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Non-biostratigraphic correlation techniques and their role in stratigraphy: examples from the Wenlock Series (Silurian) of the Midland Platform, England

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Introduction

Biostratigraphy is the principal means by which correlations can be made between sedimentary successions, and the compilation of the relative distribution of fossils forms a mainstay in the development of the geologic time scale. However, the incomplete nature of the stratigraphic record places limits on the application of biostratigraphy within many successions. In particular, age diagnostic fossils may be absent or rare, and their consequent stratigraphic distribution unreflective of their total stratigraphic range.

The Wenlock Series of the Midland Platform has been studied in detail since the foundation of the Silurian System (Murchison, 1839) (Figure 1), and the importance of this area was formally recognized in the 1980s with the establishment of the Global Boundary Stratotype Section and Points (GSSP) that define the Wenlock and its constituent stages (Sheinwoodian and Homerian) (Melchin et al. 2012). Thus, the successions that crop out within Herefordshire, Shropshire, Worcestershire and the West Midlands are among the most intensively studied of Wenlock rocks (Figure 2). Nonetheless, age diagnostic fossils, such as chitinozoans, conodonts and graptolites, are far from common resulting in age and correlation uncertainties (Cock et al. 1992).

FIGURE 1 HEREABOUTS

Figure 1. Section from the Malvern Hills to Ledbury taken from Murchison 1872 (p. 95). The Wenlock Succession consists of the Woolhope Limestone Formation (*d*), Coalbrookdale Formation (*e*) and Much Wenlock Limestone Formation (*f*).

FIGURE 2 HEREABOUTS

Figure 2. An outcrop map of the Much Wenlock Limestone Formation (upper Wenlock) showing the location of sections and boreholes discussed within the text.

The gaps in the biostratigraphic record may be filled by alternative correlation techniques, and within the Wenlock of the Midland Platform volcanic ash horizons (bentonites), sedimentary facies changes resulting from sea-level changes (sequence stratigraphy) and variations in the carbon isotopic record (carbon isotopic stratigraphy) have all been used. These correlation techniques, applied alongside the available biostratigraphy, have resulted in significant improvements in our ability to correlate across the Midland Platform and beyond. What follows herein is a summary of the application of these alternative correlation techniques.

The correlation of volcanic ash horizons

Bentonite horizons (also termed K-bentonites or metabentonites by some authors) result from the deposition of volcanic ash within a marine setting, and are a common feature of the Silurian of the Midland Platform (Huff et al. 1996). Bentonites typically consist of white, greenish-grey or rusty-orange clays (e.g. chlorite, illite, kaolinite and smectite) (Figure 3) with a minor component of volcanic phenocrysts (e.g. apatite, biotite, feldspar, quartz and zircon) (Figure 4). Individual horizons typically range in thickness between 0.1 cm and 10 cm, but occasionally exceed 50 cm. Within abandoned quarries bentonites may be readily identified by bands of vegetation which take advantage of the water that percolates along these impermeable clay-rich horizons.

FIGURE 3 HEREABOUTS

Figure 3. A prominent bentonite exposed high on the southern face of Whitman's Hill Quarry, Storridge (Herefordshire). Note the plant roots within the bentonite. The field notebook is 20 cm high and rests directly on top of the bentonite (bentonite code WH9 of Ray et al. 2013).

FIGURE 4 HEREABOUTS

Figure 4. Stereo-zoom microscope image of apatite (transparent, prismatic grains), biotite (opaque black-brown platy grains) and Fe hydroxides (brown irregular grains) from an early Wenlock bentonite collected from the Lower Hill Farm Borehole (Shropshire) (bentonite code LHF6558 of Ray 2007). This bentonite has been correlated with a bentonite in the Eastnor Park Borehole (Herefordshire), and has

been used to demonstrate synchronous deposition within the Buildwas and Woolhope Limestone formations (Ray 2007).

Bentonites are among the most geologically important deposits to be found within the sedimentary record. In particular, the occurrence of volcanogenic minerals, such as zircon, allows for the absolute radiometric dating of bentonites. Thus, bentonites contribute ages expressed in millions of years to the relative age constraints (e.g. biozones) of the sedimentary record and are therefore crucial in the construction of geologic time scales. For example, a latest Wenlock bentonite collected from Wren’s Nest Hill (Dudley, West Midlands) has provided an age of 427.86 ± 0.32 million years in close proximity to the Wenlock-Ludlow series boundary (Cramer et al. 2012), indicating that the currently accepted age for the Wenlock-Ludlow series boundary (427.4 ± 0.5 million years; Melchin et al. 2012) may be a slight underestimate. In addition to providing absolute ages, bentonites may be chemically unique and result from a single large ash cloud that can be deposited extremely rapidly. Accordingly, the chemical signature of bentonites can reveal a wealth of information relating to their magmatic origin, and the identification of the same bentonite across a region may allow for the establishment of a time-line that reflects the eruption event; with respect to the geologic time scale such events are geologically instantaneous.

The Wenlock Series (433.4 to 427.4 million years ago) of the Midland Platform contains at least 150 discrete bentonite horizons, suggesting an average duration of 40,000 years between eruptions. Core and outcrop studies demonstrate a clear clustering of bentonites within lower energy, deeper-water facies (Ray & Butcher 2010). This distribution indicates that bentonite occurrence was strongly influenced by processes affecting deposition and preservation (e.g. sedimentation rate, depositional energy, bioturbation index and reworking), as well as the frequency of eruptions. The abundance of bentonites upon the Midland Platform indicates a close proximity to one or more volcanic centers. In particular, proximal volcanic deposits (lavas and or tuffs) are reported from the East Mendips (Somerset, England), Powys (Wales) and the Dingle Peninsula (Kerry, Ireland) (Cave & Loydell 1998) (Figure 5). These represent the closest known volcanic centers and, like the majority of bentonites, are of intermediate to acid composition (Huff et al. 1996). A more detailed assessment of compositional data indicated that volcanism results from arc to within plate processes. Furthermore, there is a compositional evolution of the magmatic processes, with bentonites typically becoming progressively acidic within younger deposits.

FIGURE 5 HEREABOUTS

Figure 5. Palaeogeography, volcanic centers and the stratigraphic distribution of Wenlock bentonites upon the Midland Platform. a. Location of the Midland Platform, Wenlock palaeogeography and nearby volcanic centers: 1. Dingle Peninsula, Kerry, Ireland; 2. East Mendips, Somerset, England; 3. Powys, Wales. b. An outcrop map

of the upper Wenlock (Much Wenlock Limestone Formation) and the distribution of bentonite correlations across the Midland Platform. The coloured lines (with a star) represent correlations between sections and cores. c. The stratigraphic position (coloured stars) of bentonite correlations, as shown in b. LLAND. = Llandovery; LUD. = Ludlow; Gor. = Gorstian.

Compositional differences have allowed for the geochemical fingerprinting of Wenlock bentonites and the correlation of three discrete volcanic horizons within parts of the succession that are poorly age constrained by biostratigraphic means. Such correlations have been based upon the rare earth element composition of volcanic apatite grains (Figure 4), and have been used to demonstrate synchronous deposition within the Buildwas and Woolhope Limestone formations (lower Wenlock) (Ray 2007), and to improve stratigraphic resolution within the Much Wenlock Limestone Formation (upper Wenlock) (Ray et al. 2011; Ray et al. 2013) (Figure 5).

Bentonites have proven especially helpful in the Much Wenlock Limestone Formation and have allowed the succession at Wren’s Nest Hill, Dudley (West Midlands) to be correlated to Wenlock Edge (Shropshire) and the Malvern Hills (Herefordshire). Across this region, a particularly notable feature of the Much Wenlock Limestone Formation is the presence of a thick bentonite (12 to 30 cm) within the middle of the formation (Figures 3 and 7). This bentonite can be traced regionally not only by its unusual thickness, but also by its notably mafic composition. Furthermore, chemical and stratigraphic similarities with extremely thin bentonites found on the Baltic island of Gotland (Sweden) have led to speculation that one of these bentonites may correspond to the distal edge of the same ash cloud as that which deposited the thick bentonite across the Midland Platform (Cramer et al. 2012). Such a correlation would indicate an extremely large eruption that deposited ash at least 2000 km from the volcanic vent (Ray et al. 2013) and provide a valuable new geologic time-line.

The correlation of sea-level change (sequence stratigraphy)

Sedimentary successions may be subdivided into packages relating to changes in relative sea-level, and the correlation of these packages is one of the principal goals of sequence stratigraphy. These packages can be readily identified by an analysis of changes in sedimentary facies (i.e. changes in sedimentary structures, mineralogy, texture and fossil content) and, thus evidence of sea-level change can be identified within many successions (Figures 6 and 7). Sea-level changes may be correlated at a local to global scale and can take place over a range of durations (thousands to millions of years). However, the most stratigraphically useful sea-level changes are those that result from short-term global processes that significantly change the volume of water within the oceans. In particular, the waxing and waning of land-grounded icecaps has the potential to globally change sea-level by several tens of metres over a time scale of 100,000s of years (glacio-eustasy); thereby producing globally traceable short-duration facies changes (see Simmons, 2012). The presence of icecaps at the Silurian south pole, alongside a highly variable record of global temperature change (Trotter et al. 2016) argues for glacial processes as the principal driver of short-term Silurian sea-level change.

FIGURE 6 HEREABOUTS

Figure 6. A pronounced shift in facies from shallow marine limestones (Woolhope Limestone Formation) to deeper marine shales (Coalbrookdale Formation) reflecting a major sea-level rise within the lower Wenlock. Scutterdine Quarry, near Woolhope (Herefordshire).

The Wenlock Series of the Midland Platform contains a range of frequencies and magnitudes of sea-level change. At the broadest scale, sea-level changes correspond well with the formations that make up the Wenlock (Ray and Butcher 2010). For example, the limestones of the lower (Barr, Buildwas, Dolyhir and Woolhope limestone formations) and upper (Much Wenlock Limestone Formation) Wenlock are reflective of relative sea-level lows, while the graptolitic shales of the middle Wenlock (Coalbrookdale Formation) reflect a relative sea-level high. These changes in sea-level are not restricted to the Midland Platform and have been reported as synchronous events upon multiple palaeocontinents. Such observations argue for global sea-level change and have allowed for the construction of eustatic sea-level curves (Figure 8) (Johnson 2006; Melchin et al. 2012).

The formations of the Wenlock may be further subdivided by higher frequency changes in sea-level, which can be best seen within the shallow marine limestones of the lower and upper Wenlock. These limestones may be subdivided in multiple upward shallowing cycles (parasequences). As these parasequences are of a scale (cm to m) that can be readily observed in most quarries, they represent one of the most easily identifiable and traceable features to be found within the Wenlock successions. Parasequences can be distinguished from each other and correlated according to differences in thickness and the amount of relative sea-level change. Furthermore, sea-level trends may be observed through successive parasequences, and these stacking patterns reflect broader lithological trends that allow the Wenlock to be subdivided into members and formations.

The Much Wenlock Limestone Formation has been correlated in detail using parasequences (Ray et al. 2010; Ray et al. 2013), the synchronicity of which has been demonstrated by the correlation of bentonites (Ray et al. 2011; Ray et al. 2013). Within the West Midlands and Herefordshire, the Much Wenlock Limestone Formation can be subdivided into twelve parasequences (Figure 7), thereby providing a considerably finer stratigraphic resolution than is achievable by the current biozonation (which is limited typically to three graptolite biozones). Furthermore, based upon the estimated duration of the Much Wenlock Limestone Formation, each parasequence (and sea-level change) has a mean duration of approximately 100,000 years, which if correct, indicates that they may result from climate-driven sea-level changes brought about by variations in the orbit of the earth (Milankovitch cycles); akin to those that have resulted in the glacials and interglacials of the most recent geological past. At present the correlation of upper Wenlock parasequences is restricted to the Midland Platform, but if they are the result of global climate processes, they may offer the potential for high-resolution correlation with other palaeocontinents, exceeding thattypically provided by most biozonations.

FIGURE 7 HEREABOUTS

Figure 7. The correlation of parasequences within the Much Wenlock Limestone Formation (upper Wenlock) between Wren's Nest Hill (West Midlands) and Whitman's Hill Quarry (Herefordshire). Note the geochemical correlation of a bentonite at the base of parasequence 8 (PS8). This bentonite correlation is shown in Figure 5 and the bentonite itself, as exposed at Whitman's Hill Quarry, is shown in Figure 3.

The correlation of carbon isotopic excursions (carbon isotope stratigraphy)

Variations in the stable isotopic ratio of carbon ($^{13}C/^{12}C$ values), as measured through the stratigraphic study of marine carbonate rocks (expressed as $\delta^{13}C_{carb}$) are related to global changes in the biosphere and carbon cycle, and as such can be used to date and correlate sedimentary successions (Saltzman & Thomas 2012). Within the Silurian this technique has proven particularly helpful in the correlation of marine successions that are lacking in age diagnostic fossils. There are five widely recognised and pronounced changes in the stable isotopic ratio of carbon (carbon isotopic excursions) within the Silurian and these occur in the late Aeronian, early Sheinwoodian, late Homerian, mid-Ludfordian and across the Silurian-Devonian boundary (Figure 8). A particularly notable feature of these carbon isotopic excursions is their close association with extinction events, global temperature changes and marked sea-level fluctuations (Melchin et al. 2012; Trotter et al. 2016). Such a relationship indicates that carbon isotopic excursions reflect broader global changes in environmental conditions, which may relate to cyclic episodes of glacial advance and retreat that impacted upon the southern palaeocontinent of Gondwana at this time.

FIGURE 8 HEREABOUTS

Figure 8. Series, stages and a generalised $\delta^{13}C_{carb}$ for the Silurian System identifying the most widely recognised and pronounced carbon isotope excursions, alongside prominent extinction events (Ex.), well known glaciations (Gl.) and the global (eustatic) sea-level curve of Johnson (2006) (modified from Melchin et al. 2012).

The Wenlock Series contains two pronounced carbon isotopic excursions (the early Sheinwoodian and late Homerian carbon isotopic excursions). These excursions have been identified in successions that contain age diagnostic fossils on a number of different palaeocontinents (e.g. Baltica and Laurentia) and are therefore well-calibrated to the geologic time scale. Upon the Midland Platform these carbon isotopic excursions have been used as a means of improving age calibration and correlation. In particular, the identification of carbon isotopic excursions within the Buildwas, Woolhope Limestone, Barr Limestone, Brinkmarsh Beds and Much Wenlock Limestone formations has resulted in important reevaluations of age for these successions (e.g. Marshall et al. 2012; Hughes et al. 2014; Hughes & Ray 2016; Blain et al. 2016; Fry et al. 2017), and has greatly improved upon the age assignments achieved by biostratigraphic means alone.

An example of the application of carbon isotope stratigraphy to our understanding of the Wenlock can be taken from the type succession along Wenlock Edge (Shropshire). Here the identification of the early Sheinwoodian carbon isotopic excursion (ESCIE) within the Lower Hill Farm Borehole revealed significant problems with the established graptolite biozonation (Hughes & Ray 2016). In particular, the ESCIE did not occur within expected graptolite biozones (Figure 9), thereby suggesting that these biozones were not age equivalent to the same biozones as reported elsewhere, which do contain the ESCIE. Most notably, elsewhere the *riccartonensis* Graptolite Biozone is consistently associated with the middle of the ESCIE (Melchin et al. 2012), but this biozone within the Lower Hill Farm Borehole was reported above the ESCIE and in the lowest part the Coalbrookdale Formation. An examination of the original biostratigraphic report from the borehole (Bassett 1974) revealed only a questionable identification of *Monograptus riccartonensis*, but nonetheless this biozonal age has been taken for the base of the Coalbrookdale Formation within the type-Wenlock succession and beyond (Cocks et al. 1992). Based upon the identification of the ESCIE and the correlation of this excursion to nearby successions that contain age diagnostic fossils (e.g. chitinozoans, conodonts and graptolites) (Hughes & Ray 2016), it is apparent that the stratigraphic position of the *riccartonensis* Graptolite Biozone should correspond to somewhere within the middle of the Buildwas Formation, rather than the base of the overlying Coalbrookdale Formation. Thus, the age of the contact between the Coalbrookdale and Buildwas formations is younger than previously thought (equivalent to the *rigidus* Graptolite Biozone). In addition, the identification of the ESCIE in the Woolhope Limestone Formation of Herefordshire strongly suggests age equivalence with the Buildwas Formation, a view that has been additionally confirmed by bentonite and sequence stratigraphic correlations.

FIGURE 9 HEREABOUTS

Figure 9. The stratigraphy and carbon isotopic record from the Lower Hill Farm Borehole, Shropshire (modified from Hughes & Ray 2016). Biozones are modified from Bassett (1974) and Cocks et al. (1992). The red carbon isotopic curve represents the expected position of the Early Sheinwoodian Carbon Isotope

Excursion (ESCIE) based upon the established graptolite biozones. The blue carbon isotopic curve represents the isotopic values recorded by Hughes and Ray (2016). The regionally traceable bentonite (Ray 2007) is that referred to in Figures 4 and 5. ri. = the likely position of the *riccartonensis* Graptolite Biozone based upon the position of the ESCIE and additional biostratigraphic considerations.

Conclusions

Despite being amongst the most intensively studied of Wenlock successions, the stratigraphic correlation of the Midland Platform has proven problematical. Limitations imposed by a rarity of age diagnostic fossils, such as chitinozoans, conodonts and graptolites, have resulted in age and correlation uncertainties (Cock et al. 1992). As a means of addressing these uncertainties, the pre-existing biostratigraphic frameworks have been supplemented in recent years by the application of other correlation techniques. In particular, the geochemical finger printing of volcanic ash bands, correlation of sea-level changes, and variations in carbon isotopic record have proven crucial in increasing our stratigraphic understanding of these classic Silurian successions. Furthermore, these techniques not only offer the possibility to subdivide the rock record at an increasingly fine scale, but they inform us about the world beyond the Midland Platform and tell of ancient volcanism and plate tectonics, palaeoclimate and sea-level change, and changes in Silurian life and its influence upon the carbon cycle.

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