

## Sequence stratigraphy of the type Wenlock area (Silurian), England

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**ABSTRACT** - The type Wenlock Series is established around the village of Much Wenlock, Shropshire, England, and consists of the Buildwas, Coalbrookdale and Much Wenlock Limestone formations. Based upon new data and a re-evaluation of lithological and palaeontological data from the Lower Hill Farm Borehole and outcrops, an assessment of relative sea-level change has been made. Broadly, the type Wenlock consists of two shallow water carbonates separated by terrigenous sediments. Within this framework two major depositional sequences have been recognised, along with six higher-order sequences. These transgressive-regressive sequences have been calibrated against graptolite zonation schemes and are in general agreement with previously published Wenlock eustatic sea-level curves.

**RIASSUNTO** - [Stratigrafia sequenziale dell'area-tipo del Wenlock (Siluriano), Inghilterra] - La classica Serie del Wenlock è stata istituita presso il villaggio di Much Wenlock, in Inghilterra, e comprende le formazioni di Buildwas, Coalbrookdale e il Much Wenlock Limestone. Sulla base di nuovi dati e di un approfondito riesame dei dati litologici e paleontologici ottenuti dallo studio del Lower Hill Farm Borehole e degli affioramenti esposti, è stata compilata una curva della variazione del livello marino ed eseguito un confronto con le curve eustatiche già pubblicate. A grandi linee, il Wenlock tipo è costituito da due unità carbonatiche di acque basse separate da sedimenti terrigeni, all'interno delle quali sono state riconosciute due sequenze deposizionali principali e sei sequenze di ordine superiore. Il limite basale di sequenza è rappresentato da uno hiatus deposizionale al limite Llandovery-Wenlock, al di sopra del quale valori trasgressivi inizialmente bassi e sequenze di grado superiore portarono alla deposizione dei calcari della Buildwas Formation.

Con l'aumentare dell'evento trasgressivo, la sedimentazione carbonatica si interrompe e si instaurò un ambiente bacinale di acque profonde (Apedale Member della Coalbrookdale Formation); la relativa superficie di massima ingressione (maximum flooding surface MFS) viene collocata tra le zone a *Monograptus riccartonensis* e *Cyrtograptus rigidus*.

La sovrastante correlative conformity è evidenziata dalla presenza di un livello di arenarie fini, oltre la quale si osserva un trend generale di upward-shallowing (dalla parte alta della Zona a *C. rigidus* alla parte alta della Zona a *Cyrtograptus lundgreni*) associato ad un incremento arenaceo, che termina in corrispondenza della superficie di massima regressione (maximum regressive surface). La MFS della sequenza sovrastante è ancora all'interno della parte alta della Zona a *C. lundgreni*, al di sopra della quale la sequenza è contraddistinta da carbonati contenenti una ben rintracciabile sequenza regressiva-trasgressiva di ordine superiore nella Zona a *Gothograptus nassa*. La sedimentazione carbonatica si conclude appena al di sopra del limite di sequenza nella parte terminale della Zona *Colonograptus ludensis* ed è rimpiazzata da mudstone presenti alla base della Lower Elton Formation.

### INTRODUCTION

The type Wenlock Series is established around the village of Much Wenlock, Shropshire, and consists of a succession of limestones and silty-mudstones, which together make up the Buildwas, Coalbrookdale and Much Wenlock Limestone formations (Bassett et al., 1975; Bassett, 1989; Aldridge et al., 2000, pp. 234-253). Of these, only the Much Wenlock Limestone Formation is well exposed, forming the prominent escarpments of Benthall Edge and Wenlock Edge, which are incised by numerous limestone workings and road cuttings. Below the Much Wenlock Limestone Formation, the less resistant medial and basal formations outcrop in isolated stream sections, road cuttings and forestry tracks within the low ground of Ape Dale and Coalbrookdale. As a consequence of the fragmentary nature of medial and lower Wenlock Series outcrops, core samples recovered from the Lower Hill Farm Borehole (LHFB) (SO 5817 9788) have proven valuable in the establishment of a biostratigraphic and bentonite record (Bassett et al., 1975; Mabillard & Aldridge, 1985; Swire, 1993; Huff et al., 1996; Ray, 2007). However, unlike the overlying Much Wenlock Limestone Formation and Farley Member

of the Coalbrookdale Formation (Shergold & Bassett, 1970; Scoffin, 1971; Ratcliffe & Thomas, 1999; Ray et al., 2010), no detailed published sedimentological or sequence stratigraphic record exists for the intervals associated with the LHFB, and consequently the majority of Wenlock time.

Based upon new measured sections and those of Ray et al. (2010) for the upper quarter of the Wenlock, and a detailed lithological report for the LHFB (Fig. 1), recorded in 1973 by Dr D.E. White of the British Geological Survey (White, 1973), a near continuous record of relative sea-level (RSL) change for the type Wenlock is reported herein and compared with globally derived sea-level curves of Loydell (1998) and Johnson (2006).

### WENLOCK STRATIGRAPHY

The thickness of Wenlock sediments, as developed around the village of Much Wenlock, is as much as 380 m, deposited over a period of 5.3 million years (Ogg et al., 2008) at an average rate of 1 m every 14,000 years (see Dorning & Harvey, 1999). The biostratigraphy is

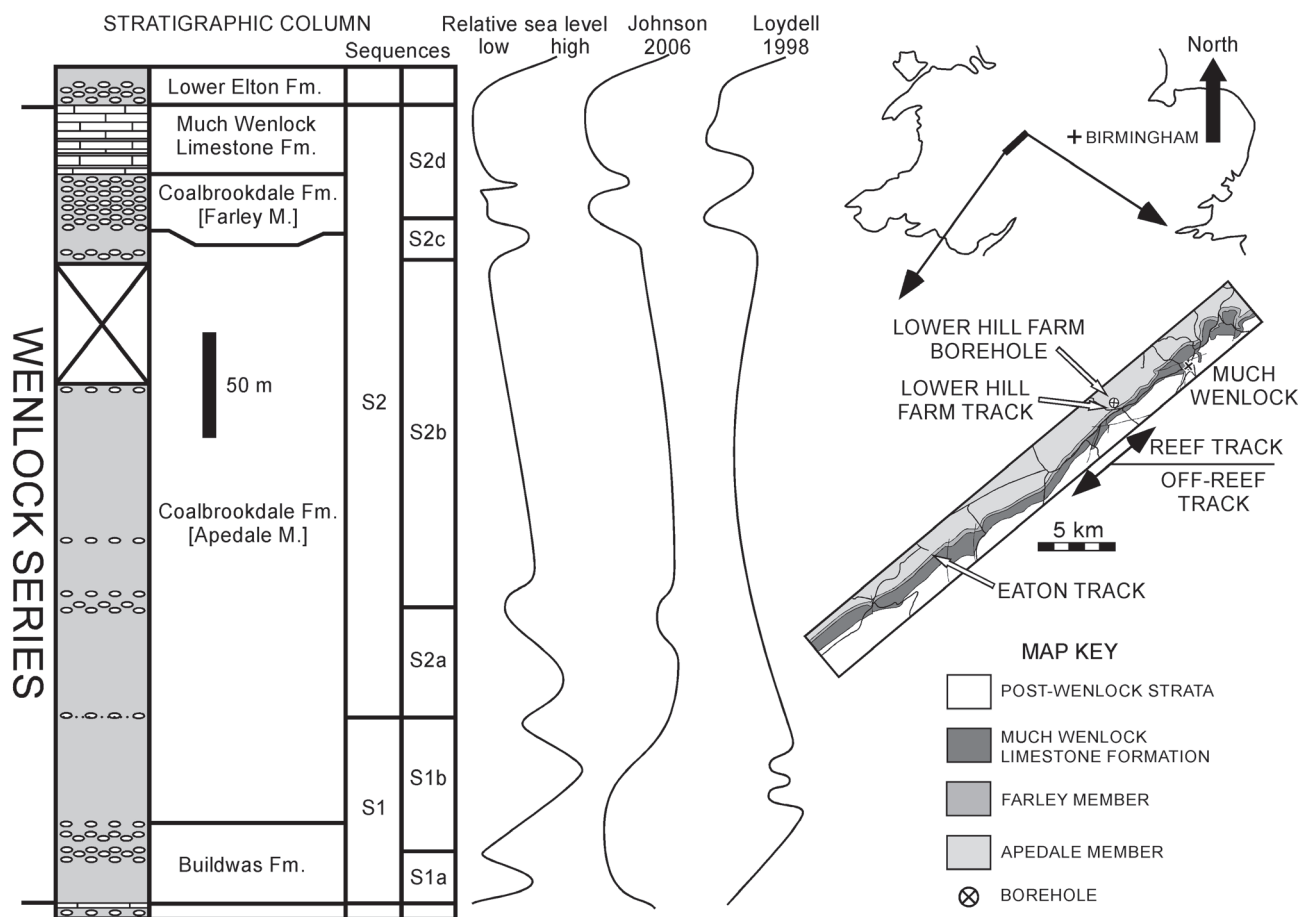


Fig. 1 - Solid geology, key measured sections not given in Ray et al. (2010) and the location of the Lower Hill Farm borehole along Wenlock Edge, Shropshire. The generalised stratigraphic column is representative of the Lower Hill Farm Borehole and the overlying strata exposed around the village of Much Wenlock. The sea-level curve and associated sequences are derived from the type Wenlock described herein, and are compared with the curves of Loydell (1998) and Johnson (2006); note that these curves have been scaled to reflect the relative positions of biozones as established in the type Wenlock area (see Figs. 2 and 3 for details).

based primarily upon graptolites and allows six zonal assemblages to be established with confidence (Bassett et al., 1975). The graptolite assemblages presented in Bassett et al. (1975) have additionally been compared to the scheme of Zalasiewicz & Williams (1999), which was developed in the nearby Builth Wells area. With the exception of the Llandovery-Wenlock boundary and the grainstone lithofacies in the upper Much Wenlock Limestone Formation, deposition appears to have been continuous and unaffected by episodes of erosion. Furthermore, the subsidence history for Wenlock Edge indicates deposition on a gently subsiding shelf that is relatively unaffected by the late Llandovery to early Wenlock episode of crustal extension and rapid subsidence observed in the Welsh Basin (Woodcock et al., 1996).

The basal Buildwas Formation consists of a 40 m succession of mudstones and subordinate nodular to bedded limestones (mudstones to wackestones) associated with 31 bentonites (Fig. 2). The presence of occasional shell debris, consisting mainly of small brachiopods, and rippled limestones indicate that the sea-

floor lay within the lower limit of storm wave-base and is comparable to Benthic Assemblage (BA) 4-5 (Brett et al., 1993) and the deeper part of the outer platform (Bassett, 1989).

The Apedale Member of the Coalbrookdale Formation makes up the majority of the thickness of the Wenlock Series and may represent as much as 282 m of mudstones, with 197 m present within the LHFB and 21 m exposed in the hillside above (SO 5790 9748). However, c. 64 m remains unexposed above Lower Hill Farm. Associated with the mudstones are siltstones, particularly in the upper third, occasional nodular to bedded limestones (mudstones to wackestones) and a single fine grained sandstone bed. In addition, 104 bentonites (Figs. 2-3) are recorded from the LHFB with a further two exposed in the hillside above. Macrofossils are rare and consist of graptolites, orthocones, small brachiopods and trilobites that occasionally show evidence of alignment and sorting, suggesting sea-floor currents potentially linked to storms. Such features are consistent with BA 5-6 (Brett et al., 1993; Aldridge et al., 2000, p. 238) and deposition on the outermost part of the platform (Bassett, 1989).

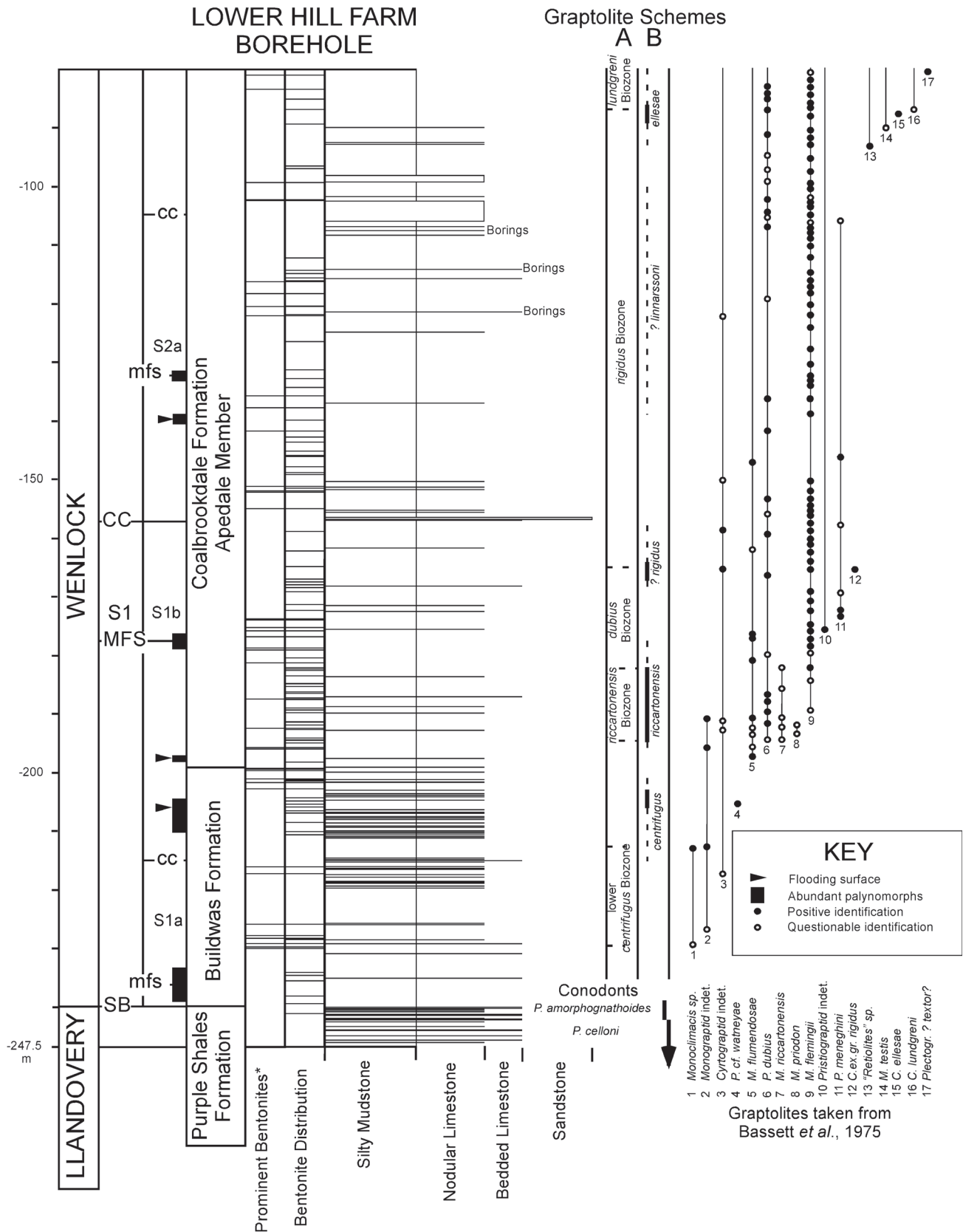


Fig. 2 - Lithostratigraphy, biostratigraphy, sequence stratigraphy and bentonite distributions within the Lower Hill Farm Borehole. The distribution of prominent bentonites is taken from Huff et al. (1996); lithological information and bentonite distributions from the British Geological Survey report of White (1973); palynomorph abundance data from Swire (1993); graptolite occurrences from Bassett et al. (1975); conodont zones from Mabillard & Aldridge (1985). Graptolite Schemes: A= Zalasiewicz & Williams (1999), B= Bassett et al. (1975). Sequence stratigraphic framework (note upper case letters refer to lower-order cycles and lower case letter higher-order cycles): SB= sequence boundary, MFS/mfs= maximum flooding surface, CC/cc= correlative conformity.

The Farley Member of the Coalbrookdale Formation and Much Wenlock Limestone Formation broadly represent an upward-shallowing succession (outer BA 1-5), consisting of silty-mudstones, nodular, bedded (mudstones to grainstones) and reefal limestones that exhibit diachronism and thickness variation along the length of the type area (Ray et al., 2010). Such variations reflect sea-floor topography and are associated with a minor shelf break situated around Easthope (Scoffin, 1971; Bassett, 1989). To the northeast of the shelf break shallower conditions prevailed, being characterised by reefs (reef tract) in the uppermost 16 m and the thickest development of both the Farley Member and Much Wenlock Limestone; 27 m and 33 m respectively. To the southwest of Easthope, reefs and associated shallow water faunas are generally absent (off-reef tract) and at Longville in the Dale thicknesses are reduced to 24.5 m and 24 m respectively. Based upon comparisons with time equivalent strata in the West Midlands, 12 upward-shallowing sequences (parasequences) can be correlated along Wenlock Edge and the northern Midland Platform and allow for the identification of a single third-order cycle of RSL change, which is punctuated by a higher-order regressive episode (Ray & Thomas, 2007; Ray et al., 2010). Bentonites are also common, but owing to the higher energy environment tend to be localised or associated with flooding surfaces.

Based upon the completeness of the sedimentary record, a lack of tectonic complication and good biostratigraphic constraint, the three formations and associated members that make up the type Wenlock (Fig. 1) should provide a detailed record of RSL change that is comparable with globally derived sea-level curves (Loydell, 1998; Johnson, 2006).

## METHODOLOGY

RSL change within the type Wenlock has been established by analysis of lithofacies patterns, palynomorph abundance events and bentonite distributions. Based upon the relative shoreward or basinward movement of these associations two broad depositional sequences have been recognised along with six higher-order sequences.

In the absence of Lower Palaeozoic calcareous plankton, carbonate production is reliant upon benthic organisms, which are most abundant in warm shallow sunlit environments that are beyond the influence of significant land-derived clastic sediments. Based upon this premise a typical land to basin succession should consist of a zone of clastic sediments that fine with increasing distance from the shoreline, a zone of carbonate production that is most productive where the sea-floor is well within the photic zone and clastic supply has a minimal impact on growth and a zone of increasing clastic dominance sourced by sediments that have been transported through the zone of carbonate production. This is the depositional model inferred herein for the Midland Platform and the type Wenlock area, and identifies the Buildwas Formation, Farley Member and Much Wenlock Limestone Formation as intervals of shelf carbonate production, and the Apedale Member as an interval of

basinal clastic deposition. Such a model is supported by bathymetry-dependent faunal associations and sedimentary structures.

The LHFB contains a detailed palynological record (Swire, 1993). In particular, high palynomorph abundances can be useful for identifying intervals of sediment starvation that are associated with transgression and the maximum flooding surface (MFS) (Armentrout, 1996). Based upon the work of Swire (1993, fig. 2), intervals that contain three or more taxa described as common or abundant have been identified as palynomorph abundance events and used as a means of identifying condensed sections.

Bentonites result from the deposition of volcanic ash within a marine environment and typically consist of clay and sand sized fractions reflecting the alteration of volcanic ash and the deposition of primary phenocrysts (Teale & Spears, 1986; Huff et al., 1996; Ray, 2007). At outcrop and within core, bentonites are easily identifiable as white, blue-grey or orange clay horizons. Within the Much Wenlock Limestone Formation and Farley Member bentonites are more frequently associated with flooding surfaces or the leeward side of reefs, reflecting increased preservation potential within lower energy environments (Ray et al., 2010). This is especially true of thin (< 1 cm) bentonites that are frequently laterally discontinuous, suggesting that even gentle sea-floor agitation by storms or bioturbation may be sufficient to remove bentonites from the geologic record. Assuming a steady input of volcanic ash across the Midland Platform, bentonite distributions may therefore reflect RSL change, particularly within those parts of the Wenlock close to the limit of storm wave-base. Accordingly an overall increase in bentonites may reflect transgression and a decrease in bentonites regression; though the potential for variations in volcanic activity means that the bentonite record should not be used in isolation. The distribution of bentonites reported for the LHFB is based upon the British Geological Survey report (White, 1973) rather than that in Huff et al. (1996) and Ray (2007), who focused only upon those bentonites of sufficient thickness (> 1 cm) for geochemical analysis.

## SEQUENCE STRATIGRAPHY

Within the type Wenlock, two broad depositional sequences have been recognised (S1 and S2), along with six higher-order sequences (S1a, b, S2a, b, c, d) (Fig. 1). Both the higher and lower order sequences contain distinct transgressive and regressive phases, and are of durations that correspond to third-order sequences, but are distinguishable according to the magnitude of RSL change. As the lower-order sequences reflect the greatest variation in RSL change and are presumably therefore the more widely recognisable, these form the framework for the description herein.

The Llandovery-Wenlock boundary within the LHFB occurs at 239.69 m (Bassett et al., 1975) and corresponds to a gradational colour change from purple to grey-green and an abrupt transition from mudstones containing numerous shelly limestone beds to mudstones and numerous bentonites. This boundary between the Purple

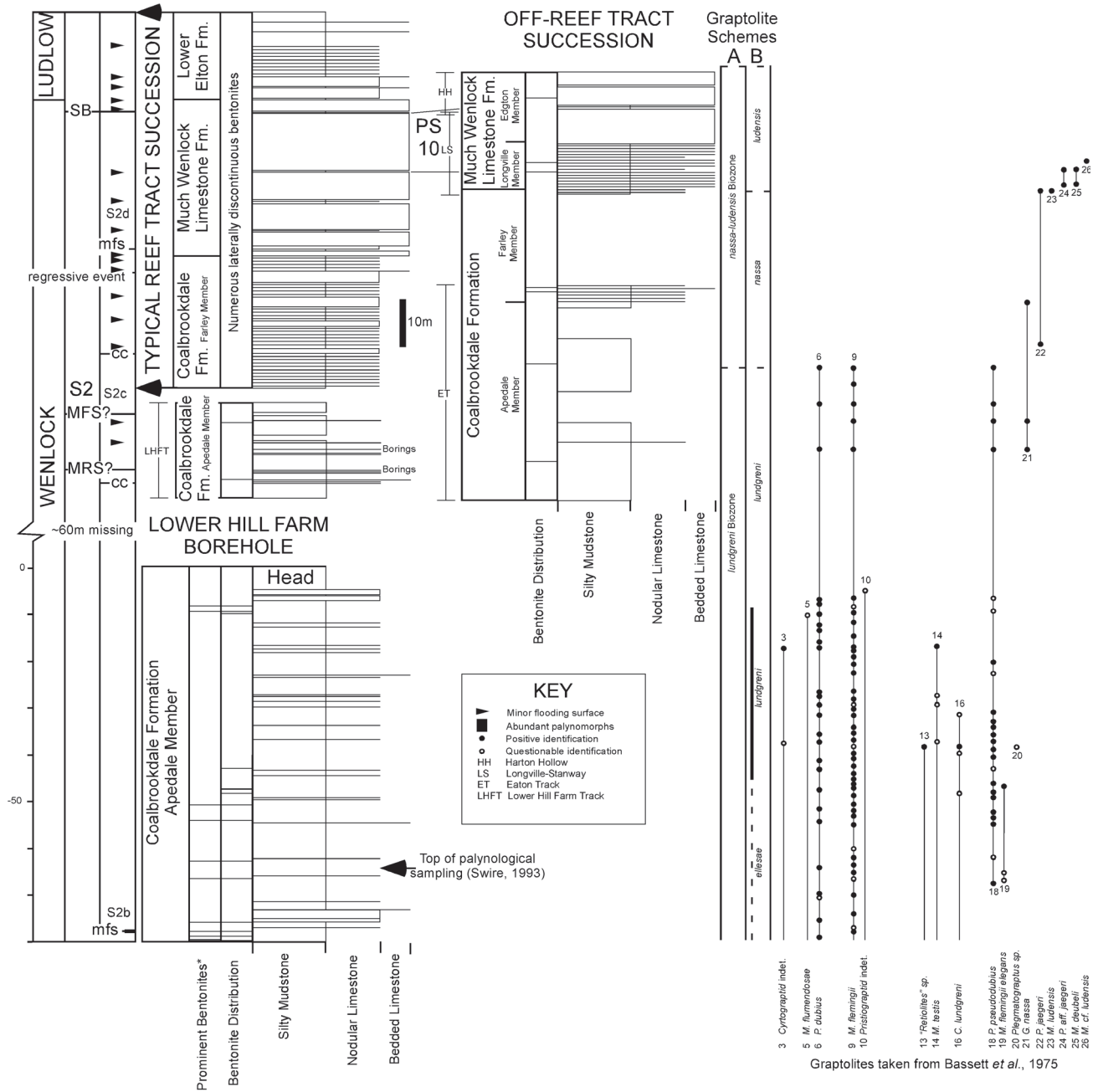


Fig. 3 - Lithostratigraphy, biostratigraphy, sequence stratigraphy and bentonite distributions within the Lower Hill Farm Borehole and overlying Wenlock strata. See Fig. 2 for information relating to the Lower Hill Farm Borehole and sequence stratigraphic framework. Within the overlying reef and off-reef tracts the Typical Reef Tract Succession, Harton Hollow and Longville-Stanway sections are all modified from figure 7 in Ray *et al.* (2010). Graptolite occurrences are from Bassett *et al.* (1975) and relate to the Eaton Track and Longville-Stanway sections. Correlation between the off-reef and reef tracts is based on the correlation of PS10 (Parasequence 10) and associated minor flooding surfaces (see Ray *et al.*, 2010).

Shales and Buildwas formations is contained within the *Pterospirifer amorphognathoides* Conodont Zone, immediately below which is the *Pterospirifer celloni* Zone (Mabillard & Aldridge, 1985, p. 95). Ogg *et al.* (2008) consider the *P. amorphognathoides* Zone to span 2.4 million years, which is equivalent to almost half the estimated duration of the Wenlock Series, yet within the LHFB the *P. amorphognathoides* Zone occurs only between 242.21 m and 239.14 m (3.07 m thick). The

apparent brevity of the *P. amorphognathoides* Zone is in contrast with the overlying relatively-expanded Wenlock biozones, indicating the presence of either a depositional hiatus or erosional unconformity and a late Llandovery to earliest Wenlock sequence boundary. The major sea-level fall associated with this sequence boundary is a widely recognised Silurian event that according to Loydell (1998) began in the mid *Cyrtograptus lapworthi* Zone and continued across the

Llandovery-Wenlock boundary into the lower *Cyrtograptus centrifugus* Zone.

The overlying sequence (S1) consists of two higher-order transgressive-regressive sequences (S1a and S1b). The initial phase of transgression (S1a) is characterised by a dominance of mudstones and numerous bentonites, with the MFS (c. 236 m) corresponding to the thickest mudstone package and an interval of high palynomorph abundance (Swire, 1993). A short phase of regression then followed and is recognised by an increase in nodular limestone bands and a decrease in the number of bentonites. Based upon the graptolites recorded by Bassett et al. (1975) this basal high-order sequence (S1a) is restricted to the *C. centrifugus* Zone (Fig. 2). However, the absence of the *Cyrtograptus murchisoni* Zone within the type Wenlock, and the questionable identification of the *Monograptus riccartonensis* and *Cyrtograptus rigidus* zones within the LHFB, may allow for the minor mid Sheinwoodian sea-level fall of Loydell (1998) to be attributable to this regressive event (*Monograptus firmus* to early *M. riccartonensis* zones).

The correlative conformity (c. 214 m) at the base of the overlying sequence (S1b) corresponds to the thickest nodular limestone interval within the Buildwas Formation. The initial phase of transgression contains two upward-shallowing mudstone to nodular limestone parasequences, the flooding surfaces of which correspond to successive palynomorph abundance events (Swire, 1993). More generally there is a progressive decrease in nodular limestones and an increase in mudstone and bentonites across the boundary between the Buildwas Formation and the Apedale Member of the Coalbrookdale Formation (199.14 m). This culminates in a mudstone and bentonite dominated interval containing the MFS (176.87 m) of the lower order S1 sequence, which is identified by a further palynomorph abundance event (Swire, 1993). The MFS occurs between the *M. riccartonensis* and *Cyrtograptus rigidus* zones of Bassett et al. (1975), and in the middle of the *Pristiograptus dubius* Zone of Zalasiewicz & Williams (1999) and most likely represents the deepest water setting developed within the type Wenlock. The MFS of S1 corresponds to cycle 5 of Johnson (2006) and the mid Wenlock sea-level high of Loydell (1998) (*C. rigidus* Zone of Bassett et al., 1975); though uncertainties within the existing graptolite zonations means that a *C. murchisoni* Zone sea-level high of Loydell (1998) cannot be excluded. The overlying regression is associated with a decrease in the number of bentonites and the return of occasional nodular limestone bands.

The correlative conformity between S1 and S2 is marked by a fine grained reddish-brown sandstone layer (156.51 m) that occurs within the upper and lower *C. rigidus* zones of Bassett et al. (1975) and Zalasiewicz & Williams (1999) (Fig. 2) respectively. Sandstones within basinal settings are often indicative of a pronounced RSL fall and are rare within the Coalbrookdale Formation, only being described from the Usk Inlier (Bassett, 1974). Here in the Usk Inlier they occur at 45 m, 37.5 m and 4.5 m below the base of the Much Wenlock Limestone, but are poorly dated (post-*M. riccartonensis* Zone). Within the type Wenlock no such upper sandstone beds are known, but siltstone beds within the upper 50 m of the LHFB are

common and, along with an increase in the frequency of nodular limestone bands and decrease in the occurrence of bentonites, indicate a general pattern of RSL fall.

In detail, the upward-shallowing trend within S2 and the Apedale Member is reflected by the occurrence of prominent limestone intervals formed during the regressive phases of higher-order sequences S2a and S2b. Within the LHFB the most prominent of these nodular limestone intervals occurs within the *Cyrtograptus ?linnarssoni* Zone of Bassett et al. (1975) or upper *C. rigidus* Zone of Zalasiewicz & Williams (1999) and is associated with bored limestone nodules, indicative of winnowing as the sea-floor became more frequently influenced by storms. Based upon relative position and age, it is likely that these limestones are coeval with those reported from the middle Coalbrookdale Formation of the Woolhope Inlier (Taylor, 1963), and the minor sea-level low of Johnson's cycle 5 (2006).

The upper part of S2b is poorly defined in the current study, with c. 64 m of the Apedale Member above Lower Hill Farm not exposed. Assuming the Apedale Member shallowing-upward trend continues through the unexposed section, the correlative conformity of S2b corresponds to a previously described prominent nodular limestone interval (Greig et al., 1968, p. 177; Dorning & Harvey, 1999) contained within a forestry track (SO 5790 9748) in the hillside above Lower Hill Farm. Within the forestry track bored limestones nodules are also present, as is much of the S2c sequence, offering the opportunity to observe many of the same features described from the borehole report.

Sequences S2c and S2d represent the transition from clastic to carbonate dominated systems. Of particular note is the absence of sandstones within S2, which are present within the Apedale Member of the LHFB and, more notably, in the Usk Inlier (Bassett, 1974). It seems likely that the broad phase of RSL fall responsible for bringing sandstones onto the Midland Platforms ends within S2c and the upper *Cyrtograptus lundgreni* Zone, thereby identifying S2c as containing the maximum regressive surface and overlying MFS of S2.

The carbonate dominated S2d sequence that contains the Farley Member and Much Wenlock Limestone Formation has been described in detail by Ray et al. (2010) and is therefore only briefly addressed herein. However, comparisons with the underlying Wenlock suggest that S2d represents a period of RSL standstill, allowing benthic carbonate producers to proliferate and aggrade. In summary, the basal correlative conformity has been identified by correlation with the West Midlands and occurs within the uppermost *C. lundgreni* Zone. The overlying transgression is poorly expressed along Wenlock Edge, being represented by aggradation within the Farley Member. At the top of the Farley Member, a higher-order regressive interval occurs (a single parasequence) and is overlain by the MFS within the lowest Much Wenlock Limestone Formation. Both the regression and overlying MFS are attributable to the *Gothograptus nassa* Zone and correspond to the mid Homerian sea-level fall of Loydell (1998) and cycle 5a of Johnson (2006). The lower third of the Much Wenlock Limestone is associated with aggradation, followed by a regression and the establishment of significant reef

development within the Much Wenlock Limestone (*Colonograptus ludensis* Zone). The upper sequence boundary and the top of S2 are contained within crinoidal grainstones (uppermost *C. ludensis* Zone) that show evidence of shallow marine winnowing and erosion rather than subaerial exposure. Overlying S2 are transgressive crinoidal grainstones that quickly give way to deeper water silty-mudstones associated with the Lower Elton Formation of the Ludlow Series.

## CONCLUSION

Based upon a combination of detailed lithological description, palynomorph abundance events and bentonite distributions, the type Wenlock can be described in terms of six transgressive-regressive sequences superimposed upon two higher-amplitude transgressive-regressive sequences that span the Wenlock. Furthermore, comparisons with the transgressive-regressive cycles described by Loydell (1998) and Johnson (2006) indicate numerous similarities suggesting a eustatic control on the RSL change described herein.

The base of the first of the two higher-amplitude sequences indicate the presence of a sequence boundary characterised by erosion or a depositional hiatus at the Llandovery-Wenlock boundary, above which initially slow rates of transgression and higher-order sequences result in the deposition of the limestones of the Buildwas Formation. As the rate of transgression increased, carbonate deposition ceased and a deepwater, basinal setting became established, the MFS of which occurs between the *M. riccartonensis* and *C. rigidus* zones of Bassett et al. (1975), and the middle of the *P. dubius* Zone of Zalasiewicz & Williams (1999). The overlying correlative conformity is marked by the presence of a fine grained sandstone bed, above which there is a general upward-shallowing trend associated with higher-order sequences and terminating at the maximum regressive surface. This lowstand infilling of the accommodation space generated during the underlying transgression occurs between the upper and lower *C. rigidus* zones of Bassett et al. (1975) and Zalasiewicz & Williams (1999) and the upper *C. lundgreni* Zone. The MFS of the overlying S2 sequence is also contained within the upper *C. lundgreni* Zone, above which the sequence is characterised by carbonates containing a widely traceable higher-order regressive-transgressive sequence within the *G. nassa* Zone. Carbonate deposition terminates just above the sequence boundary in the uppermost *C. ludensis* Zone and is replaced by basal mudstones of the Lower Elton Formation.

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