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Lithofacies and sedimentary cycles within the Late Dinantian (late Brigantian) of Fife and East Lothian: is a sequence stratigraphical approach valid?

A. M. Kassi, J. A. Weir, J. McManus and M. A. E. Browne

ABSTRACT: The late Brigantian topmost parts of the Pathhead Formation (Aberlady Formation in East Lothian) and the succeeding Lower Limestone Formation crop out widely in Fife and East Lothian. The successions include nine deltaic, coastal floodplain and marine shelf cycles (cyclothems), of which the lowest examined terminates the Pathhead and Aberlady Formations and the remaining eight constitute the Lower Limestone Formation.

The cyclothems conform broadly to the 'Yoredale' transgressive/regressive pattern in which a transgressive marine shelf phase is succeeded by delta progradation and terminates with a fluvial delta plain phase. Cycles may combine to form compound cyclothems up to more than 50 m thick, in which a basal, typically complete initial cycle of Yoredale pattern is succeeded by up to five base-absent minor cycles. These are thinner, more variable and less laterally persistent units in which the marine phase is weakly represented or absent.

Cyclothems reflect successive marine flooding events, possibly under eustatic control, succeeded by delta progradation and, ultimately, leading to extensive palaeosol formation, including coal seams. Sedimentation and palaeosol formation were partly controlled by fault-induced differential subsidence and are likely to have been related to autocyclic processes. Local uplift and subsidence associated with vulcanicity, as at Kinghorn and Elie, have led to thickening or thinning of sediments accumulated in a given time period.

Initial cycles initiate longer-period allocycles, corresponding broadly to third-order Exxon Production & Research (EPR) Type 1 sequences having a periodicity of around 1 Ma, within the Milankovitch orbital band. Two parasequences constitute each initial cycle: a lower, initiated on a marine flooding surface, and an upper, bounded by the base of the lowest thick sandstone in the cycle; cyclothem bases and sequence bases thus alternate. Parasequences and sequences are less well defined in minor cycles due to the problem of tracing the combined disconformity and soil profile of the underclay beyond the edge of channel sandstones. Minor cycles were controlled primarily by short-period autocyclic sedimentary and, or, tectonic processes, including delta-lobe switching and differential subsidence.

Although we have attempted to interpret the deposits of Fife and the Lothians in terms of sequence stratigraphy, we are not fully convinced that the patterns of associated changes widely recognised within the framework of sequence stratigraphy can be confidently applied in succesions in which autocyclic changes feature strongly in an area undergoing active basin subsidence associated with strike-slip faulting. There is no doubt that some of the cyclicity discerned in the late Brigantian successions of eastern Scotland was related to eustatic sea level changes, which gave rise to the widespread limestone platforms or marine bands. The formation of eight cyclothems within the 2·5–3·5 Ma of late Brigantian suggests a cyclicity of about 400 ka, which corresponds to the long period eccentricity cycles of Milankovitch rather than the 0·5–5·0 Ma of third-order EPR cycles.

KEY WORDS: Carboniferous, cyclic sedimentation, Lower Limestone Formation, palaeosol, Pathhead Formation, sequence stratigraphy.

The late Brigantian Pathhead Formation of Fife correlates with the upper part of the Aberlady Formation in East Lothian (Browne *et al.* 1997). These formations and the succeeding Lower Limestone Formation (Clackmannan Group) together comprise a succession of limestones, mudstones, siltstones, sandstones, and palaeosols, which constitute a number of cyclical units initially interpreted as delta-dominated (Fielding *et al.* 1988; Francis 1991), but now recognised as representing a comprehensive array of marine shelf, coastal plain and fluvial deltaic palaeoenvironments. The Lower Limestone Formation is conformably overlain by the Limestone Coal Formation (Namurian, Pendleian; Paterson & Hall 1986; Browne *et al.* 1997). The Pathhead Formation is exposed in the coastal section between Pittenweem and Pathhead, and the broadly equivalent Aberlady Formation crops out in the Dunbar area (Davies *et al.* 1986), though precise correlation between the two areas is uncertain. The Lower Limestone Formation crops out in both areas, and elsewhere in the Midland Valley of Scotland (Read 1994) (Fig. 1a and b).

The principal aim of this paper is to test whether the concepts embodied in the Exxon Production and Research (EPR) Company's sequence-stratigraphy project (Posamentier & Vail 1988) are applicable to the topmost cycle of the Pathhhead Formation in Fife and of the Aberlady Formation

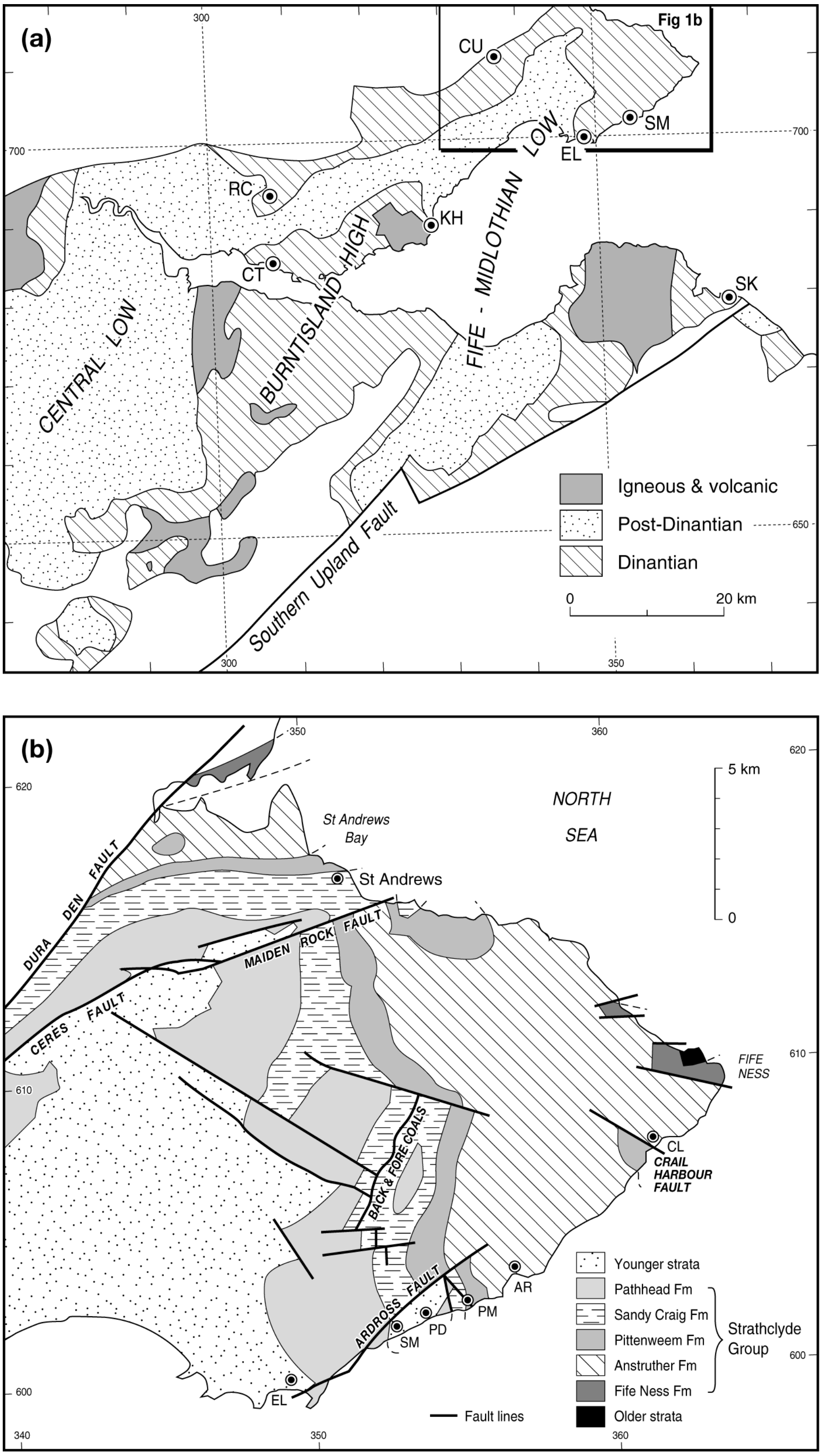

Figure 1 (a) Outline geology of eastern Midland Valley of Scotland (adapted from Francis 1991). Locality abbreviations: CT, Charlestown; CU, Cults; EL, Elie; KH, Kinghorn; RC, Roscobie; SK, Skateraw; SM, St Monans. Pre-Dinantian outcrops unornamented. Inset (top right) shows overlap of Figure 1(b) (East Fife map) on to this map. (b) Distribution of Dinantian formations in East Fife. Locality abbreviations: EL, Elie; SM, St Monans; PD, Pathhead; PM, Pittenweem; AR, Anstruther; CL, Crail.

in the Dunbar area, East Lothian, and of the Lower Limestone Formation in both areas. The cyclicities of the successions and their variations are also examined in detail.

The study has been carried out partly in the area which provided the basis for the facies analysis by Fielding *et al.* (1988) of the successions exposed in the eastern limb of the St Monans Syncline in the Pathhead–St Monans section, east Fife. The original analysis has been revised in the field, simplified and modified in detail, to serve as a basis for comparison not only with the western limb of the St Monans Syncline, but also with the coastal sections between Kinghorn and Seafield, and the Skateraw, Barns Ness and Millstone

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Neuk coastal sections near Dunbar. Outcrops of the Lower Limestone Formation around Elie and in quarries at Roscobie, Cults and Charlestown in central and west Fife were investigated in lesser detail for corroborative evidence, and recent British Geological Survey borehole records from the Cults-Glenrothes area were consulted.

1. Sedimentary cycles

The Brigantian sedimentary succession of the Midland Valley of Scotland consists of a number of repetitive transgressive-regressive cycles consisting dominantly of siliciclastic lithotypes, and subordinate, but laterally persistent bioclastic marine carbonates. The cyclicity corresponds broadly to the classic 'Yoredale' pattern (cf. Phillips 1836). Fuller accounts of the general pattern are given by diverse authors, including Belt (1975), Fielding *et al.* (1988), Johnson & Nudds (1996), Weibel (1996) and Cameron *et al.* (1998).

1.1. The sedimentary cycle defined

The concept of the sedimentary cycle was introduced by Udden (1912) under the designation of 'cycle', applicable to a rock unit bounded above and beneath by unconformities or disconformities, and in particular by the erosive bases of channel sandstones. The concept was extended to Pennsylvanian cyclical successions in Illinois by Wanless & Weller (1932), who introduced the term 'cyclothem'. The concept as defined is, however, less than satisfactory, on grounds of problems in tracing disconformities beyond the channel facies and into deltaic interdistributary successions (Weibel 1996). Such successions include palaeosol horizons representing pauses in deposition, though correlation of any palaeosol with a bounding disconformity remains a problem. By contrast, maximum flooding surfaces and zones and related marine-flooding surfaces (MFS: Van Wagoner *et al.* 1990; Weibel 1996), together with the associated sedimentary horizons (marine limestones and mudstones), may be traced with confidence over areas of many hundreds of square kilometres, as in the Carboniferous successions of the Midland Valley of Scotland.

In recent studies, Forsyth *et al.* (1996) and Cameron *et al.* (1998) have favoured starting the cyclothem at the base of the limestone. Marine mudstone and limestone are, however, commonly interbedded, as in the Hurlet (Second Abden) Limestone, raising a problem of pinpointing the transgressive climax. However, authors including Belt (1975), Johnson & Nudds (1996) and Weibel (1996) regard the Marine Flooding Surface (MFS), or the marine transgression itself, as the definitive criterion. Again this assumes that a specific bed can be identified in the succession, rather than several candidates within an exposure. We therefore propose to adopt not the Marine Flooding Surface as the cycle boundary, but the Maximum Flooding Zone, as representing the end of a significant period of emergence, erosion and pedogenesis. This surface is usually at the base of the massive bed of limestone, or a distinct marine band, and is commonly developed above a coal, Type 1 palaeosol of Fielding *et al.* (1988). We also use the long-established term 'cyclothem', rather than adopting the more cumbersome designation 'Transgressive-Regressive Unit' of Weibel (1996).

The Marine Flooding Surface may be incised as a ravinement surface, into or completely through the pedogenised and heterolithic delta plain sequence of the previous cycle, or it may take the form of unbroken deposition as the nature of the environment remains in an accretional mode. The limestone may display external and internal karstic surfaces, now firmly established as penecontemporary emergence features (Vanstone 1998). These surfaces with small scale relief and the interbedding of mudstone and limestone are related to geologically brief periods of progradation, probably of a few hundreds or thousands of years duration, suggesting the intervention of EPR 5th or higher order cyclic processes or the precessional cycles of Milankovitch, which brought about the alternations of delta or coastal advance and retreat (cf Fig. 9c).

In their interpretations of the successions in eastern Fife, Fielding *et al.* (1988) categorised the many lithofacies into three Facies Associations, A, B and C, representing sediments of coastal and inner marine shelf, prodelta and delta front, and delta plain depositional environments respectively. Limestones or marine bands, the bases of which are taken to represent the Maximum Flooding Zone, ultimately pass upwards into a largely siliciclastic coastal mud flat, pro-delta and channelised delta front succession, coarsening upwards from mudstone to fine-grained sandstone. These together constitute the progradational marine-delta facies association B of Fielding *et al.* (1988). A discontinuity initiates the fluvial–delta plain facies association, basically channelised, heterolithic deposits in the interdistributaries, and typically terminating with coals and seatrocks, and limited on top by the succeeding Marine Flooding Surface.

1.2. Cyclostratigraphy

The succession studied is tabulated in terms of cyclothems as defined above (Table 1). Apart from sequences -1 and 0, together constituting the Blackbyre (St Monans White) cyclothem, the cyclothems correspond to the sequences of Fielding *et al.* (1988).

Thick cycles (5 m upwards) may constitute complete cyclothems in their own right, or may be succeeded by one or more minor cycles to form compound cyclothems, in which the basal cycle is an initial cycle (Johnson & Nudds 1996; Fig. 2). In the present area minor cycles are mostly base-absent, lacking the marine facies association A, and in some instances also lacking lower levels of the facies association B heterolithic unit. Minor cycles may reflect switching of delta lobes or localised fluctuations in sea level, which were insufficiently high and sustained to establish brackish to marine lithotypes, and reflect a lower order of cyclicity (sub-Milankovitch) superimposed on the initial cycles. Table 1 summarises the cyclostratigraphy and Figure 3 correlates it with a suggested sequence stratigraphy. Cyclothems are given Arabic numerals, minor cycles are also numbered. Cycles, both initial and minor, are commonly bounded beneath by palaeosols.

The Blackbyre (St Monans White) cyclothem (1) and the Hurlet (St Monans Brecciated) cyclothem (1) are solitary cycles terminating with coals, which, together form a condensed succession. The Blackhall (Charlestown Main) cyclothem (2) is mudstone-dominated and includes a facies B3 sharply-based sandstone 6 m thick. The Milngavie (Mill Hill) Marine Band (3) is a coal-cyclic compound cyclothem 14 m thick. The initial cycle includes 7 m of sharply-based facies B3 sandstone, and a single minor cycle is 4·2 m thick. The Main Hosie (Seafield) cyclothem (4) displays 12 m of mudstone in a total thickness of 16 m. The Mid Hosie (Lower Kinniny) cyclothem (5) is compound and coal-cyclic throughout. The initial cycle commences with an upward-coarsening interval 5 m thick. This is channelised and bears 3 m of erosive sandstone. The next 17·4 m of strata form five minor base-absent cycles. Minor cycles ll and lV include erosive or sharply-based sandstones. The Second Hosie (Mid Kinniny) cyclothem (6) is dominated by facies association A mudstones, which reach a thickness of 8·6 m. The Top Hosie Limestone is

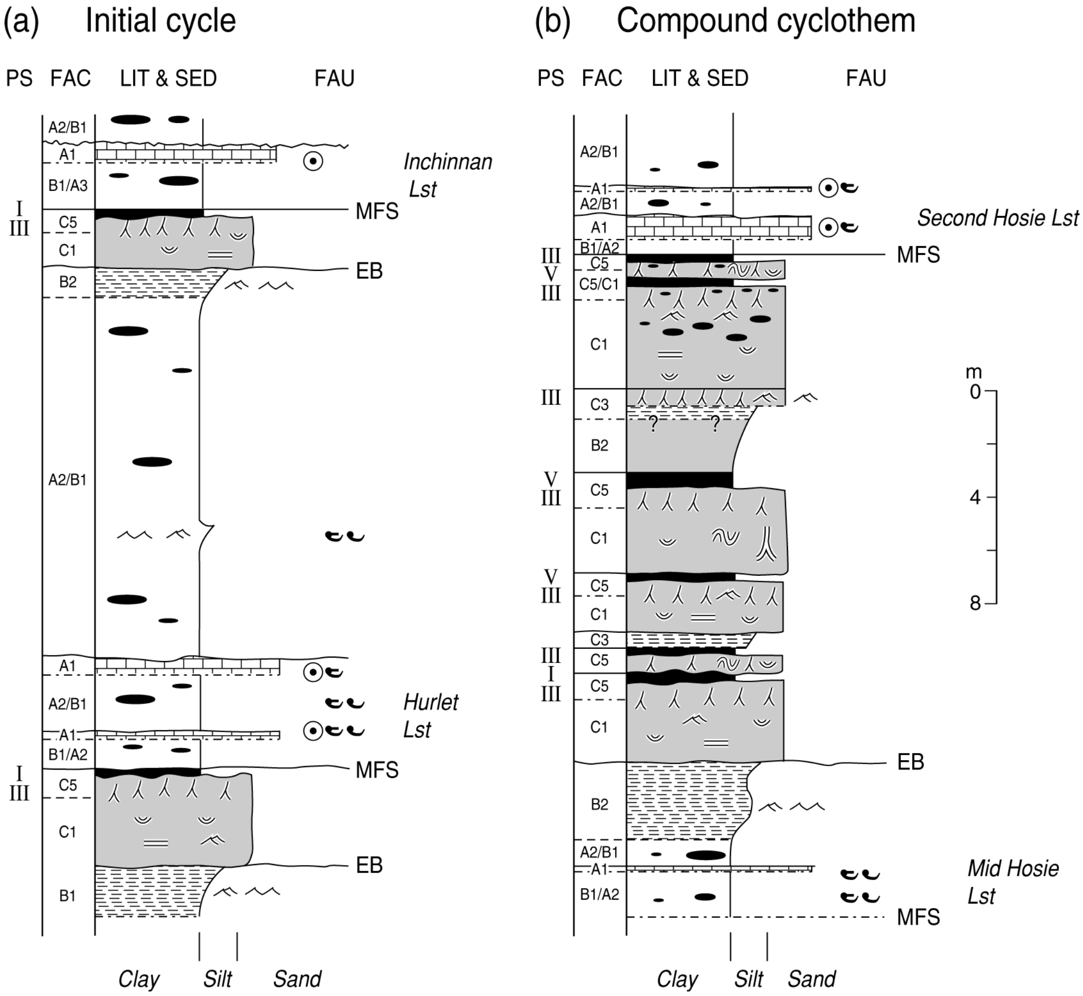

Figure 2 (a) Diagram of initial cycle between Hurlet (Brecciated) and Inchinnan (Charlestown Green) Limestones in St Monans Harbour section, [NO 523 014]; lithotypes and contacts interpreted in terms of sequence stratigraphy. (b) Diagram of Mid Hosie (Lower Kinniny) compound cyclothem, Pathhead–St Monans section, Figure 4 [NO 533 017]. MFS=initial marine flooding surface; EB=erosional base; SB=sequence boundary. Key as in Figure 5.

laterally impersistent. At St Monans it is either merged with the Second Hosie (Mid Kinniny Limestone), or is represented by a centimetres-thick limestone bed 1·2 m above the Second Hosie Limestone (Kassi *et al.* 1996, 1998). In East Lothian the Second and Top Hosie limestones are not preserved (Browne *et al.* 1997).

There is a progressive upward increase in siliciclastic input at least to the level of the Second Hosie cyclothem, and the Blackhall (Charlestown Main) cyclothem ushers in a climax of carbonate deposition. In the Kinghorn section, minor cycles are restricted to cyclothems including the Hurlet (Second Abden) Limestone and the Milngavie (Mill Hill) Marine Band. Likewise, only two minor cycles were observed in the Skateraw Harbour section, above the Blackhall (Middle Skateraw) and Main Hosie (Chapel Point) Limestones (Figs 4–8). This reduction in siliciclastic input may reflect a reduction in sediment supply or deposition in more distal positions on the marine shelf.

Thicknesses of individual cycles and proportions of lithotypes were observed to vary from locality to locality and also within individual cyclothems, even within a distance of less than 1 km, e.g. the Blackhall (Charlestown Main) cyclothem between the eastern and western limbs of the St Monans Syncline (Fig. 4). Channelised sandstones are commonly involved as they are strongly constrained laterally, and outcrops wedge out, e.g. that underlying the Milngavie (Mill Hill) Marine Band; this body, which is included in the log Figure 4, accounts for much of the discrepancy between the present interpretation and that of Fielding *et al.* (1988, fig. 2).

An isolated initial cycle in one section may expand laterally into a compound cycle. Conversely, cycles and cyclothems may merge. This may take place within cycles, e.g. in the Blackhall (Charlestown Main) cyclothem east of Kinghorn [NT 279 885], in which siltstone and sandstone horizons (denoting minor cycles) are lacking (Fig. 7), being replaced by marine mudstones alternating with thin lenticular limestone interbeds. Coal seams also tend to split, and several separate seams may occur within one cyclothem. This duplication is considered to reflect medium-term EPR fourth-order, autocyclic processes, shorter in duration than the 3rd-order allocyclic process generating the initial cycles and compound cyclothems, and longer than the fifth-order autocyclic processes which produce the limestone-shale alternations and the internal karstic surfaces in limestones (cf. Fig. 9c). Merging of entire cyclothems may also take place, for example in the Dunbar area, where the Milngavie (Mill Hill), Main Hosie (Chapel Point) and Mid Hosie (Lower Kinniny) cyclothems are believed to combine into a single mudstone-dominated unit between the Blackhall (Charlestown Main) and Second Hosie (Mid Kinniny) Limestones.

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Table 1 Cyclostratigraphy and correlation of cyclothems in the St Monans-Pathhead and Dunbar areas with the standard Midland Valley of Scotland (Glasgow) succession. East Fife names are quoted first in brackets, Dunbar names second. Based on Fielding *et al*. (1988) and Browne *et al*. (1997). St Monans syncline eastern limb [NO528 016]

Lower Limestone Formation	
Cyclothem 8	Top Hosie (Upper Kinniny, Barns Ness) Limestone Cyclothem (doubtfully present at St Monans; may be represented by a thin crinoidal limestone rib 1·2 m above the Second Hosie Limestone)
Cyclothem 7	Second Hosie (Mid Kinniny) Limestone Cyclothem (absent at Dunbar)
Cyclothem 6	Mid Hosie (Lower Kinniny Marine Band, Chapel Point) Limestone Cyclothem
Cyclothem 5	Main Hosie (Seafield Marine Band, Upper Skateraw) Limestone Cyclothem
Cyclothem 4	Milngavie (Mill Hill) Marine Band (Limestone absent at Dunbar)
Cyclothem 3	Blackhall (Charlestown Main, Middle Skateraw) Limestone Cyclothem
Cyclothem 2	Inchinnan (St Monans Little, Lower Skateraw) Limestone Cyclothem
Cyclothem 1	Hurlet (St Monans Brecciated, Upper Longcraig) Limestone Cyclothem
Pathhead Formation	
Cyclothem -1	Blackbyre (St Monans White, Middle Longcraig) Limestone Cyclothem (includes Fielding *et al.* (1988) sequence 0)

Cyclothem numbers given are based on the sequences of Fielding *et al*. (1988). However, their sequence 0 equates with the Alum Shale and Hurlet Coal interval of the Glasgow area, and completes our Cyclothem -1.

2. Facies, facies associations and palaeosols

As indicated above, the three Facies Associations, A, B and C, of Fielding *et al*. (1988) represent sediments of coastal and inner marine shelf, prodelta and delta front, and delta plain depositional environments respectively. The lithofacies comprising each association were numbered from 1 upwards in approximate ascending order of occurrence. Their work provides a framework for the present account, but extension of the study area beyond St Monans entails modifications to their table 2 and sedimentary log (Fig. 4), a revised field interpretation being presented herein as Figure 5.

2.1. Sedimentary lithofacies

Two facies constitute ***Facies Association A***. Facies A1 comprises sheet-like, mainly bioclastic limestone, representing fully marine sediments commonly deposited in clear, warm water. The presence of karstic surfaces within the normally thin limestones underlines the fact that the marine waters were shallow, permitting exposure of the sea floor for not inconsiderable periods. Facies A2 consists of sheet-like bodies of thinly laminated claystone, representing starved marine shelf and prodelta deposits.

Facies Association B includes three lithofacies. Facies B1 consists of upward-coarsening claystone to fine-grained sandstone successions. These are distal delta front sediments displaying wave and current ripples (many starved), load casts and flute markings, ironstone nodule trails and lenses and occasional thin dolostone beds. Trace fossils are abundant and varied, and dominantly of marine provenance (cf. Belt 1975). Body fossils are scarce and are dominated by species of *Naiadites*. Facies B2 embraces upward-coarsening sandstones representing medial and lateral delta front deposits. These show wave and current cross-lamination and uneven lamination. Facies B3 is a complex channelised delta plain assemblage embracing two contrasting subfacies: laterally extensive sandstones and siltstones up to 0·7 m thick, representing interdistributary deposits, and erosively-based sandstone up to 8 m thick, having channel-fill or sheet-like morphology, internal erosion surfaces, cross-lamination and occasional basal intraclast conglomerates. A varied ichnofossil assemblage includes both marine and nonmarine components. The facies may represent a distributary mouth bar deposit on the proximal delta front.

Facies Association C completes the cyclothem and contains five lithofacies. Facies C1 is an upward continuation of Facies B3 on to the prograding delta plain, and is an erosively-based, nonmarine sandstone up to 3 m thick closely similar to a Facies B3 sandstone, incised into the underlying cyclothem. Facies C2 consists of thinly interbedded fine sandstones and claystones interpreted as levée deposits. Facies C3 is a heterolithic succession representing both marine and nonmarine, crevasse-derived interdistributary sediments deposited on lobes. Facies C4 constitutes upward-coarsening successions up to 3 m thick, representing minor interdistributary mouth bar sediments. Coal and coaly claystone form the final Facies, C5. This also constitutes a Type I palaeosol, and is commonly interbedded with Facies C3.

2.2. Palaeosols

The succession includes numerous palaeosol horizons (Figs 4–8), classified into four types, two being derived from hydromorphic (waterlogged) and two from freely-drained soils (Fielding *et al*. 1988). Hydromorphic derivatives include impure 'duff' coals (Type I), and largely inorganic gleys (Type II), comprising successions of fine-grained, grey siliciclastic sediments containing roots, rootlet casts and ironstone concretions. Freely-drained types include sandstone-derived ganister (Type III) and derivatives of heterolithic successions with pronounced horizonation and colour differentiation (Type IV). Palaeosols typically occur as compound profiles, wherein freely-drained types pass upwards into gleys, and these in turn into coals as hydromorphic stigmarian vegetation became established. Palaeosols are preferentially developed on delta plain interdistributary areas, and reflect relatively lengthy periods of stability for pedogenesis.

3. Correlation of cyclicity and sequence stratigraphy

As with the upper part of the Limestone Coal Formation (Read 1995) and the Pennsylvanian of Illinois (Weibel 1996), our attempt to apply to the succession the EPR concepts of sequence stratigraphy (Posamentier *et al*. 1988, 1992; Posamentier & Vail 1988; Van Wagoner *et al*. 1988, 1990) was not a straightforward process, and the end-product is deemed not entirely convincing. The principal criteria for establishing a sequence in EPR terms are firstly, the presence of a discernible unconformity, and secondly, the recognition elsewhere of the conformable interval with which the hiatus correlates (Van Wagoner *et al*. 1990). Options for locating cyclothem and parasequence boundaries are discussed in detail by Weibel (1996, Fig. 1).

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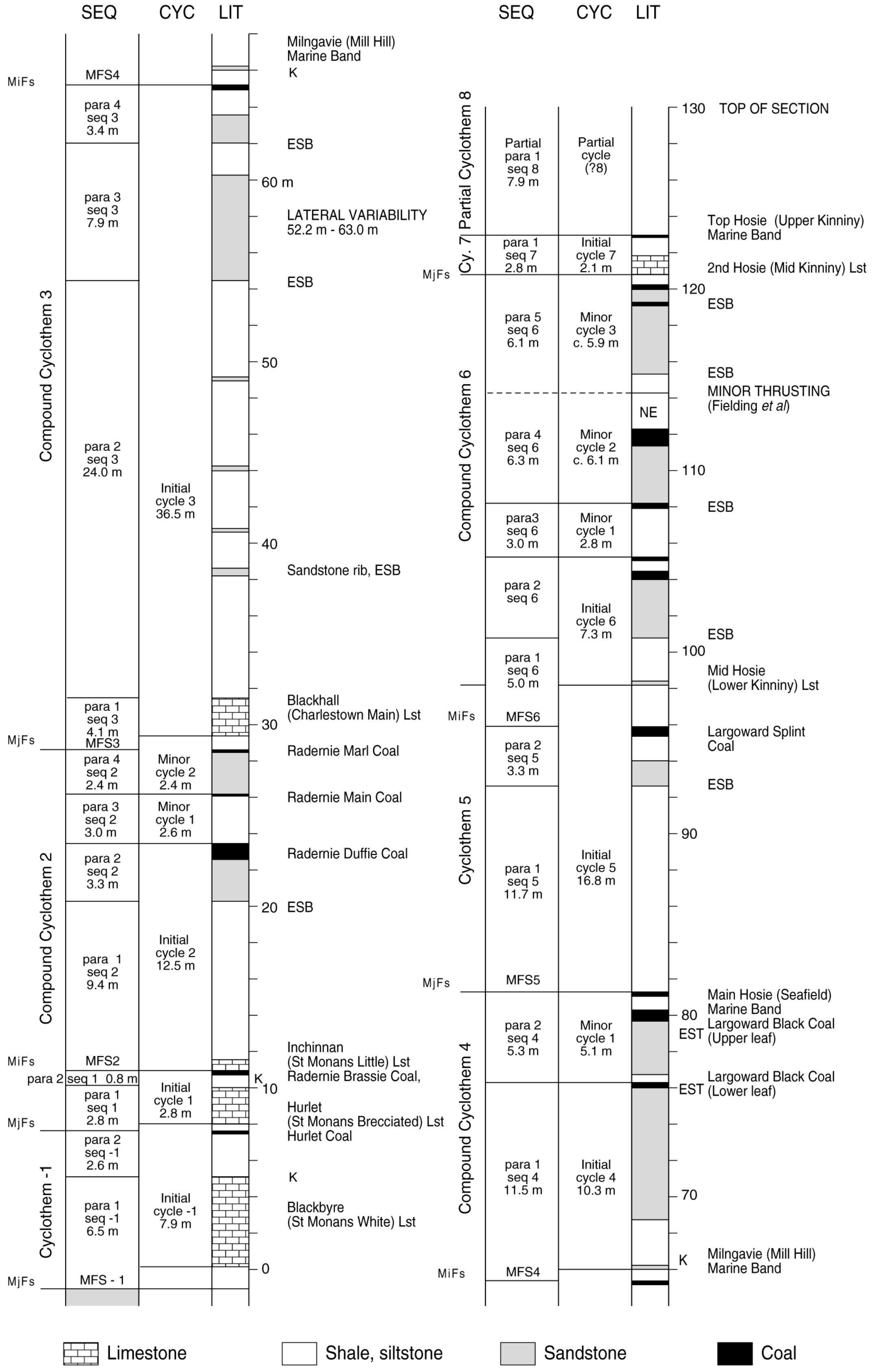

Figure 3 Cyclothems and sequence stratigraphy of the Pathhead–St Monans section. Abbreviations: seq, sequence; para, parasequence; SB, sequence boundary; MFS, marine flooding surface. K, karstic limestone top; ESB, erosive sandstone base; EST, erosive top. NE, no exposure. Uncertain contact, dashed line. Symbol '#' in SEQ columns connects with symbol '#' in KEY BEDS column, locating details of thin sequences and parasequences.

3.1. Sequence and parasequence boundaries

Whilst the marine intervals in the study area represent significant marine flooding episodes, there are no significant unconformities bounding the cycles, and no deeply incised valley fills are known. The thin, initial Blackbyre (St Monans White) and Hurlet (St Monans Brecciated) cyclothems lack channelised

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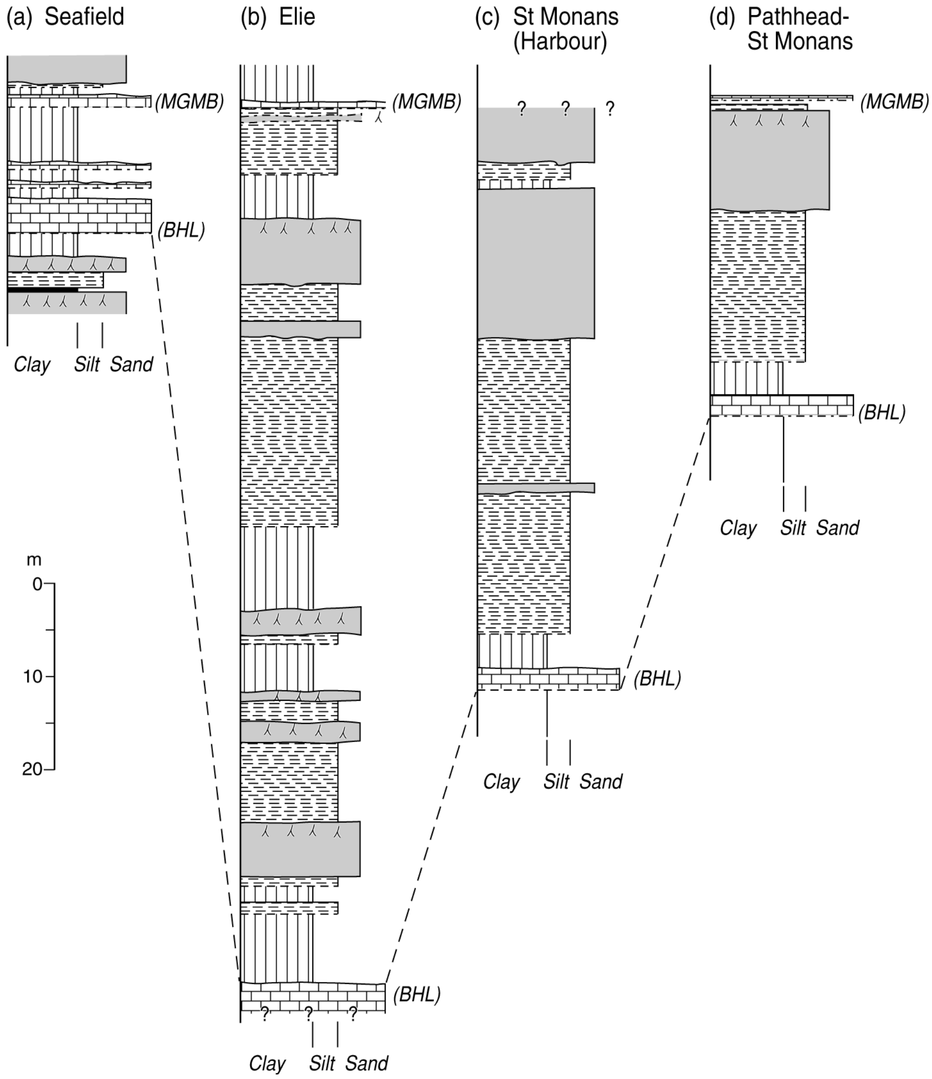

Figure 4 Sedimentary logs of Blackhall cycle, to illustrate variability in thickness and character: MGMB = Milngavie (Mill Hill) Marine Band, BHL = Blackhall (Charlestown Main) Limestone. Key as in Figure 5.

sandstones. In these instances, karstic limestone tops, signifying at least phases of emergence and erosion, initiate the sequences. Otherwise sequence boundaries must lie at erosive bases of sandstones of Facies B3 or C1. Such sequence limits do not correspond to the 'sequences' of Fielding *et al.* (1988, fig. 4), which start at major marine flooding surfaces.

Erosively-based sandstones are considered to have been deposited during falling stages of lowstand shorelines (Hampson *et al.* 1995), and as such to be attributable to lowstand systems tracts (Fig. 9). Moreover, it is arguable that not all instances of sea-level fall are accompanied by fluvial rejuvenation and valley incision, and, conversely, not all instances of fluvial rejuvenation and valley incision are associated with sea-level fall (Posamentier & James 1993; Posamentier & Vail 1988). Accepting erosive sandstone bases as sequence boundaries, transgressive, highstand and lowstand systems tracts may be recognised (Fig. 9b).

3.2. The transgressive phase

In some cyclothems, palaeosols have developed in the uppermost levels of Facies B3 and C1 sandstones, otherwise these pass upwards into upward-fining levée and overbank intervals of Facies C2 and C3, reflecting channel abandonment. These intervals relate to preliminary stages of transgression, indicating rising base levels, when rivers were ponded back and clastic input was much reduced (Fielding *et al.* 1988; Aitken 1994). Peats developed on the pedogenised interdistributaries and were ultimately overwhelmed by rising sea level, introducing brackish to marine claystones of Facies A2 and initiating the transgressive systems tract. The sharp contact reflects the first significant marine flooding surface within the sequence.

Facies Association A represents deposition during periods of high sea level. Although Read & Forsyth (1989, 1991) believed that karstic surfaces terminating several limestones were related to submarine wave erosion, defining minor flooding (ravinement) surfaces, Vanstone (1998) has subsequently demonstrated that karstification is solely a freshwater or rainfall-induced phenomenon. Some limestones of Facies A1, for instance the Hurlet (Second Abden), are interbedded with thin marine claystones of Facies A2, expressing short-term fluctuations of depositional conditions. These geologically rapid successions of minor flooding and emergence events are reflected in multiple karstic surfaces within the limestones. These imply a depositional surface held at or near sea level for a protracted period. Both the karstic features and the limestone alternations may reflect superimposition of EPR 5th- and 6th-order autocyclic processes or, alternatively, superposition of the Milankovitch cycles (Fig. 9c). However, the numbers and the degrees of solution represented by the karstic surfaces vary along individual limestone horizons, so that an

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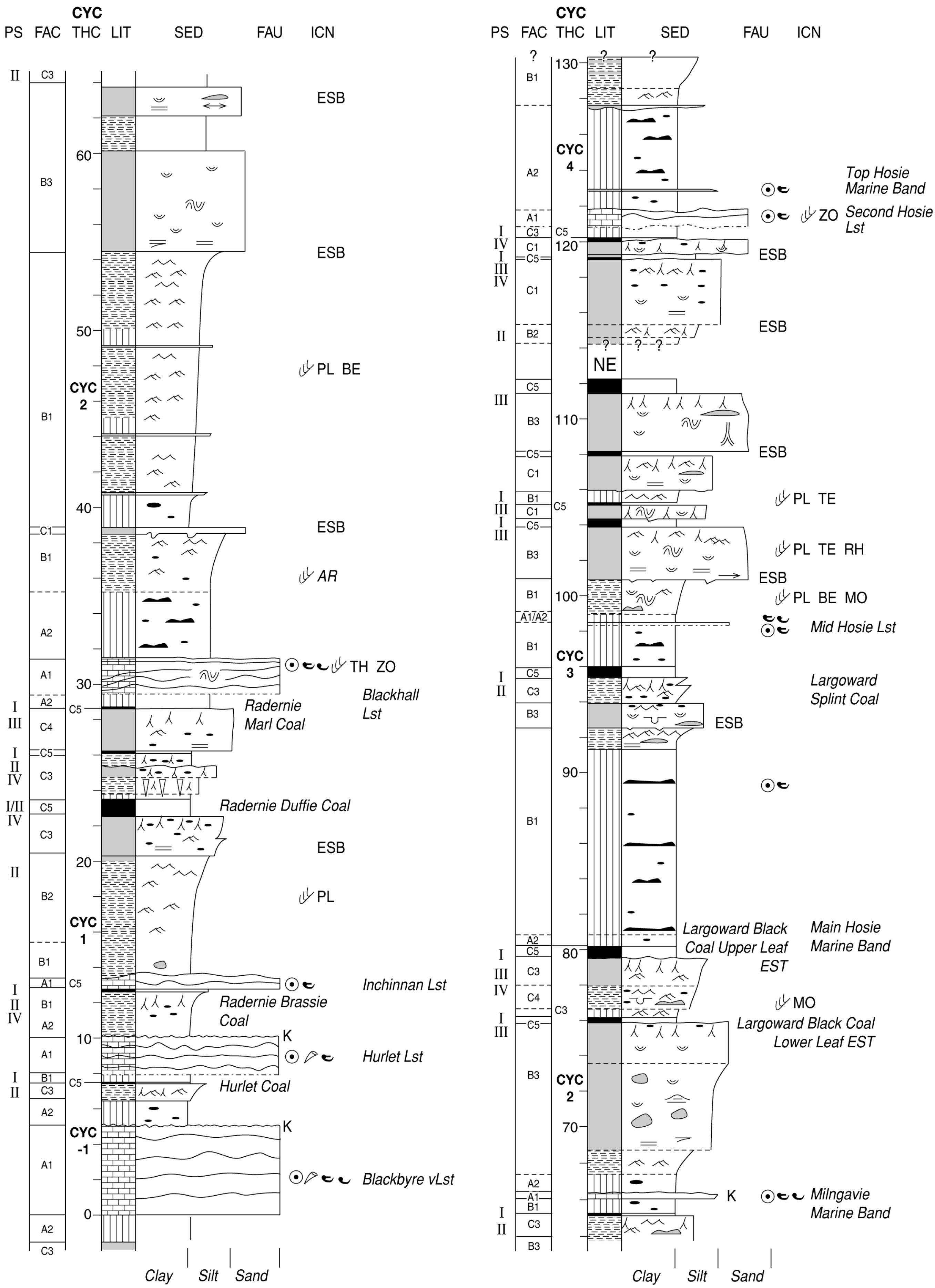
PS FAC CYC THC LIT SED FAU ICN
ESB
PL BE
AR
TH ZO
Blackhall Lst
Radernie Marl Coal
Radernie Duffie Coal
PL
Inchinnan Lst
Radernie Brassie Coal
Hurlet Lst
Hurlet Coal
Blackbyre vLst
Clay Silt Sand
Top Hosie Marine Band
ZO Second Hosie Lst
NE
PL TE
PL TE RH
PL BE MO
Mid Hosie Lst
Largoward Splint Coal
Largoward Black Coal Upper Leaf EST
Main Hosie Marine Band
MO
Largoward Black Coal Lower Leaf EST
Milngavie Marine Band

Figure 5

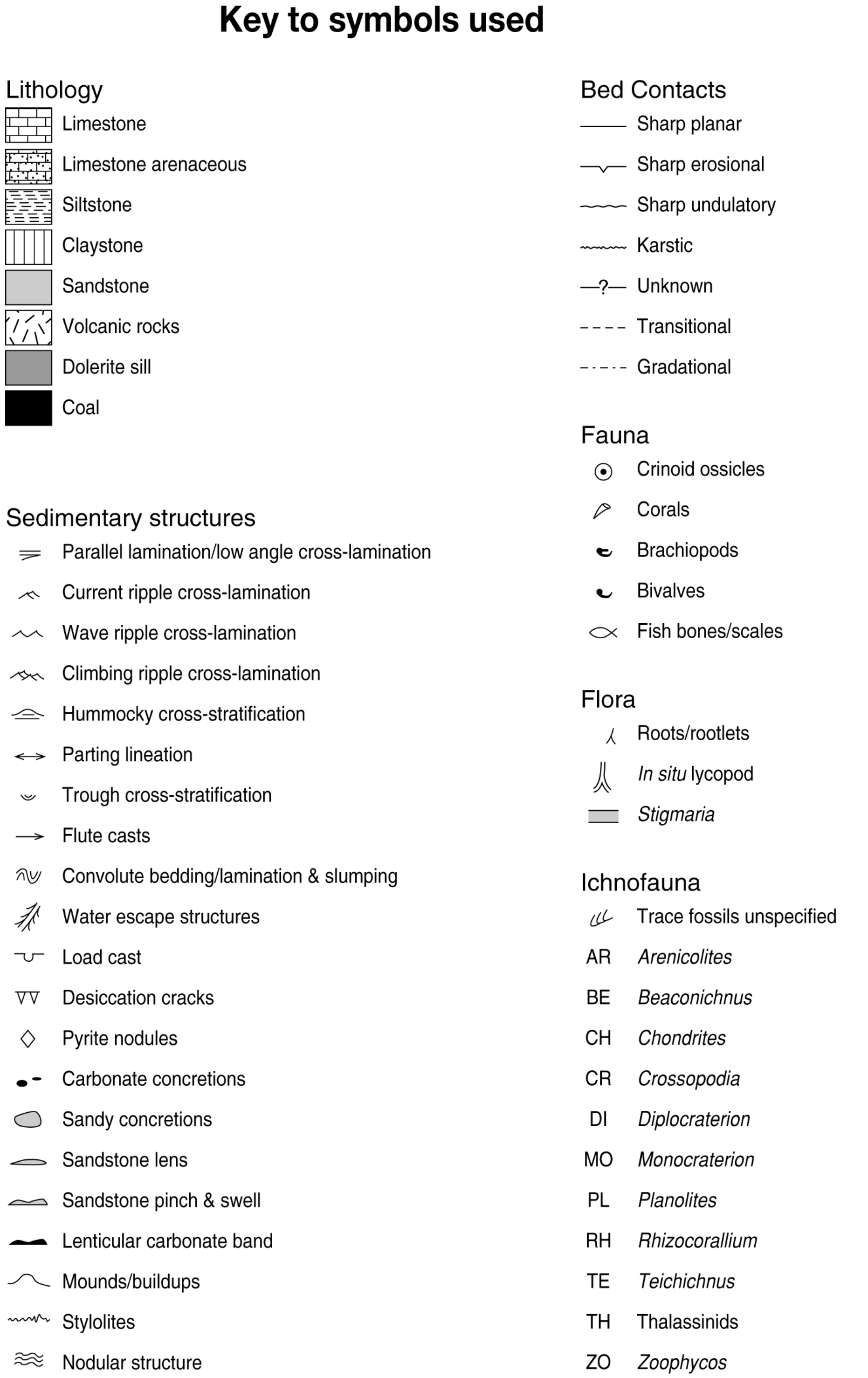

Figure 5 Revised and simplified sedimentary log of St Monans shore section on the east limb of the St Monans Syncline. Abbreviations: PS, palaeosol types; FAC, facies types; THC, thickness; LIT, lithology; SED, sedimentary structures; FAU, faunas; ICN, ichnofossils; ESB, erosional sandstone base; EST, erosive top; K, karstic limestone top. For details of lithofacies see Fielding *et al.* (1988), fig. 4 and table 2.

additional mechanism allowing for differential uplift and subsidence is needed. Mudstones exemplify condensed intervals, and the limestones are believed to correspond to maximum flooding periods (Posamentier *et al.* 1988; Loutit *et al.* 1988).

Parasequences are not clearly recognisable within transgressive systems tracts; minor cycles are restricted to only certain cyclothems and are not laterally persistent. Likewise, in that the numbers and degrees of erosion represented by the karstic surfaces vary along individual limestone horizons, an additional mechanism for uplift and subsidence on a local scale is needed. The features are considered not to have been formed exclusively as a result of flooding events, but to have been controlled at least partially by tectonic subsidence in growth synclines associated with dextral strike slip or oblique slip controls in addition to autocyclic events (Hooper *et al.* 2002; Underhill *et al.* 2002).

3.3. Highstand and lowstand phases

Heterolithic Facies B1 successions mark the initiation of delta prograding, and represent highstand stages ranging from just after the 'R' (rising) inflection point to a period before the 'F' (falling) inflection point (Fig. 9). Lower contacts of heterolithic

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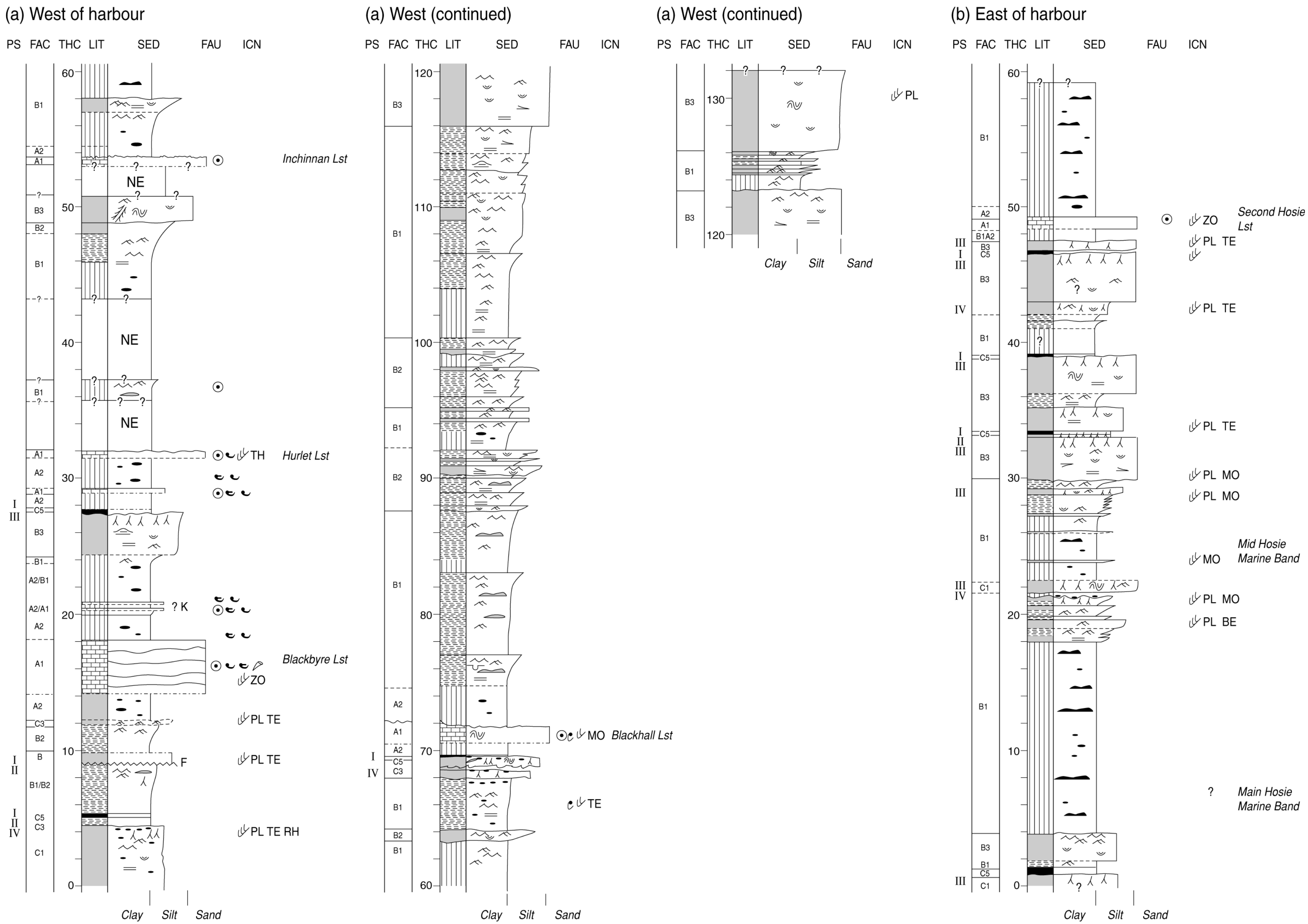

Figure 6 Sedimentary log of St Monans shore section on W limb of St Monans Syncline. Key and abbreviations as in Figure 5, *plus*: F, fault; K, karstic surface. ('N E' intervals to scale).

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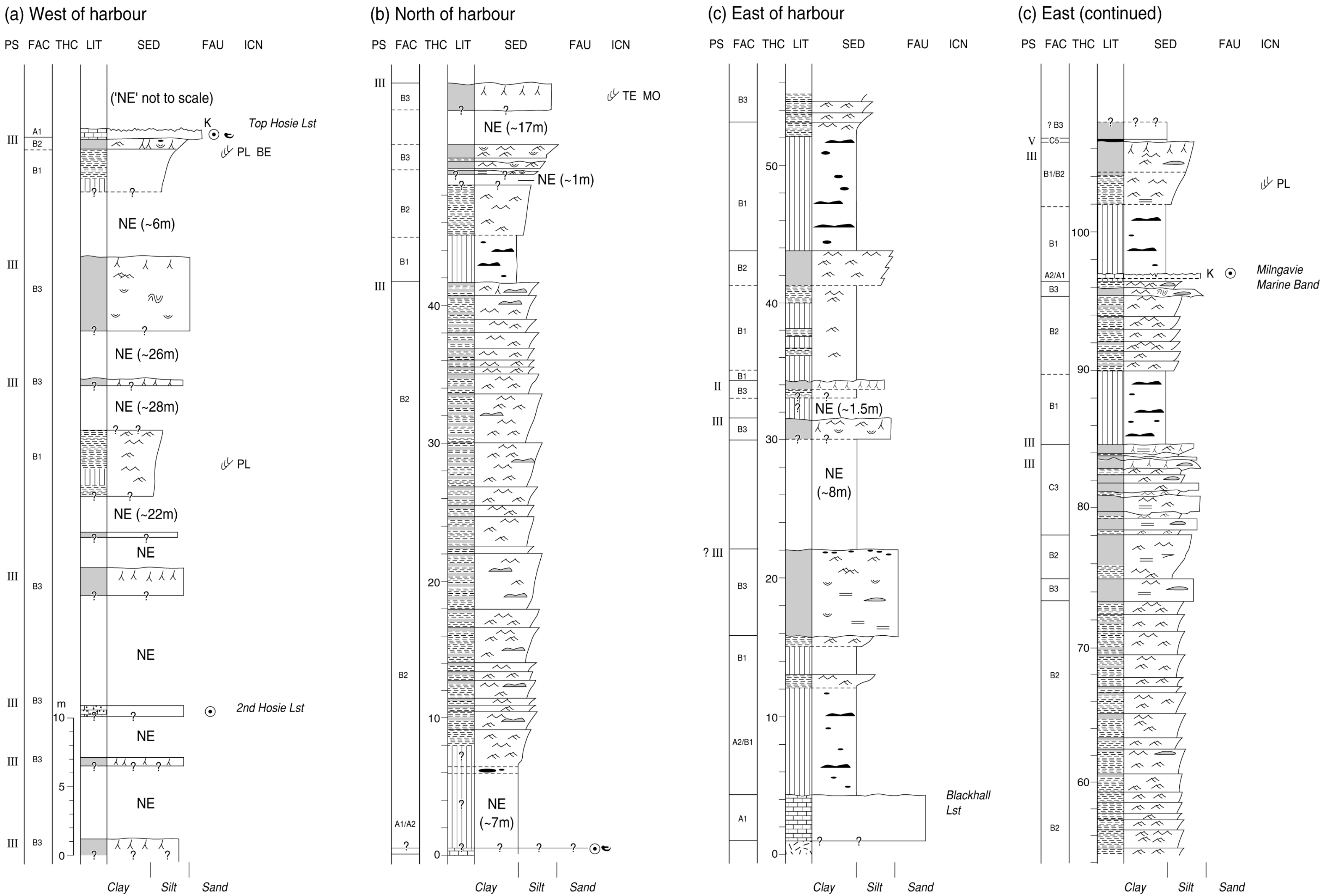

Figure 7 Sedimentary log of Elie shore section ('N E' intervals in columns (a) and (b), indicating no exposure, are not to scale, some represented thicknesses estimated). Key and abbreviations as in Figure 5.

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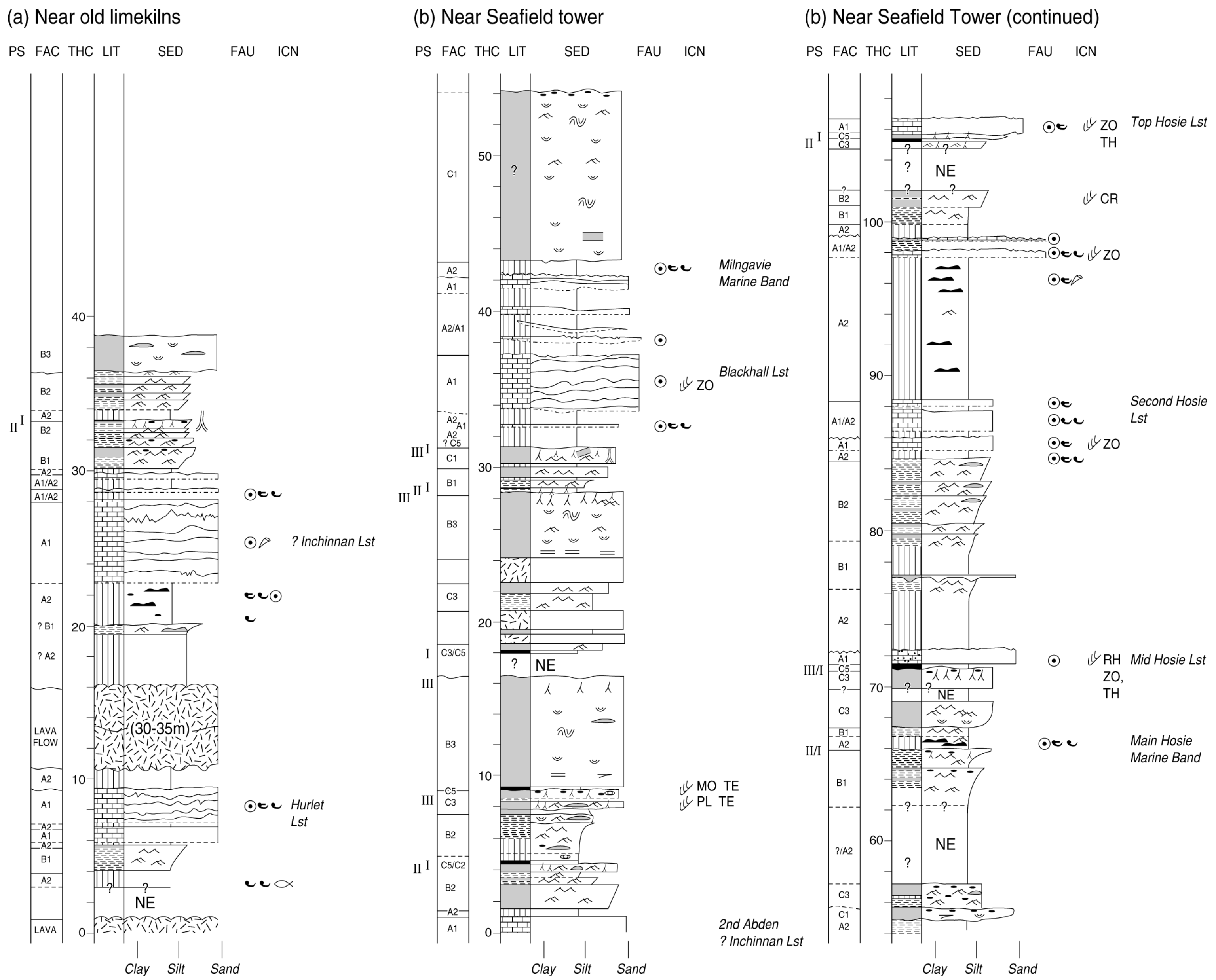

Figure 8 Sedimentary log of shore section E of Kinghorn ('N E' intervals in columns (a) and (c) are to scale). Key and abbreviations as in Figure 5.

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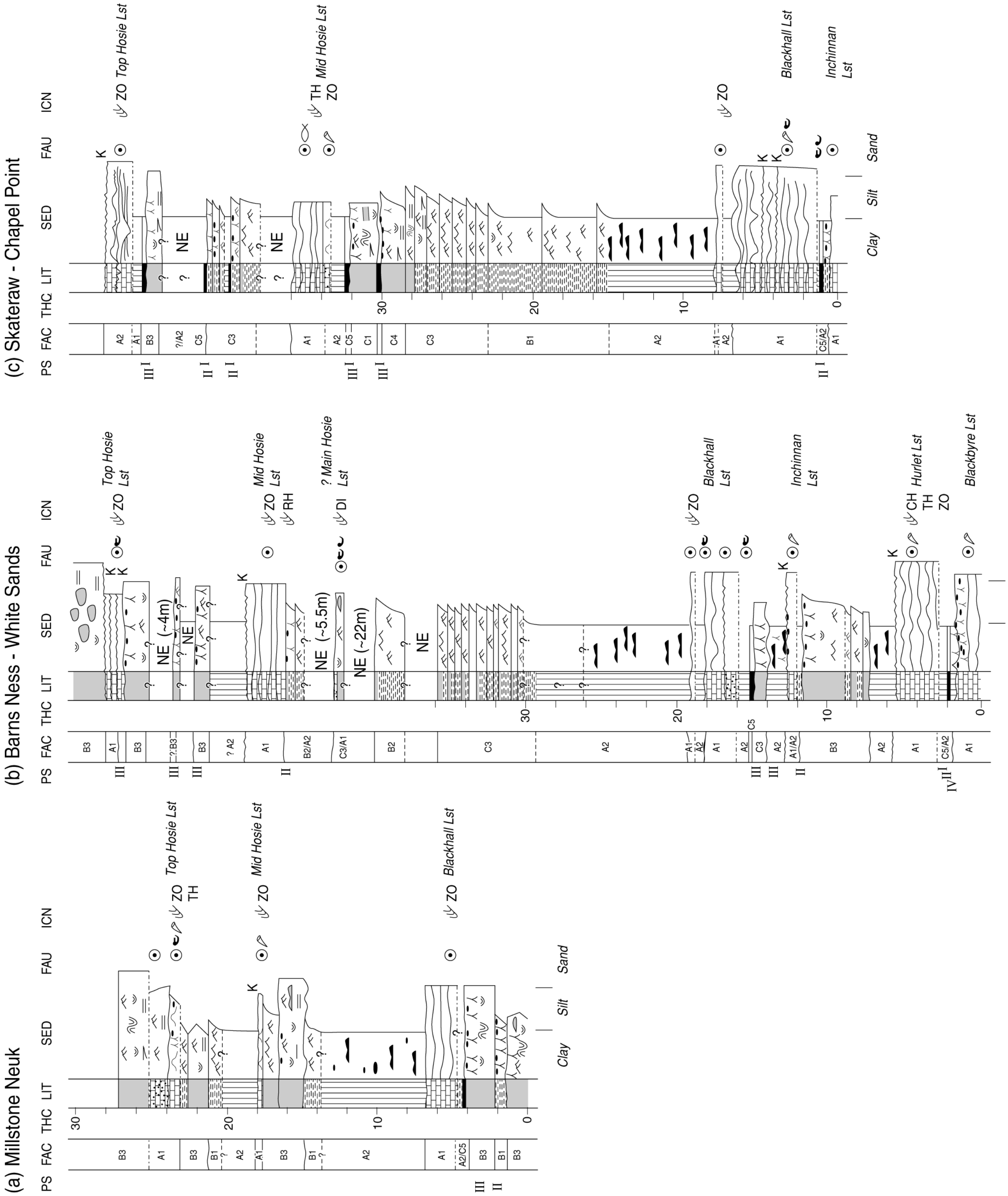

Figure 9 Sedimentary log of shore sections near Dunbar ('N E' intervals are not to scale, but the represented thicknesses are estimated). Key and abbreviations as in Figure 5.

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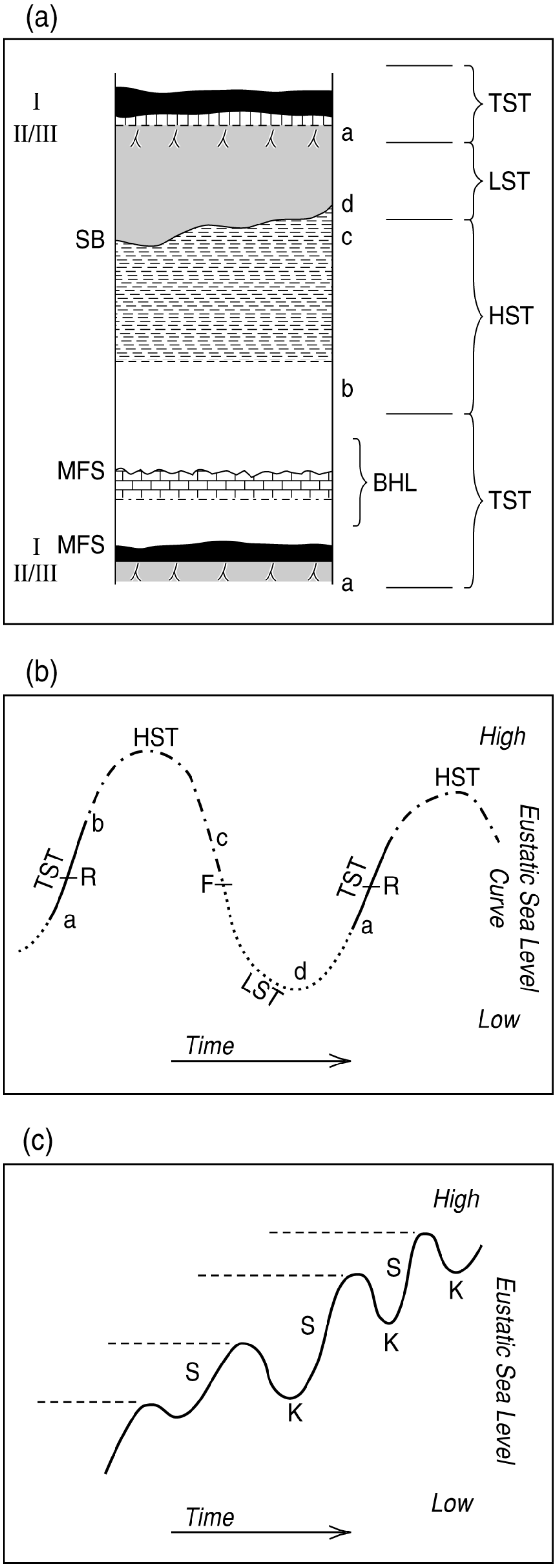

Figure 10 (a) Schematic lithological succession within cycle, illustrating positions of key surfaces and systems tracts. (b) Hypothetical eustatic curve showing positions of inflexion points and systems tracts for sequences. Lower case letters 'a'–'d' = points on postulated eustatic curve and corresponding positions in lithological succession. 'R' and 'F' = inflexion points in eustatic curve marking maximum rate of eustatic rise and eustatic fall respectively. Other abbreviations: HST, highstand systems tract; LST, lowstand systems tract; TST, transgressive systems tract. Key as in Figure 4; I/II/III, palaeosol types. (c) Relationship of internal karstic surfaces and tops to pauses in long-term marine flooding, related to short-period (EPR 5th order) autocycles. K, karstic surface; S, shale in order of deposition or formation.

intervals are typically transitional; only one, that above the Hurlet (Second Abden) Limestone, was observed to truncate both the Facies A1 and (upper) A2 intervals. Bases of heterolithic successions mark the positions of maximum flooding (downlap) surfaces on to which overlying highstand systems tracts downlap.

In addition to summarising the cyclostratigraphy, Figure 3 offers a sequence-stratigraphical interpretation of the Pathhead–St Monans section. Despite the small scale of the Midland Valley of Scotland as compared with, for instance, the area of continuity encompassed by the Westphalian marine bands between Britain and the Donetz Basin, the degree of lateral continuity throughout the Midland Valley of Scotland of the main limestones is considered by the authors to justify at least this attempt to test the concept.

3.4. Duration of cycles

Initial cycles within the Lower Limestone Formation are interpreted as long-period allocycles *sensu* Read & Forsyth (1991). According to Gradstein & Ogg (1996) the duration of the Brigantian and Asbian was 15 Ma, during only part of which the succession under discussion accumulated. The duration of the entire Brigantian has been estimated as between 4·5 and 6 Ma (Menning *et al.* 2001), so that each of the eight cycles in the late Brigantian would have averaged 350–400 ka. Such cycles are shorter than the minimal estimate (0·5 Ma) given for third-order EPR cyclicity (Payton 1977; Posamentier & Weimer 1993). However, they do approximate to the longest (410 ka) solar cycles of Milankovitch. The 90 ka difference between the two forms of cycle is relatively small, but is, as yet, unreconciled. Comparable cycles in the Limestone Coal Formation of the area embracing Glasgow and Stirling have been interpreted as sequences rather than parasequences (Read & Forsyth 1989 1991); marine flooding surfaces are, however, scarce in this formation, marine bands being represented by only two persistent horizons. Here there are several less persistent *Lingula* bands (Cameron *et al.* 1998).

4. Depositional controls

Controls on cyclic sedimentation within the upper part of the Limestone Coal Formation have been comprehensively discussed by Read (1994, 1995). Controlling factors were considered to have been eustatic changes in sea level, subsidence related to contemporary rifting, and tectonic uplift of the northeastern source areas, coupled with autocyclic sedimentary processes. Dewey & Strachan (2003) demonstrated that during the late Caledonian, at least until the Famennian unconformity at about 370 Ma, orogenic activity in the Midland Valley area was dominated by transtensional motion between sinistral strike-slip faults parallel to the Highland Boundary and Southern Upland faults. As Variscan tectonic activity increased into the Carboniferous, the area became increasingly dominated by dextral strike-slip motion reactivating the faults and creating sedimentary basins separated by upwarped areas (Hooper *et al,* 2002; Underhill *et al.* 2002).

4.1. The case for eustatic sea level changes

The primary control over depositional cyclicity, whether attributed to the low-frequency (third-order EPR) allocyclicity or the long-period eccentricity cycles of Milankovitch, is considered to be eustatic rise in sea level (Read 1994, 1995; Pickard 1994), as marine transgressions may be traced throughout the Midland Valley, and farther afield (Read 1994). The transgressions mark widespread flooding episodes comparable in proven local extent to those represented by the

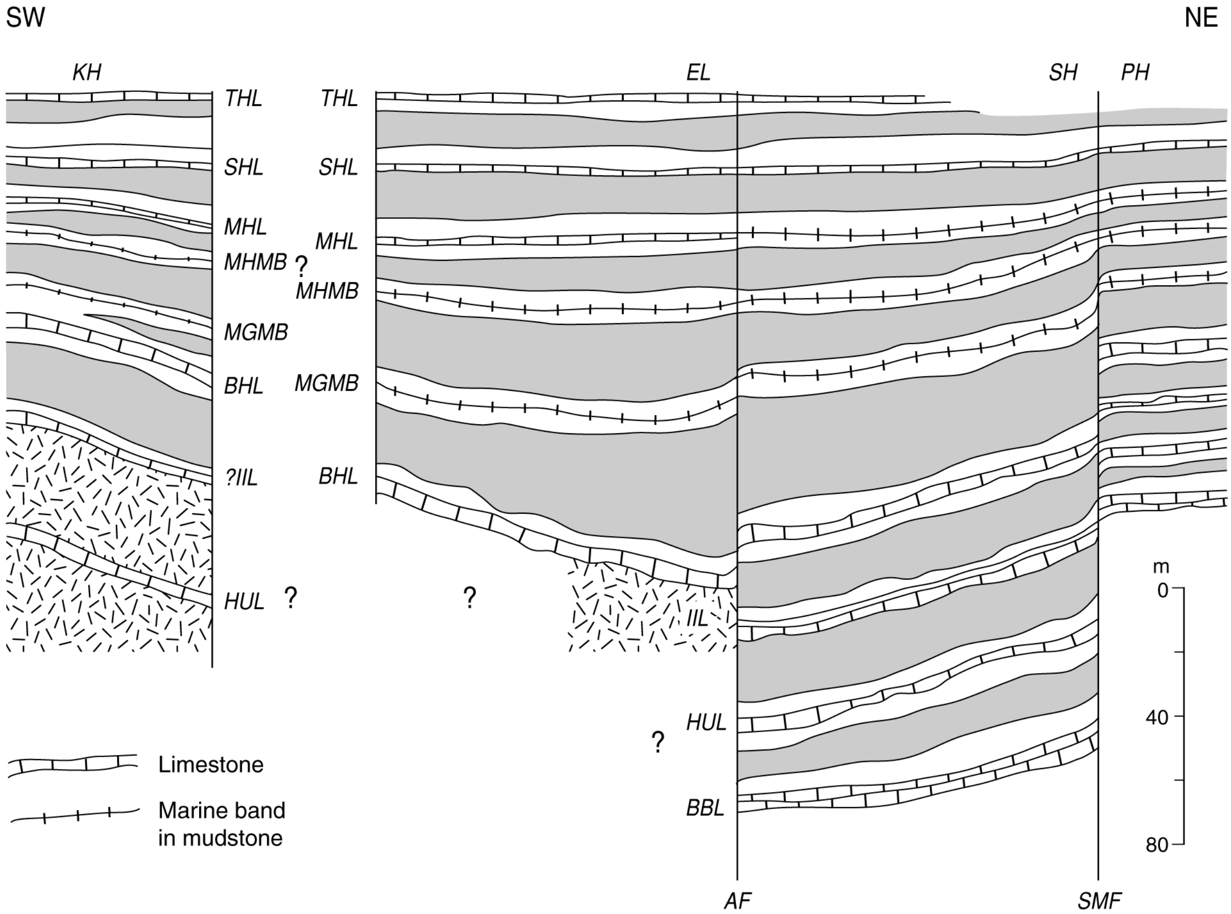

Figure 11 Schematic horizontal section through St Monans White cyclothem and Lower Limestone Formation to illustrate thickness variability, based on thicknesses measured along approximate NE–SW line. Sandstone-dominated successions stippled. Letters KH, EL, SH and PH=approximate positions of Kinghorn, Elie, St Monans Harbour and Pathhead sections respectively. AF and SMF=Ardross and St Monans Harbour faults. Aerial distance between KH and PH approximately 25 km. BBL, HUL, IIL, BHL, MHL, SHL, THL are the Blackbyre, Hurlet, Inchinnan, Blackhall, Mid Hosie, Second Hosie and Top Hosie Limestones respectively. MGMB and MHMB are the Milngavie and Main Hosie Marine Bands.

most persistent Westphalian marine bands, customarily regarded as eustatically controlled (Leeder 1988). For these successions cyclothem recurrence intervals of around 1 Ma have been proposed (Klein 1990; DeBoer 1991), falling within the range of third-order EPR eustatic cycles (0·5–5 Ma: Mitchum & Van Wagoner 1991).

As indicated above, the recent improvements in precision of dating techniques have enabled Menning *et al*. (2001) to recognise the relatively brief duration of the Brigantian, so that a 400 ka periodicity, closely approximating that of the long-period eccentricity Milankovitch orbital parameters, becomes a more likely control for the successions under examination here. The Milankovitch cyclicity is regarded as the most effective agent in climatic forcing (DeBoer 1991) and may well give rise to glacio-eustatic rises of sea level, recurring during periods of global greenhouse conditions (Ziegler *et al*. 1987; Haq *et al*. 1988).

Dewey (1982) believed that intraplate stresses leading to sea level changes may have been active during deposition of the Lower Limestone Formation, in Brigantian times, operating as a subordinate control superimposed on a dominant, primary mechanism of eustatic sea level change. Cloetingh (1988) has argued that such stresses acting within the time span of a million years could produce widespread variations in sea level, though recurrence of this phenomenon in rhythmic fashion is considered highly doubtful (Read & Forsyth 1989). At present there is no evidence to indicate whether the dextral strike or oblique slip along the fault systems known to have been active in the Midland Valley of Scotland responded to the stresses in a regular manner through time.

It may be useful to note here that Gale (in Doyle *et al*. 1994) summarised that Milankovitch-band cycles varied within the range 10·0 ka–1·0 Ma, with their main frequencies at 19–23 ka (precession cycles), 41 ka (obliquity cycles), 106 ka (short period eccentricity cycles), and 410 ka (long period eccentricity cycles). The 400 ka cycles fall in the Milankovitch-galactic-band (perihelion-extinction cycles). The autocyclic periodicity in the Mississippi delta is on a much shorter time scale, and shows major lobe avulsion at approximately 1 ka intervals and crevasse splay lifetimes of 120–150 a (Coleman & Gagliano 1964; Wells *et al*. 1984; Roberts 1997).

In that the Milankovitch cycles are superposed upon each other, the occurrence of precession or obliquity cycles towards and during the stage of highest sea level associated with the long period eccentricity cycles would permit repeated periods of limestone deposition, followed by emergence and karstification, re-submergence and carbonate deposition, re-emergence and karstification; a pattern observed in the limestones of the late Brigantian successions.

4.2. Subsidence related to rifting

Palaeocurrents within the St Monans section display a consistently unimodal distribution towards the west-southwest (Greensmith 1965; Fielding *et al*. 1988), consistent with both the Lower Limestone Formation isopachs (Browne 1986) and those reported from the Forth Approaches graben system

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(Floyd 1994). Thickness and lithofacies variations indicate that the faults bounding the basin were syndepositional and active during the Brigantian, and probably throughout the Visean. Contrasts between the eastern and western limbs of the St Monans Syncline decrease progressively upwards, successions above the Main Hosie (Seafield) Marine Band being closely comparable in both limbs (Fig. 11). A synsedimentary fault trending roughly north–south, considered to be located between the two limbs within St Monans Harbour, is held responsible for these variations, the thicker succession of the western block having been laid down on the downthrown side. The systematic decrease in lithofacies contrast is attributed to a corresponding decrease of activity on the fault with time. An even greater successional contrast exists between the St Monans and Dunbar areas – a decrease from over 200 m W of St Monans to less than 60 m at Skateraw. There are also strong successional contrasts across the Ardross Fault between St Monans and Elie (Figs 4–6).

This significant thickness and lithofacies variability supports a paradigm of tectonic subsidence associated with contemporaneous faulting, possibly within a series of half-graben structures formed along secondary shear faults at angles from the main ENE trending strike-slip faults which currently bound the south-east Fife coast. The sediment successions thin across anticlinal axes and also on the upthrown sides of faults, with successional breaks and amalgamation of cycles. The distribution pattern of the minor cycles suggests, firstly, that tectonic processes, associated with autocyclic sedimentary processes and channel lobe switching, played a major role in their development, and secondly, that during periods when compound cycles were being deposited, basin areas were comparatively more active, providing greater accommodation space. This proposal is supported by the significant increase in the number of minor cycles above the Blackhall (Charlestown Main) Limestone within a distance of less than 5 km (Figs 4, 6), from none at St Monans to five at Elie. Subsidence was rendered differential; firstly, by contemporaneous faulting; secondly, through lateral constraint of the basins by flanking major faults; and thirdly, through partial separation of the basins by earlier or coeval volcanic depocentres. These included the Clyde Plateau Volcanic Formation, the Bathgate Hills Volcanic Formation and Kinghorn Volcanic Formation Formation foci (Francis 1991).

The isopach map of the Lower Limestone Formation emphasises the high thickness variability of the formation (Browne 1986). A belt of maximum thickness trends ENE–WSW, and is bounded by identifiable fault lines (cf. Fig. 1b; Fielding *et al*. 1988; Burn 1990). These include the Ardross Fault to the southeast and the Ceres, Maiden Rock and Dura Den faults to the northwest. Fielding *et al*. (1988) consider this northern margin of a periodically active basin bounded by these faults as the most likely configuration of the East Fife sedimentary depocentre. This small transtensional feature is situated some 10 km NW of, and trends parallel to, the Forth Approaches graben (Floyd 1994).

Strata-bound synsedimentary deformation features are present through much of the Dinantian succession (Burn 1990; MacGregor 1996), and although most may be explained by syndepositional activity, some may be responses to contemporaneous tectonic activity (Dewey 1982).

Lateral impersistence of palaeosols is considered to be related to proximity to the footwalls of intermittently active faults during deposition (Fielding *et al*. 1988). For example, many coal seams are altered in quality and thickness across the faults. The proportions of bright coals is greater between the faults than outside them (Landale 1837; Fielding *et al*. 1988; Burn 1990). Landale (1837) suggested that hanging walls were zones of enhanced and accelerated subsidence, generating groundwater seepage areas conducive to development and preservation of peat. Freely-drained palaeosols may be more widespread, especially below the first deposits of the marine Facies Association A, which marks the eustatic rise of sea level (Leeder 1988; Read & Forsyth 1989; Read 1988, 1994, 1995).

The pattern of tectonic subsidence within the Midland Valley of Scotland was much more complex than the simple ‘trap door’ model of Read & Forsyth (1991), as tectonic subsidence was differential, and resistant rocks may have been emerging on the floor of the shelf. For instance, local faulting is discernible in East Fife, as at Pathhead, Ardross and Elie. Depositional basins were constrained laterally and partially separated by flanking ‘highs’ – areas of minimum subsidence which correspond to volcanic depocentres, earlier or contemporaneous (Francis 1991).

4.3. Tectonic uplift and autocyclic processes

During the late Brigantian a combination of eustatic control coupled with subsidence and autocyclic delta-lobe switching associated with tectonic uplift became established and continued for much of the remainder of the Carboniferous. Initial cycles were controlled primarily by eustatic rises of sea level coupled with sustained delta progradation, whilst minor cycles are postulated as having been dominated by crevassing and delta-lobe switching, especially in the relatively proximal area of East Fife. These autocyclic processes were likely to have been associated with dip-oblique fault controlled intrabasinal subsidence. Subsidence was intermittent rather than continuous, periodically swamping an otherwise continuously prograding delta complex. The number of cycles produced by such processes is known to be closely related to net subsidence, tending to increase proportionally to subsidence (Read & Dean 1982; Read & Forsyth 1989). Read (1994) argues that three orders of cyclicity – ‘long’, ‘intermediate’ and ‘short’ – recognised within the Scottish Namurian A succession, were eustatically controlled. Though eustatically-controlled initial cycles correspond to ‘long’ allocycles, this is unlikely to apply to the minor cycles. Certain initial cycles with well-developed claystone intervals may correspond to the ‘short’ (high frequency) allocycles of Read (1994), which have been interpreted as lying within the lower range of Milankovitch orbital parameters (Berger 1988).

4.4. Other processes

Delta advance. Some workers (Francis 1991; Fielding *et al*. 1988; Belt 1975, 1984) suggest that the successions represent simple delta advance, combined with fluctuations of river and distributary channel positions, together with local variations in subsidence and periodic sea level rises. Francis (1991) suggests that a generally shallow depth of water (<20 m), coupled with a thick Carboniferous succession (3·5 km), effectively implies an equal amount of subsidence, this broadly keeping pace with deposition throughout the period. Such a thick succession of mainly fine-grained sediments is not typical of rift systems. Variations in the amount of subsidence from place to place were controlled by basement lineaments, mostly having an ENE–WSW or Caledonoid trend, and which are believed to have been dextral strike-oblique slip faults (Hooper *et al*. 2002).

Cyclicity of the upper part of the Strathclyde Group and the Lower Limestone Formation has also been related to periodic progradation of deltas into shallow marine waters, followed by subsidence and abandonment (Frazier 1967; Fielding *et al*. 1988). Whilst there is strong evidence of widespread and regularly-repeated sea level oscillations during the Dinantian

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and Pendleian (Holdsworth & Collinson 1988), evidence of tectonic activity is also well documented (e.g. Fielding *et al.* 1988).

Vulcanism. Vulcanism remained active during deposition of the Lower Limestone Formation between the Central Coalfield (Kincardine Basin) and Fife–Midlothian basins (Bathgate Hills depocentre), whilst within the present area the Burntisland volcanic focus was also the location of a contemporarily active anticline and of associated carbonate build-ups (Pickard 1992). In both the Bathgate and the Burntisland depocentres, volcanic rocks are intercalated with the sediments at the base of the Lower Limestone Formation, beneath the Hurlet Limestone.

5. Conclusions

The topmost cycle of the Pathhead Formation and the whole of the succeeding Lower Limestone Formation constitute facies associations characteristic of fluvially-dominated, marine-influenced deltaic and offshore marine environments laid down in a repetitive succession of cyclical units or cyclothems. Cycles are classified into initial, minor and compound types. Complete Yoredale-type cyclothems are considered to extend from one limestone base to the next limestone base. Initial cycles are isolated, complete and laterally-extensive cycles commencing with a marine shelf facies. They may constitue cyclothems in their own right, or may be succeeded by up to five or more minor cycles to form compound cyclothems. Minor cycles are base-absent units commonly lacking marine intervals. Locally, in response to penecontemporaneous upwarping, one or more cyclothems may form a condensed marine succession of mudstone and limestone. The superposition of short- and long-period Milankovitch cycles may have permitted not only the development of minor depositional cycles but also enabled alternating periods of carbonate deposition and palaeokarst formation during phases of highest relative sea level. Conversely, deposition in a subsiding basin leads to an abnormally thick succession dominated by mudstone.

Deposition was initiated in a marine and coastal plain setting. Delta progradation was followed by stillstand, dewatering and sediment compaction, leading to delta lobe abandonment. Modern crevasse splay deposits in the Mississippi delta are known to yield local, 'minor' cycles of deposition up to 30 m in thickness (Wells *et al.* 1984). Dewatering and compaction reduce this thickness very substantially, to scales similar to those observed in the minor cycles recorded here (<5 m).

Extensive pedogenesis took place on delta plain interdistributary tracts, including coal formation. These units reflect a series of repeated deltaic progradations preceded by eustatic sea level rises. Alternations of coal and siliciclastic delta plain sediments may relate to cyclical processes, but it is not clear whether these were of Milankovitch or EPR type. Interbedding of limestones and mudstones and development of external and internal karstic surfaces are taken to indicate the susperposition of long- and short-period Milankovitch cycles. These may also have encouraged rapid alternations of delta advance and retreat through inducing short-term climatic modifications.

Conspicuous unconformities and correlated conformable successions are lacking in the area. Taking the bases of thick sandstones as sequence boundaries, initial cycles parallel but do not correspond to EPR third-order type 1 sequences with recurrence intervals of around 1 Ma. A cycle commences at a marine flooding event which also initiates the second parasequence of the associated sequence. The lowest erosively-based sandstone inaugurates the first parasequence of the succeeding sequence.

Two parasequences constitute each initial cycle: a lower one, initiated on a marine flooding surface, and an upper one, bounded by the base of the lowest thick sandstone in the cycle. The lower parasequence is second and uppermost in its sequence, and the upper parasequence is first in the succeeding sequence. Cycle bases and sequence bases therefore alternate, and sequences correspond to cyclothems. Minor cycles form single parasequences.

Based on the evidence from which this account is given, the case for organisation of the Lower Limestone Formation succession of SE Scotland into sequences of EPR type is, however, less than convincing. This is partly due to the problem of diagnosing the equivalent of the erosional sandstone base away from the ravinement, and following this into and through the interdistributaries, and may also be due to lack of exposures in the depositional slope direction. The pattern of cyclicity follows closely that established for the Pennsylvanian of Illinois, in which unconformable cyclothem boundaries are again not regionally traceable and the marine flooding surface is defined as the precursor of the cyclothem or 'Transgressive-Regressive Unit'.

The variability of the succession, the extensive synsedimentary deformation and the association with volcanic depocentres, all indicate that sedimentation was distributed, if not controlled, by contemporaneous tectonic activity manifested in differential subsidence within fault-bounded basins. Geophysical exploration in the nearby offshore Forth Approaches area confirms that these basins were primarily related to strike-or oblique-slip fault movement rather than to rifts and grabens as believed by earlier workers.

Whilst cyclicity was partly overlain by other factors, including tectonism and volcanism, eustasy was the major controlling factor throughout the depositional basin. Autocyclic sedimentary processes, including crevassing, delta lobe switching, channel migration and avulsion, overrode the allocyclicity to the extent of partially masking the effects of eustatic oscillations, especially in more proximal parts of the East Fife–Lothian basin. Such processes are held responsible for the development of the minor cycles. Conversely, effects of allocyclic control, principally eustatic sea-level oscillations, are dominant in the more distally situated areas of shelf deposition, where fully marine facies are proportionally more abundant than siliciclastic lithotypes.

Thus the authors believe that the repetitive successions of sediments in the Lower Limestone Formation can be related to to the Exxon-based sequence patterns only with difficulty. The patterns of change can be satisfactorily explained in terms of Milankovitch cycles, with the several sets of cycles superposing to give relatively rapid sea level changes within an overall pattern of change with a period approaching 400 ka. We believe that the details of deposition in adjacent areas differ due to the activity of autocyclic phenomena coupled with syndepositional tectonism and vulcanicity.

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7. References

Aitken, J. F. 1994. Coal in a sequence stratigraphic framework. *Geoscientist* **4**, 9–12.

Belt, E. S. 1975. Scottish Carboniferous cyclothem patterns and their palaeoenvironmental significance. *In* Broussard, M. L. (ed.) *Deltas – models for exploration*, 427–9. Houston: Houston Geological Society.

Belt, E. S. 1984. Origin of Late Dinantian cyclothems, East Fife, Scotland. *In Compte Rendu, 9th International Congress on Carboniferous Stratigraphy and Geology* **3**, 570–88. Champaign, Illinois 1979.

Berger, A. 1988. Milankovitch theory and climate. *Reviews in Geophysics* **26**, 624–57.

Browne, M. A. E. 1986. The classification of the Lower Carboniferous in Fife and Lothian. *Scottish Journal of Geology* **22**, 24–5.

Browne, M. A. E., Dean, M. T., Hall, I. H. S., McAdam, A. D., Monro, S. K. & Chisholm, J. I. 1997. A lithostratigraphical framework for the Carboniferous rocks of the Midland Valley of Scotland. NERC: *British Geological Survey Onshore Geology Series, Technical Report WA/96/29*.

Burn, M. J. 1990. *Controls on the geometry of Carboniferous deltas; East Fife, U.K. and East Kentucky, U.S.A*. Unpublished Ph.D. thesis, Oxford Polytechnic.

Cameron, I. B., Aitken, A. M., Browne, M. A. E. & Stephenson, D. 1998. Geology of the Falkirk district. *Memoirs of the British Geological Survey* **428**. London: H.M.Stationery Office.

Cloetingh, S. 1988. Intraplate stresses: a tectonic cause for third-order cycles in apparent sea level? *In* Wilgius, C. K., Hastings, B. S., Posamentier, H., Van Wagoner, J., Ross, C. A. & Kendall, C. G. St C. (eds) *Sea-level changes: an integrated approach. Society of Economic Paleontologists and Mineralogists, Special Publication* **42**, 19–29. Tulsa, Oklahoma.

Coleman, J. M. & Gagliano, S. M. 1964. Cyclic sedimentation in the Mississippi River deltaic plain. *Transactions of the Gulf Coast Association of Geological Societies* **14**, 67–80.

Davies, A., McAdam, A. D. & Cameron, I. B. 1986. Geology of the Dunbar district. *Memoirs of the British Geological Survey* **430**. London: H.M. Stationary Office.

DeBoer, P. L. 1991. Comment – Pennsylvanian time scales and cycle periods. *Geology* **19**, 408–9.

Dewey, J. F. 1982. Plate tectonics and the evolution of the British Isles. *Journal of the Geological Society, London* **139**, 371–412.

Dewey, J. F. & Strachan, R. A. 2003. Changing Silurian-Devonian relative plate motion in the Caledonides: sinistral transpression to sinistral transtension. *Journal of the Geological Society, London* **160**, 219–30.

Doyle, P., Bennett, M. R. & Baxter, A. N. 1994. *The Key to Earth History*. Chichester: John Wiley & Sons.

Fielding, C. R., Al-Rubai'i, M. & Walton, E. K. 1988. Deltaic sedimentation in an unstable tectonic environment – the Lower Limestone Group (Lower Carboniferous) of East Fife, Scotland. *Geological Magazine* **125**, 241–55.

Floyd, J. D. 1994. The derivation and definition of the Southern Upland Fault: a review of the Midland Valley–Southern Uplands terrane boundary. *Scottish Journal of Geology* **30**, 51–62.

Forsyth, I. H., Hall, I. H. S. & McMillan, A. A. 1996. Geology of the Airdrie district. *Memoirs of the British Geological Survey* **429**. London: H.M. Stationary Office.

Francis, E. H. 1991. Carboniferous. *In* Craig, G. Y. (ed.) *The Geology of Scotland* (3rd ed.), 347–92. London: Geological Society Publishing House.

Frazier, D. E. 1967. Recent deltaic deposits of the Mississippi delta: their development and chronology. *Transactions of the Gulf Coast Association of Geological Societies* **17**, 287–315.

Gradstein, F. M. & Ogg, J. 1996. A Phanerozoic time scale. *Episodes* **19**, 3–4.

Greensmith, J. T. 1965. Calciferous Sandstone Series sedimentation at the eastern end of the Midland Valley of Scotland. *Journal of Sedimentary Petrology* **35**, 223–42.

Hampson, G. H., Howell, J. A. & Flint, S. S. 1995. Lowstand versus highstand coastlines: evidence for fundamental changes from the Blackhawk Formation and Mancos Shale, Book Cliffs, Utah. *Abstract of the British Sedimentological Research Group Annual Meeting* December 1995, 40. Edinburgh.

Haq, B. U., Hardenbol, J. & Vail, P. R. 1988. Mesozoic and Cenozoic chronostratigraphy and eustatic cycles. *In* Wilgius, C. K., Hastings, B. S., Posamentier, H., Van Wagoner, J., Ross, C. A. & Kendall, C. G. St C. (eds) *Sea-level changes: an integrated approach. Society of Economic Paleontologists and Mineralogists, Special Publication* **42**, 71–108. Tulsa, Oklahoma.

Holdsworth, B. K. & Collinson, J. D. 1988. Millstone Grit cyclicity revisited. *In* Besly, B. M. & Kelling, G. (eds) *Sedimentation in a synorogenic basin complex: the Upper Carboniferous of Northeast Europe*. Glasgow: Blackie.

Hooper, M. D., Davies, S. J., Underhill, J. R., Monaghan, A. & Browne M. A. E. 2002. Evolution of the Carboniferous Central Coalfield of the Midland Valley of Scotland and implications for the regional tectonic setting. *Abstract of Conference Hydrocarbon Resources of the Carboniferous, Southern North Sea & Surrounding Onshore Areas*, 59. Leeds: Yorkshire Geological Society.

Johnson, G. A. L. & Nudds, J. R. 1996. Carboniferous biostratigraphy of the Rookhope Borehole, County Durham. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **86** (for 1995), 181–226.

Kassi, A. M., Weir, J. A. and McManus, J. 1996. Sedimentary basin evolution and sequence stratigraphy of Upper Dinantian successions of eastern Scotland. *Unpublished report to European Commission*.

Kassi, A. M., Weir, J. A., Browne, M. A. E. and McManus. J. 1998. The stratigraphy and depositional context of a temporary exposure in the Anstruther Formation (Strathclyde Group), Anstruther Wester, Fife. *Scottish Journal of Geology* **34**, (2), 127–32.

Klein, G. de V. 1990. Pennsylvanian time scales and cycle periods. *Geology* **18**, 455–7.

Landale, D. 1837. Report on the geology of the East of Fife Coalfield. *Transactions of the Highlands Agricultural Society of Scotland* **11**, 265–348.

Leeder, M. R. 1988. Recent developments in Carboniferous geology: a critical review with implications for the British Isles and N. W. Europe. *Proceedings of the Geologists Association* **99**, 73–100.

Loutit, T. S., Hardenbol, J, Vail, P. R. & Baum, G. R. 1988. Condensed sections: the key to age dating and correlation of continental margin sequences. *In* Wilgius, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. & Van Wagoner, J. C. (eds) *Sea level changes: an integrated approach. Society of Economic Paleontologists and Mineralogists, Special Publication* **42**, 183–213. Tulsa, Oklahoma.

MacGregor, A. R. 1996. *Fife and Angus Geology: an Excursion Guide* (3rd Ed). Edinburgh: Pentland Press.

Menning, M., Weyer, D., Drozdzewski, G., van Ameron, H. W. J., Wendt, I. 2001. A Carboniferous timescale 2000: Discussion and use of geological parameters as time indicators from central and western Europe. *Geologisches Jahrbuch, Hannover* A156, 3–44.

Mitchum, R. M. & van Wagoner, J. C. 1991. High-frequency sequences and their stacking patterns: sequence-stratigraphic evidence of high-frequency eustatic cycles. *Sedimentary Geology* **70**, 131–60.

Paterson, I. B. & Hall, I. H. 1986. *Lithostratigraphy of the late Devonian and early Carboniferous rocks in the Midland Valley of Scotland. British Geological Survey Report* **18**, No. 3. London: H.M. Stationary Office.

Payton, C. E. (ed.) 1977. *Seismic stratigraphy – applications to hydrocarbon exploration*. Tulsa, Oklahoma: *American Association of Petroleum Geologists, Memoir* **26**, v. 11.

Phillips, J. 1836. *Illustrations of the geology of Yorkshire: or a description of the strata and organic remains. Part 2 – the Mountain Limestone District*. London: John Murray.

Pickard, N. A. H. 1992. Depositional controls on Lower Carboniferous microbial buildups, eastern Midland Valley of Scotland. *Sedimentology* **39**, 1081–100.

Pickard, N. A. H. 1994. Sedimentology of the Upper Dinantian Charlestown Main Limestone: implications for the controls on cyclothem deposition, eastern Midland Valley of Scotland. *Scottish Journal of Geology* **30**, 15–31.

Posamentier, H. W. & James, D. P. 1993. An overview of sequence-stratigraphic concepts: uses and abuses. *In* Posamentier, H. W., Summerhayes, C. P., Haq, B. U. & Allen, G. P. (eds) *Sequence stratigraphy and facies associations. Special Publication of the International Association of Sedimentologists* **18**. Oxford: Blackwell Scientific Publications.

Posamentier, H. W. & Vail, P. R. 1988. Sequences, systems tracts, and eustatic cycles. *American Association of Petroleum Geologists Annual Meeting*, Houston, March 20–23, 1988. Tulsa, Oklahoma.

Posamentier, H. W. & Weimer, P. 1993. Siliciclastic sequence stratigraphy and petroleum geology – where to from here? *Bulletin of the American Association of Petroleum Geologists* **77**, 731–42.

Posamentier, H. W., Jarvey, M. T. & Vail, P. R. 1988. Eustatic controls on clastic deposition – conceptual framework. *In* Wilgius, C. K., Hastings, B. S., Kendall, G. St. C., Posamentier, H. W., Ross, C. A. & Van Wagoner, J. C. (eds) *Sea-level changes: an integrated approach*. *Society of Economic Paleontologists and Mineralogists, Special Publication* **42**, 109–24. Tulsa, Oklahoma.

Posamentier, H. W., Allen, G. P. & James, D. P. 1992. High resolution sequence stratigraphy – the East Coulee Delta. *Journal of Sedimentary Petrology* **62,** 310–17.

Read, W. A. 1988. On Silesian sedimentation in the Midland Valley of Scotland. *In* Besly, B. M. and Kelling, G. (eds) *Sedimentation in a synorogenic basin complex: Upper Carboniferous of northwest Europe*, 222–41. New York: Chapman and Hall.

Read, W. A. 1994. High-frequency glacial-eustatic sequences in early Namurian coal-bearing fluviodeltaic deposits, central Scotland. *Special Publication of the International Association of Sedimentologists* **19**, 413–28. Oxford: Blackwell Scientific Publications.

Read, W. A. 1995. Sequence stratigraphy and lithofacies geometry in an early Namurian coal-bearing succession in central Scotland. *In* Whateley, M. K. G. & Spears, D. A. (eds) *European coal geology*. *Geological Society, London, Special Publication* **82**, 285–97.

Read, W. A. & Dean, J. M. 1982. Quantitative relationship between numbers of fluvial cycles, bulk lithological composition and net subsidence in a Scottish Namurian basin. *Sedimentology* **29**, 181–200.

Read, W. A. & Forsyth, I. H. 1989. Allocycles and autocycles in the upper part of the Limestone Coal Group (Pendleian E1) in the Glasgow–Stirling region of the Midland Valley of Scotland. *Geological Journal* **24,** 121–37.

Read, W. A. & Forsyth, I. H. 1991. Allocycles in the upper part of the Limestone Coal Group (Pendleian, E1) of the Glasgow–Stirling region viewed in the light of sequence stratigraphy. *Geological Journal* **26**, 85–9.

Roberts, H. H. 1997. Dynamic Changes of the Holocene Mississippi River Delta Plain: The Delta Cycle. *Journal of Coastal Research* **13**, 605–27.

Udden, J. A. 1912. Geology and mineral resources of the Peoria Quadrangle. *United States Geological Survey Bulletin* **506**, 1–103.

Underhill, J. R., Monaghan, A. & Browne M. A. E. 2002. Controls on Carboniferous Basin Development and Petroleun Prospectivity in the Midland Valley of Scotland. *Abstract of Conference Hydrocarbon Resources of the Carboniferous, Southern North Sea & Surrounding Onshore Areas*, 66. Leeds: Yorkshire Geological Society.

Vanstone, S. D. 1998. Late Dinantian palaeokarst of England and Wales: implications for exposure surface development. *Sedimentology* **45**, 19–37.

Van Wagoner, J. C., Mitchum, R. M. & Posamentier, H. W. 1988. Key definitions of sequence stratigraphy (part 2). *In* Bally, A. W. (ed.) *Atlas of seismic stratigraphy*. *American Association of Petroleum Geologists Studies in Geology* **1**, 11–12. Tulsa, Oklahoma.

Van Wagoner, J. C., Mitchum, R. M., Champion, K. M. & Rahmanian, V. D. 1990. *Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies*. *American Association of Petroleum Geologists Methods in Exploration Series*, 7. Tulsa, Oklahoma.

Wanless, H. R. & Weller, J. M. 1932. Correlation and extent of Pennsylvanian cyclothems. *Geological Society of America Bulletin* **43**, 1003–16.

Weibel, C. P. 1996. Applications of sequence stratigraphy to Pennsylvanian strata in the Illinois Basin. In Witzke, B. J., Ludvigson, G. A. & Day, J. (eds) *Paleozoic Sequence Stratigraphy: Views from the North American Craton*. *Geological Society of America, Special Paper* **306**, 332–9.

Wells, J. T., Chinburg, S. J. & Coleman, J. M. 1984. *The Atchafalaya River Delta: Report 4. Generic Analysis of Delta Development*. Technical Report HL-82–15, Vicksburg, Mississippi: US Army Corps of Engineers.

Ziegler, A. M., Raymond, A. L., Gierlowski, T. C., Horrel, M. A., Rowley, D. B. & Lottes, A. L. 1987. Coal, climate and terrestrial productivity: the present and early Cretaceous compared. *In* Scott, A. C. (ed.) *Coal and coal-bearing strata: recent advances*. *Geological Society, London, Special Publication* **32**, 25–49.

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