) and indicates the presence of an earlier parasequence (Walmsley 1958, Austin & Bassett 1967, Barclay 1989).

The overlying Trostre Limestone Member represents a shallowing from the silty mudstone flooding surface, but in a more offshore setting than the underlying sandy siltstones and sandstones. Furthermore, the uniformity of the Trostre Limestone Member indicates limited changes in water depth and a broadly aggradational succession; suggestive of an early transgressive systems tract. Based upon this interpretation, the boundary between the shallowest part of the Ton Siltstone Formation and the overlying early transgressive systems tract represents a sequence boundary and combined transgressive surface. In the carbon isotope record, a minor positive excursion occurs below the sequence boundary and combined transgressive surface, while above this surface there is a progressive rise in values to the first peak of the Homerian CIE, which occurs half way up the Trostre Limestone Member. A similar relationship between sea-level change and carbon isotope values occurs elsewhere on the Midland Platform. At Malvern and Dudley rapid regression is marked by a transition from the offshore silty mudstones of the Coalbrookdale Formation to the nearshore grainstones of the basal few metres of the Lower Quarried Limestone Member (Much Wenlock Limestone Formation). This is associated with a minor positive carbon isotope excursion prior to a sequence boundary (Fig. 8). The overlying remainder of the Lower Quarried Limestone Member contains the first peak of the Homerian CIE, and exhibits either gradual deepening or, where carbonate productivity allowed, further gradual shallowing, and is reflective of the early transgressive systems tract (Ray *et al.* 2020).

The uppermost Ton Siltstone Formation that is developed above the Trostre Limestone Member is poorly resolved in this study, but has been previously described (Bassett 1974, Barclay 1989, Sheridan 2002). The replacement of the Trostre Limestone Member by offshore silty mudstones marks a shift from gradual to rapid deepening (early to late transgressive systems tract) and the development of a maximum flooding surface (eustatic Highstand 5a of Johnson (2006)), above which the occurrence of siltstones and sandstones indicate a slowing in the pace of transgression and shallowing (regressive systems tract) (Fig. 8). Within the Much Wenlock Limestone Formation of Malvern and Dudley this interval contains a broad trough in carbon isotope values and corresponds to the replacement of bedded

limestones (Lower Quarried Limestone Member) by more offshore silty mudstones and nodular limestones (Nodular Beds Member), which are in turn replaced by bedded and reefal limestones (Ray *et al.* 2020). Falling carbon isotopic values near the top of the Trostrey Limestone Member and rising values across the boundary between the Ton Siltstone and Usk Limestone formations likely reflect the start and finish of the broad trough in carbon isotope values observed elsewhere.

Integration of carbon isotope data and sequence stratigraphy across the boundary between the Ton Siltstone and Usk Limestone formations

The boundary between the Ton Siltstone and Usk Limestone formations is associated with the onset of the second peak of the Homerician CIE at Little Cwm Dowlais Farm Quarry (Figs 5, 8). The boundary has also been briefly described within British Geological Survey digital borehole records from the Gas Council 5 borehole near Ty'n-y-caeu Quarry. Within the borehole 3 m of Usk Limestone Formation are immediately underlain by 0.6 m of cross-bedded fine-grained micaceous sandstone, below which are a further 9.2 m of mudstones containing sandy and silty partings, with occasional limestones. The development of similar sandstones near the top of the Ton Siltstone Formation has also been described from the Weir Wood Road Cutting and a temporary excavation across the central part of the Usk Inlier (Bassett 1974, Sheridan 2002). Like the sandstone beds developed elsewhere in the formation, these sandstones are considered reflective of regression to a nearshore setting. However, at Little Cwm Dowlais Farm Quarry the boundary between the formations is underlain by 1.2 m of silty mudstones. Erosion at this boundary is indicated by a sharp undulating contact (Fig. 3C) and the reworking of sediments into the overlying limestones; as silty mudstone rip-up clasts and quartz grains. It is unclear as to the amount of erosion at this boundary, or if the absence of sandstones is a result of localised non-deposition and/or local erosion. Nevertheless, it seems likely that the abrupt introduction of massive cross-bedded crinoidal grainstones into the study area would have been accompanied by submarine erosion of the underlying formation. The crinoidal grainstone lithofacies of the lower division of the Usk Limestone Formation are reflective of a high energy nearshore carbonate shoal, developed close to fair-weather wave base. However, the presence of coral-bryozoan biohermal mounds and an abundance of delicate *Fenestella* bryozoans (Fig. 7B) suggest that sheltered areas of sea-floor were available for colonisation.

Integration of carbon isotope data and sequence stratigraphy within the Usk Limestone Formation

High-resolution correlations between the Much Wenlock Limestone Formation at Dudley, Malvern, and Wenlock Edge have been made using parasequences (Ray *et al.* 2010, 2020; Coe & Ray 2022). However, within the Usk Inlier limited exposure has hindered their identification. Nevertheless, within the Usk Limestone Formation there are four prominent offshore silty mudstone horizons, often overlain by upward shallowing successions, which appear representative of flooding surfaces developed at the base of parasequences (Fig. 5). At Cilwrgi Quarry the lower division of the Usk Limestone Formation contains a silty mudstone horizon that separates shoal and biohermal limestones, while at Little Cwm Dowlais Farm and Ty'n-y-caeu quarries the lower and upper divisions of the Usk Limestone Formation are separated by a prominent silty mudstone horizon (Figs 3E, 5). At Little Cwm Dowlais Farm Quarry, the basal flooding surface of the upper division is overlain by nodular limestones and silty mudstones that grade upwards into increasingly thickly bedded grainstones with occasional silty mudstone rip-up clasts (Figs 5, 7C–E), indicative of an upward shallowing succession. Above, and only partly exposed, are nodular limestones and silty mudstones overlain by massive wave ripple grainstones, indicative of a further flooding surface and episode of shallowing. Previous descriptions of Little Cwm Dowlais Farm Quarry indicate that 3.2 m of grainstone overlain by nodular limestones occurred above the present exposure (Squirrell & Downing 1969, p. 20), and that the top of the upper division presently exposed at Ton Quarry approximates to this part of the succession. There, a broad upward deepening succession is indicated by increasingly fine grained and nodular limestones, the replacement of a diverse shallow marine fauna by one dominated by only brachiopods (i.e. *Atrypa* sp.), and an increase in the proportion of marl and silty mudstones (Fig. 7F). Within this succession a prominent silty mudstone flooding surface occurs at 0.9 m below the boundary with the Lower Forest Beds (Figs 3F, 5), as well as another flooding surface at the formational boundary.

Having identified four silty mudstone flooding surfaces within the Usk Limestone Formation, their correlation with flooding surfaces and parasequences observed elsewhere on the Midland Platform can be assessed. Notably, the second peak of the Homerician CIE within the Usk Limestone Formation contains two subpeaks (P2a and P2b), which have a clear equivalence on the curves from the upper half of the Much Wenlock Limestone Formation at Malvern and Dudley (Fig. 8). The shape of the second peak at Usk appears most comparable to that from Dudley. There the start and finish of the

second peak coincide with flooding surfaces, with an additional four flooding surfaces within the second peak, suggestive of correlation with the four flooding surfaces within the Usk Limestone Formation. Furthermore, the P2a subpeak at Dudley corresponds to the lower division of the Usk Limestone Formation, and at both locations is associated with a single flooding surface and the onset of bioherm development, indicating a synchronous episode of marked shallowing. Based upon the regional correlation of the second peak of the Homeric CIE and the four associated flooding surfaces, the sequence boundary and combined transgressive surface identified at Malvern, Ludlow and Dudley likely corresponds to a position midway through the upper division of the Usk Limestone Formation; perhaps associated with the thickly bedded grainstone with silty mudstone rip-up clasts observed at Little Cwm Dowlais Farm Quarry (Figs 5, 8). Accordingly, the Usk Limestone Formation begins with the regressive systems tract progradation of a carbonate system into an area of exposed, storm-dominated shelf, as indicated by the deposition of high energy grainstone shoals of the lower division. The upper division of the Usk Limestone Formation, with its greater diversity of limestone lithofacies, indicates a more sheltered setting developed within a carbonate platform, which was protected from storms by fringing shoals and bioherms (regressive and early transgressive systems tracts). Within the uppermost part of the upper division, and above the sequence boundary and combined transgressive surface, the development of nodular limestones is reflective of the early transgressive systems tract, which culminates at Usk and across the wider Midland Platform with the replacement of limestones by offshore silty mudstones in the Gorstian (late transgressive systems tract).

Significance of the Homeric stratigraphy of the Usk Inlier

Based upon the integration of carbon isotope data and sequence stratigraphy the Homeric of the Usk Inlier can be correlated with the rest of the Midland Platform (Fig. 9). Such correlations show that the Usk Inlier succession is most like the outer part of the Midland Platform (*e.g.* Wenlock Edge), where a single prominent biohermal limestone unit (Much Wenlock Limestone Formation) occurs above locally developed nodular limestones within silty mudstones (Farley Member of the Coalbrookdale Formation).

Correlations of the Homeric CIE and associated sea-level changes between Avalonia, Baltica and Laurentia have been published by numerous authors (Cramer *et al.* 2012, 2015; Danielsen *et al.* 2019; Klock *et al.* 2025) and highlight the same general relationships described herein

(Figs 2, 8). These changes in carbon isotope values and sea-level can be used to correlate the upper Ton Siltstone and Usk Limestone formations with the wider Midland Platform (Fig. 9), as well as with key successions on Baltica and Laurentia. However, beyond the establishment of a refined stratigraphy for the Homeric of the Usk Inlier, the Homeric CIE developed within a conformable and varied succession of nearshore and offshore sediments is unusual and worthy of further comment. Notably, in contrast with the majority of the Midland Platform (Ray *et al.* 2010, 2020; Fry *et al.* 2017) and the epicontinental sea that covered southeastern Laurentia (Danielsen *et al.* 2019, Klock *et al.* 2025), the Usk Inlier succession contains two sandy siliciclastic influxes indicative of two episodes of regression. Of these, the wave-rippled sandy siltstones and sandstone outcropping at Weir Wood Cliff and in association with the onset of the Homeric CIE, are of particular interest, being analogous to records from Gotland (Sweden) (Fig. 9); an area that contains some of the best documented examples of the onset of the Homeric CIE, sea-level change, and the associated faunal extinctions (*e.g.* Calner *et al.* 2006a, b, 2012; Calner 2008). Within the nearshore Hunninge-1 core (Gotland, Sweden) the Gannarve Siltstone Member (Fröjel Formation) represents a regressive upward-coarsening influx of current-rippled siliciclastics, which culminates in the onset of the Homeric CIE and an unconformity surface (Calner 1999, Calner & Säll 1999, Calner *et al.* 2006a), and as such mirrors the sandy siltstones of the Ton Siltstone Formation, as developed below the sequence boundary and combined transgressive surface. Above the unconformity in the Hunninge-1 core is a transgressive succession within the Bara Oolite and Mulde Brick Clay members (Halla Formation). As with the Trostrey Limestone Member of the Usk Inlier, the higher carbon isotopic values and the first peak of the Homeric CIE are restricted to the carbonate-rich parts of this succession (the Bara Oolite Member and overlain lower half of the Mulde Brick Clay Member), which reflect gradual deepening (early transgressive systems tract) prior to the offshore mudstones associated with the maximum flooding surface and the upper half of the Mulde Brick Clay Member (Calner *et al.* 2006a, chart 1). While the Weir Wood Cliff section shares many similarities with the Hunninge-1 core, it lacks an unconformity surface and evidence of subaerial exposure, suggesting a more offshore setting, as appears to be the case for the whole of the Midland Platform. Upon Gotland, subaerial erosion and the subsequent onlap of the resultant karstic rocky shoreline, indicate a relative sea-level fall of at least 16 m, and a subsequent sea-level rise of at least the same amount during the early phase of transgression (Calner & Säll 1999, Johnson 2006). A scoured, mineralized surface in silty carbonate mudstones, interpreted as

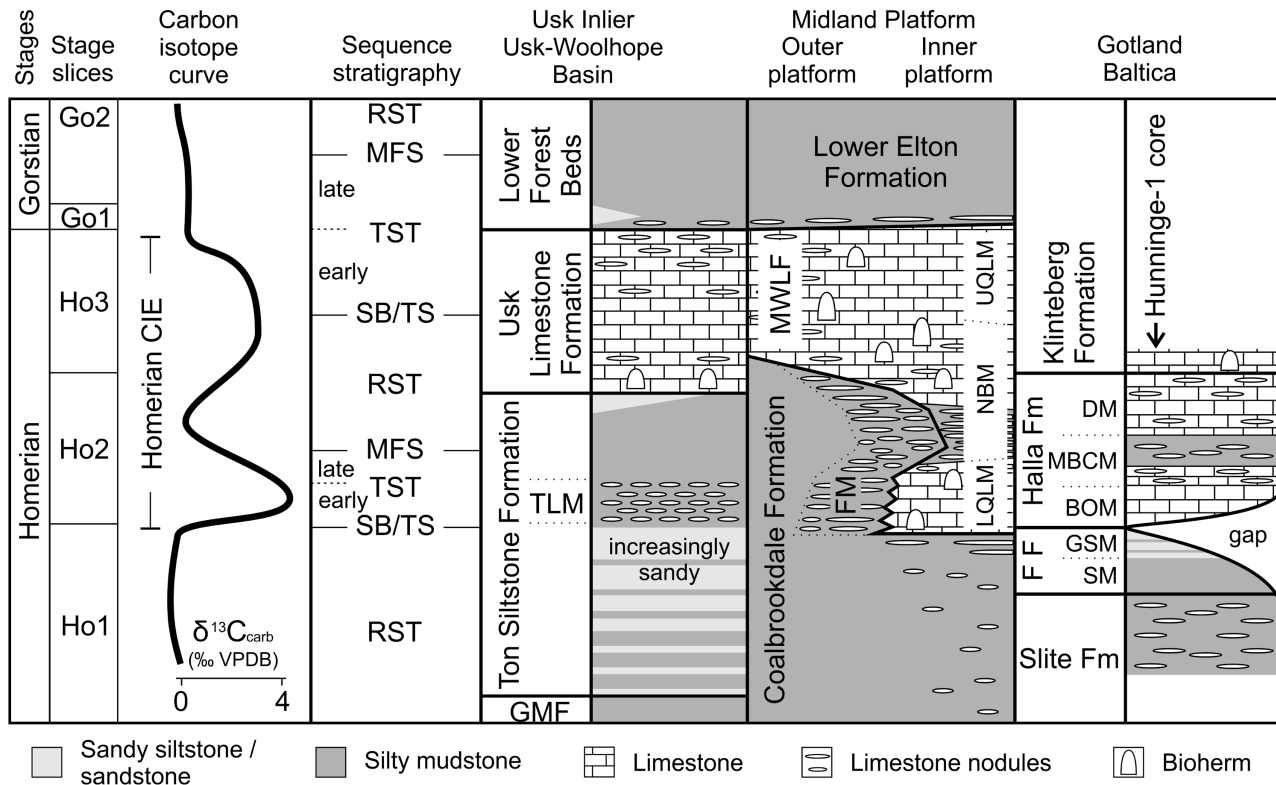


Figure 9. A comparison of the Homerian lithostratigraphical units of the Usk Inlier with those of the wider Midland Platform and Gotland (Sweden), based upon correlations with the geologic timescale (Melchin *et al.* 2020), carbon isotope trends and sequence stratigraphy (see caption for Fig. 2). On the Midland Platform successions representative of the outer platform include southern Wenlock Edge and Ludlow, while the inner platform is representative of Dudley, Walsall, Abberley, Malvern and May Hill (Fig. 1). Note that the Much Wenlock Limestone Formation (MWLF) of the inner platform consists of lower and upper limestones (Lower Quarried Limestone and Upper Quarried Limestone members – LQLM, UQLM), separated by nodular beds (Nodular Beds Member – NBM), while the outer platform succession consists solely of an upper limestone unit, below which are locally developed nodular limestones within silty mudstones (Farley Member of the Coalbrookdale Formation – FM). The Gotland column is representative of a nearshore succession and the Hunninge-1 core (after Calner 1999; Calner & Säll 1999; Calner *et al.* 2006a, 2012), and shows the position and local extent of the unconformity and stratigraphic gap developed at the onset of the Homerian CIE. Abbreviations: BOM – Bara Oolite Member; DM – Djupvik Member; FF – Fröjel Formation; GMF – Glascoed Mudstone Formation; GSM – Gannarve Siltstone Member; MBCM – Mulde Brick Clay Member; SM – Svarvare Member; TLM – Trostre Limestone Member.

a possible epikarst, has also been reported from this level in Podolia, Ukraine (Jarochowska *et al.* 2016). Within a more offshore setting, the Grötlingbo-1 (Gotland, Sweden) and Bartoszyce (Peribaltic Trough, Poland) cores lack the unconformity and lithological variability of the Hunninge-1 core (Porębska *et al.* 2004; Calner *et al.* 2006a, b). However, in association with the onset of the Homerian CIE, and immediately above a regionally traceable sequence boundary/correlative conformity is a narrow band of laminated mudstones. These laminated mudstones may have equivalence to the silty mudstone flooding surface at Weir Wood Cliff, which occurs between the sequence boundary and base of the Trostre Limestone Member. Notably, this flooding surface at Weir Wood Cliff represents the short-term introduction of offshore deposits that do not return until the late transgressive systems tract, and as such identifies an important eustatic event during the onset of the Homerian CIE that may be as pronounced as the preceding regression.

Conclusions

- (1) The stratigraphy of the upper Ton Siltstone and Usk Limestone formations of the Usk Inlier has been investigated by carbon isotope analysis, sedimentary logging, and sequence stratigraphic interpretation of representative sections. These have allowed for the creation of a composite section, and facilitated comparisons with successions of a similar age elsewhere upon the Midland Platform.
- (2) The globally-recognised Homerian (Silurian) carbon isotope excursion (CIE) is identified from the Usk Inlier, with the first and second peaks documented from the limestone lithofacies of the Ton Siltstone (Trostre Limestone Member) and Usk Limestone formations.
- (3) The magnitudes of the two peaks of the Homerian CIE are strongly influenced by the depositional setting with

the relatively offshore nodular limestones of the Trostrey Limestone Member containing a diminutive first peak (0.6‰), when compared with the second peak (2.3‰) that is developed in the nearshore Usk Limestone Formation.

(4) A sequence stratigraphic interpretation has been facilitated by the occurrence of competing siliciclastic and carbonate sedimentary systems, which result from the proximity of the Usk Inlier to the landmass of Pretannia. Notably, the two Homeric eustatic regressions associated with the Homeric CIE are expressed by nearshore wave-rippled sandy siltstones and sandstones.

(5) The lithological expression of the onset of the Homeric CIE within the Usk Inlier identifies a regressive influx of siliciclastics followed by a pronounced transgression, and is analogous to records from Gotland (Sweden).

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