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Climatic Influences on Upper Carboniferous (Serpukhovian to Mid-Bashkirian) Sedimentary Sequences in the UK Pennine and Other European Basins

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Abstract

Upper Carboniferous successions in European sedimentary basins contain cyclothems related to glacial cycles of approximately 100 Ky duration. Within the UK Pennine Basin both simple and complex cyclothems are recognized. In the latter, mid-cycle deltas were flooded by sea-level rises, possibly related to short period orbital forcing events. They were followed by late cycle forced regression delta channels and then by incised coarse-grained channels active after the glacial maximum. Other European successions commonly contain coarse incised channel fills in the same cyclothems; these were deposited during colder glacial periods. Simple cyclothems formed during warmer periods contain only lobate mid-cycle deltas. The distribution of different cyclothem types is not random. Correlation with the eastern Australian succession using revised published radiometric dates from Eastern Europe suggests that the early Namurian C1 glaciation in Australia correlates with a group of Pennine complex cycles of late Pendleian to early Arnsbergian age. The C2 glaciation began just prior to the late Kinderscoutian and possibly lasted into the early Langsettian; the Pennine succession shows evidence for a number of colder periods with complex cycles, especially in the late Kinderscoutian and mid Marsdenian. The intervening period, particularly from Alportian to mid Kinderscoutian was warmer.

Keywords

Carboniferous, Climate, Glacial, Cyclicity, Pennines, Europe

1. Introduction

For almost 100 years [1] it has been known that late Paleozoic successions contain glacial deposits. Three glacial periods occurred in the Late Devonian, Mid Tournaisian and mid to late Visean [2]. A detailed chronology from Eastern Australia [3] [4] suggests that from the Serpukhovian to the Moskovian there were four more separate glacial periods, each of no more than up to a few million years' duration. Ice-age related climatic changes are world-wide in their effects. Carboniferous equatorial cyclothems of North America have been linked to climate and sea-level changes related to the formation and decay of Southern Hemisphere ice sheets [5]. Increased understanding of Carboniferous equatorial region successions developed from the numerous sedimentology studies of the 1960's, 70's and 80's and more recently sequence stratigraphy, with many studies carried out in North America [6], in the northern England Pennine Basin [7]-[13], the Ruhr Basin [14] [15] [16] and the Lublin Basin [17].

Southern Hemisphere Carboniferous successions with glacial deposits had a relatively poor preservation because they are largely terrestrial. Equatorial successions that developed within continuously subsiding basins have the potential to provide a more complete record of late Paleozoic climate change. Attempts at paleo-climate reconstruction have been made for the Canadian Maritimes Basin [18], where some of the Namurian is missing, the UK Pennine Basin [19]; and the Donetsk Basin [20].

The paper reviews the sedimentary successions of the Namurian and early Langsettian (**Table 1**) from a number of sedimentary basins in Europe (**Figure 1**). This is largely based on the existing literature supplemented by fieldwork carried out by the author. By far the most extensively researched succession occurs in the northern England Pennine Basin (**Figure 1**). It originated in the early Carboniferous [22] and contained a number of extensional sub-basins, separated by more slowly subsiding blocks (**Figure 2**). By Namurian time the whole area was undergoing thermal subsidence. Subsidence rates varied significantly and

Table 1. Stratigraphic position of sequence discussed in relation to the North American and wider European stratigraphies, with ages from Davydov *et al.* (2012) [21].

			North America	*Russia*			*NW Europe*		This Paper
CARBONIFEROUS	LATE	Pennsylvanian	Morrowan 323.2Ma	Bashkirian	UPPER	Silesian	Westphalian 318.5Ma	Duckmantian	↓
								Langsettian	▨
							Namurian 329.2Ma	Yeadonian	▨
								Marsdenian	▨
								Kinderscoutian	▨
								Alportian	▨
								Chokierian	▨
	EARLY	Mississippian	Chesterian	Serpukhovian				Arnsbergian	▨
								Pendleian	▨
				Visean	LOWER	Dinantian	Visean	Brigantian	

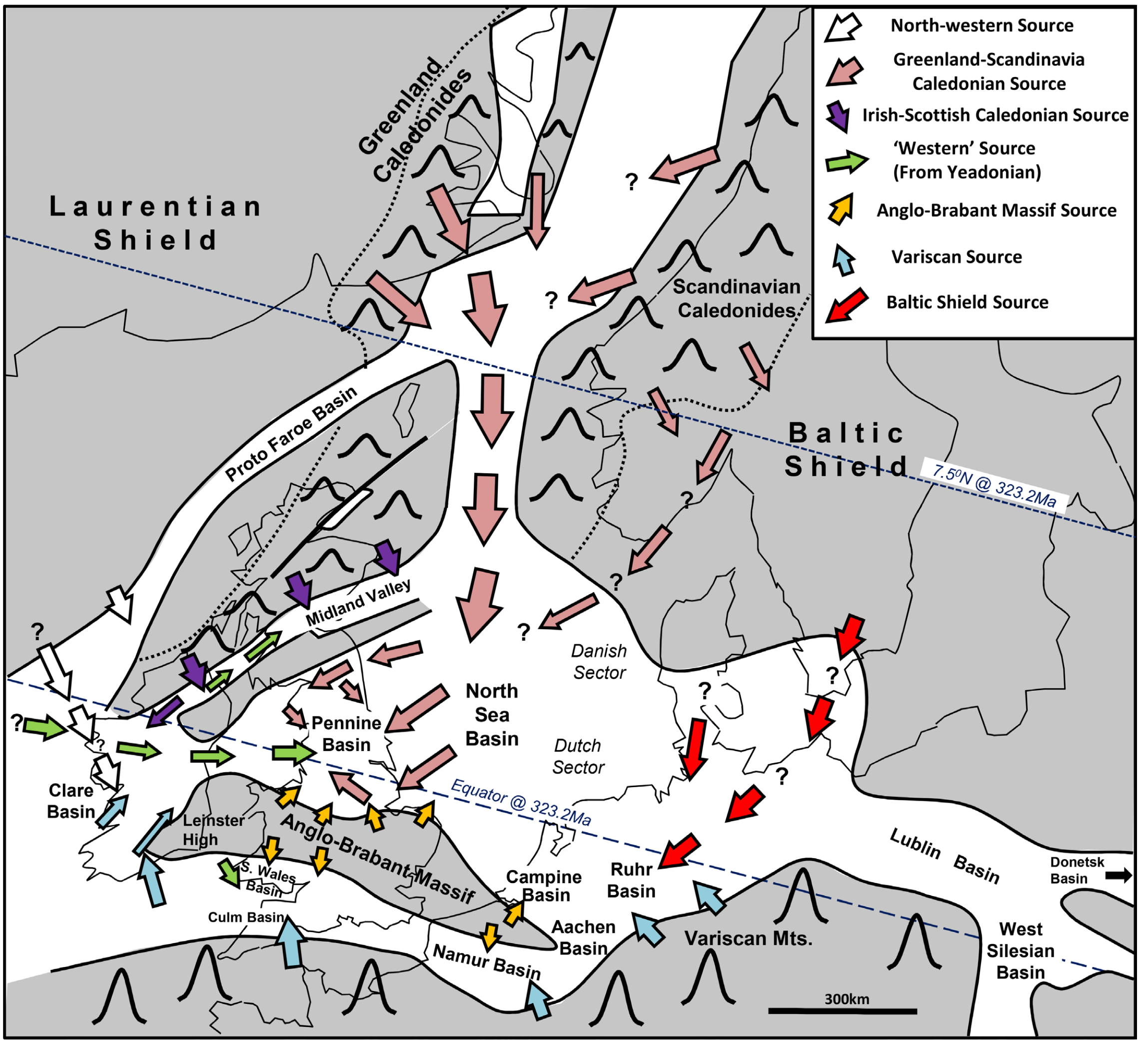


Figure 1. Early Upper Carboniferous palaeogeography of West-Central Europe: showing the major sedimentary basins and main fluvial sediment inputs. Data from various sources; see text. Lines of latitude from Scotese (2014) [30].

successions over some of the blocks continued to be thinner than in the sub-basins. The biostratigraphy is known in great detail with marine bands providing a reliable correlation down to approximately 100,000 years (Section 4.2). The basin extends out into the larger North Sea Basin which has now been penetrated by over 100 gas wells and a selection of these is shown in **Figure 3**. All released well data are available online, including core photographs on the BGS website, although biostratigraphic and sedimentology studies are commonly excluded. General accounts are provided in [23] [24].

The Ruhr Basin in Germany (**Figure 1**) is a foreland basin with high rates of subsidence in the late Namurian. In the basin centre the Namurian succession is over 3000 m thick [15] [16] [25] and is mainly known from borehole data, with only limited outcrop exposure. Much of the early Namurian (Serpukhovian) is in non-deltaic basin facies [25] [26], but a very detailed biostratigraphic breakdown is available for the overlying deltaic succession from early Marsdenian

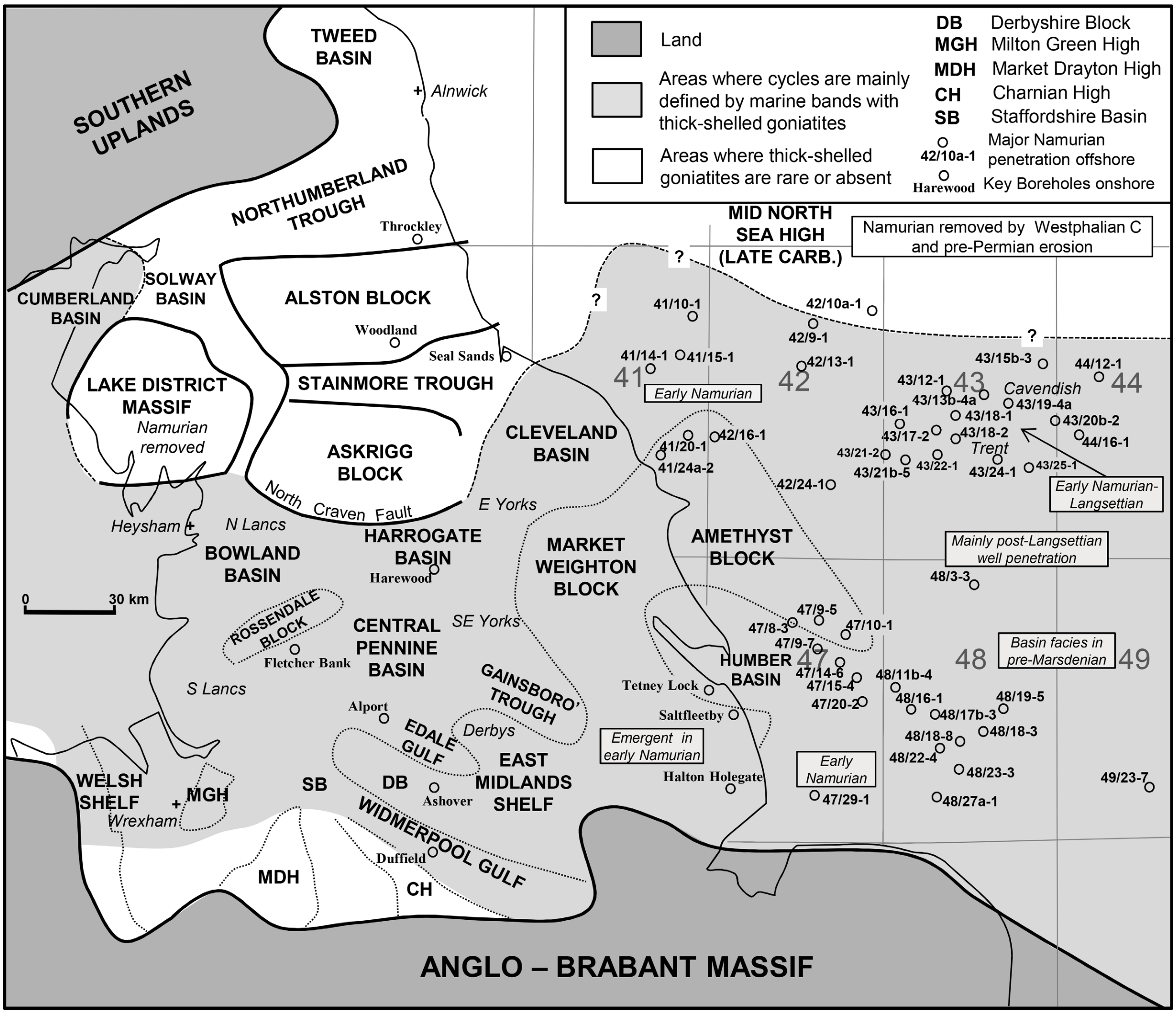


Figure 2. Major blocks, sub-basins and land areas in the Pennine Basin of Northern England and adjacent UK North Sea Basin; plus major Carboniferous well penetrations. (Sub-basins are commonly named as "basin", "trough" or "gulf". Blocks are sometimes called "shelf" or "massif"). Mainly after Pharaoh *et al.* (2009) [44] Waters *et al.* (2008, 2014) [45] [46].

through into the Langsettian [27] [28] [29], which allows correlation with the Pennine Basin succession. Although there are only a small number of modern sedimentology and sequence-stratigraphy studies available [15] [16], high rates of subsidence provide a lot of detail on intra-cycle events, which are less evident in other more slowly subsiding basins. Other sedimentary basins which provide useful data through parts of the sequence include various basins in Ireland, plus sedimentary basins in Scotland. South Wales is a foreland basin with high rates of subsidence towards the late Namurian, which is similar to basins in SW England, France, Belgium, Holland and east Europe (**Figure 1**). These are also briefly reviewed.

The paper also discusses how the sedimentological and faunal data may provide evidence for climate change and associated sea-level changes and how these varied through the period; with possible links to orbital forcing. The western European data are then compared to the published evidence for far-field climate changes in the southern hemisphere and a new correlation between the West European succession and the Australian glacial chronology is proposed.

2. Pleistocene Glaciations as an Analogue for the Carboniferous?

The chronology of the Pleistocene glaciations is now well established through detailed air temperature changes documented by ice cores [31] [32] and sea temperature changes estimated using foraminiferal oxygen isotope ratios in deep-ocean cores [33] [34]. The sea and air temperature data provide indirect evidence for ice sheet accumulation and decay (**Figure 3(A)**). Combining these with the sea-level [35] and ice volume calculations [36] shows that major glacial periods lasting c100 Ky, with sea-level falls of up to 120m, have only existed for the last 900 Ky [37]. Summaries of back-calculations of orbital forcing parameters after [35] [38] [39] [40] [41] [42] [43] over the late Pleistocene glacial period

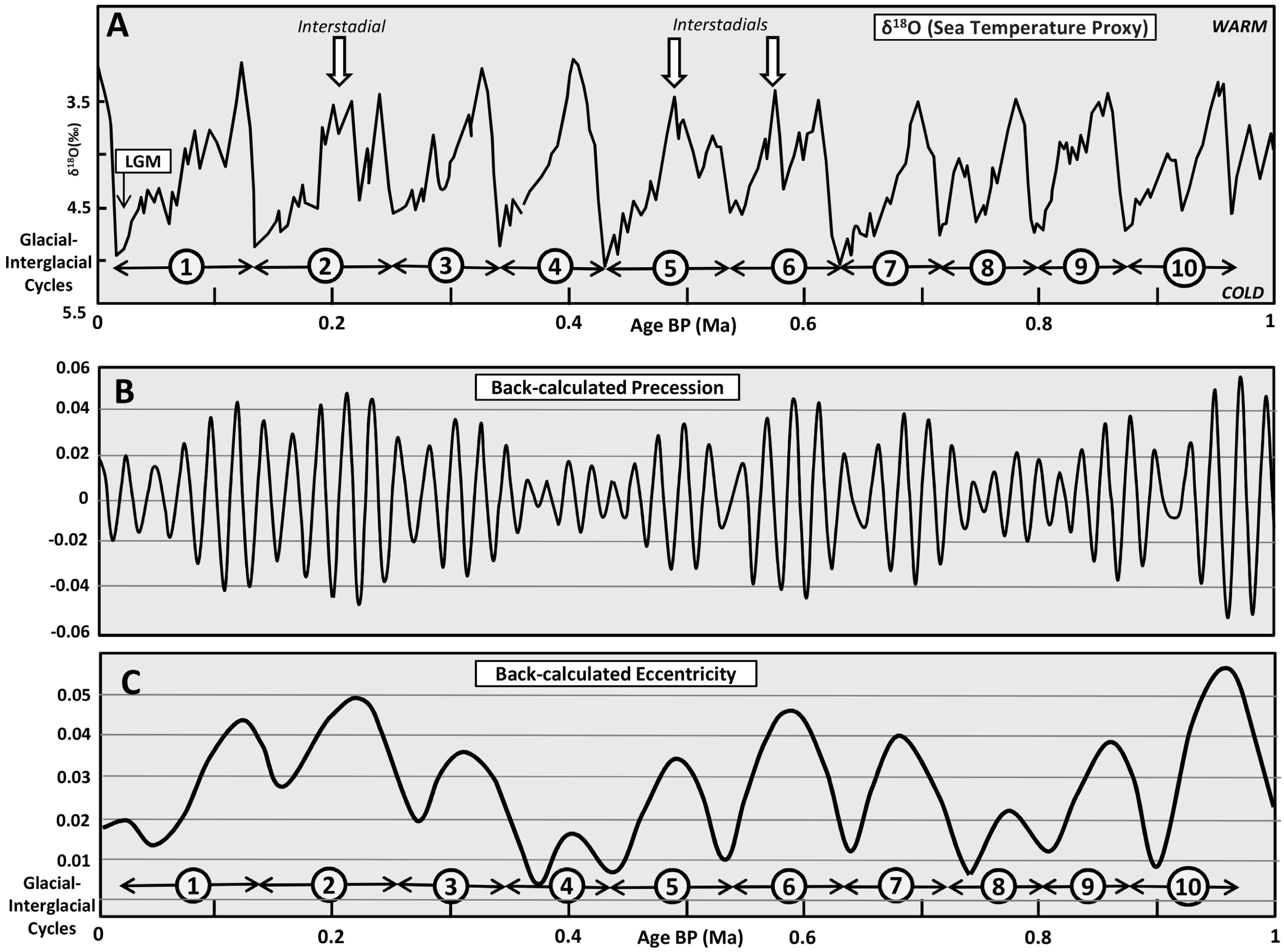


Figure 3. (A) Temperature variations from the LR04 stack for the last 1 My (Lisiecki and Raymo 1995). [34]; ((B), (C)) Back-calculated precession & eccentricity for the last 1 My (Berger and Loutre 1991) [38]. The arrows show where strong precessional forcing events cause significant temperature variation.

are shown (**Figure 3(B)** and **Figure 3(C)**). The four parameters are: long-eccentricity, approximately 400 Ky, short-eccentricity, approximately 100 Ky; obliquity, which averages 41 Ky and precession, which averages 23 Ky. These back-calculations show an apparent correlation between the short-eccentricity forcing periods (**Figure 3(C)**) and the glacial cycles defined by the temperature data (**Figure 3(A)**).

In spite of the obvious dominance of 100 Ky cycles, short eccentricity (100 Ky) forcing is not strong enough alone to account for the temperature changes seen. Increased modulation of precession over the 100 Ky eccentricity period enhances ablation and hence increased ice melting, whilst decreased modulation allows ice sheets to grow in response to obliquity forcing [47]. **Figure 4(A)** shows the temperature record for the last glacial cycle, based on the Vostock ice core in Antarctica [32]. Although the eccentricity is weaker at the end of the 400

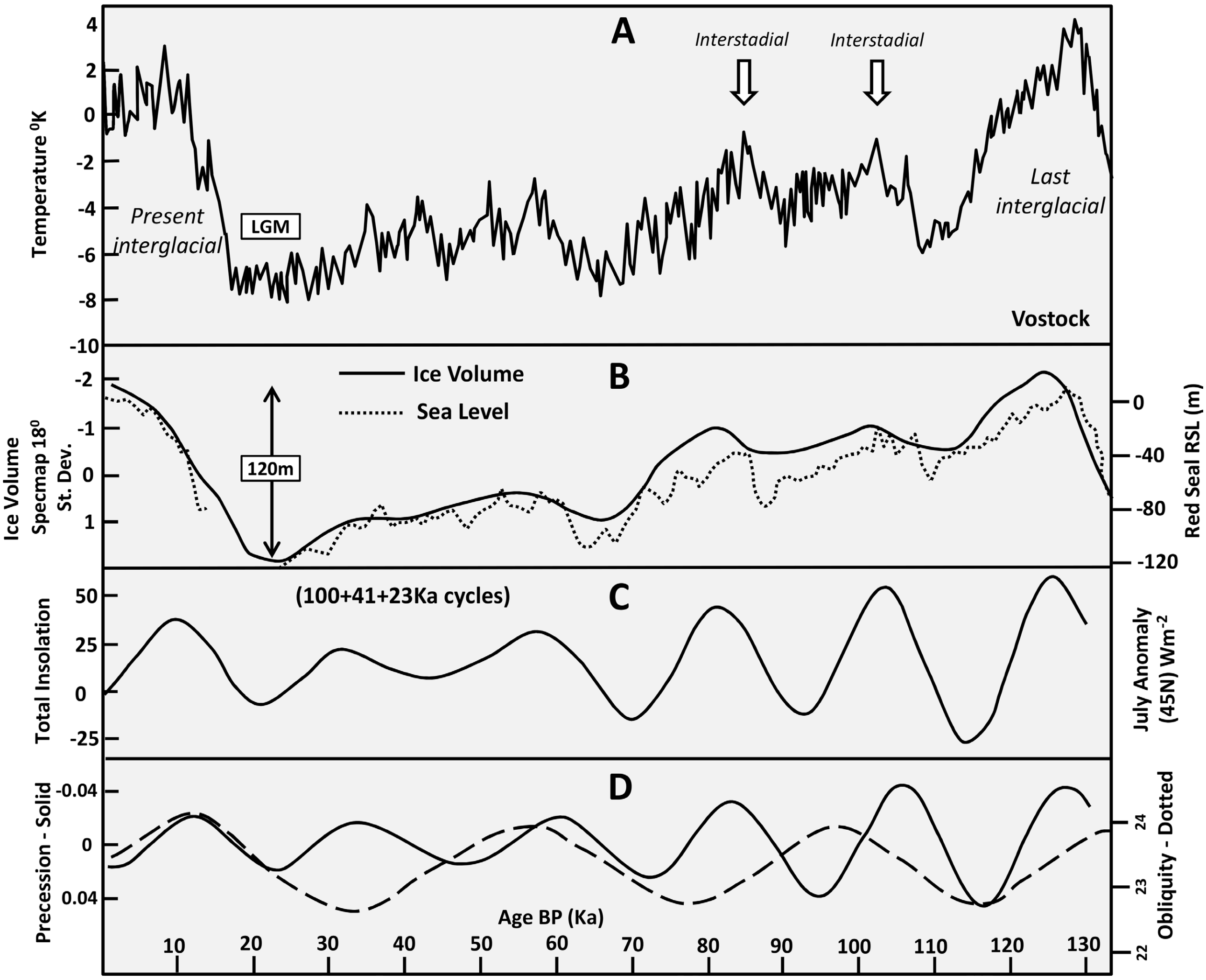


Figure 4. Last Glacial cycle: temperature data from the Vostock Ice Core (Petit *et al.* 1999) [32]. Calculated ice volume (Imbrie *et al.* 1984) [36] and Red Sea sea-level fluctuation (Siddal *et al.* (2003) [35]. Back-calculated total insolation, precession and obliquity (Berger & Loutre 1991) [38]. The arrows show where temperature peaks correlate with the back-calculated total insolation and precession curves.

Ky long-eccentricity cycle, it still shows variations in temperature, with two secondary peaks (**Figure 4(A)**, arrowed) forming interstadials, which punctuated the longer-term temperature drop culminating in the Late Glacial Maximum (LGM). These temperature fluctuations caused variations in calculated ice volumes and hence sea levels (**Figure 4(B)**) [47] which relate closely to the total insolation curve (**Figure 4(C)**). Precessional forcing events, back-calculated in **Figure 4(D)**, formed a large component of this insolation variation.

Many of the modern interpretations of Carboniferous sequences are seen through a prism of the recent Pleistocene events, which took place over a period of less than 1 My. This episode was very short in comparison to the 50 My over which the Carboniferous ice ages occurred. Therefore, to what extent is the short late Pleistocene period an analogue for the much longer Carboniferous? Obvious differences between the two periods include the very different disposition of the oceans and continents [30]; the different locations, extents and elevations of the major ice sheet accumulation areas [48] [49]; the likely higher oxygen content of the Carboniferous atmosphere [50]; reduced solar luminosity [51] and differences in the orbital forcing periods; although these were limited and some parameters can be back-calculated into the Carboniferous [40].

3. Western European Palaeogeography and Fluvial Systems

The Western European sedimentary basins were filled by fluvio-deltaic sediments transported by rivers from several different catchment areas (**Figure 1**) These are sufficiently far apart to have experienced different types of climate, although all would have been subject to the same world-wide climate changes associated with the waxing and waning of the southern hemisphere ice sheets. All of the basins were obviously subject to identical glacio-eustatic sea level changes. Tectonic influences; source-area uplift and variable rates of subsidence complicate the climatic interpretation of the various successions.

The most important sediment source for the Pennine Basin was the northern Caledonian river system which crossed the North Sea before terminating in the Basin (**Figure 1**) [52] [53] [54]. An emerging consensus suggests a primary source in the Greenland Caledonides, with a possible secondary source in Scandinavia [55]-[59]. The southern parts of the Pennine Basin also received sediments from the Anglo-Brabant Massif [53] [54] [60] [61] [62] [63], a large island within the equatorial belt (**Figure 1**). This was also the major sediment source for South Wales [64] [65] (**Figure 1**, **Figure 2**). From late Namurian times onwards a third “western” source became increasingly important in the Pennine Basin [53] [54] [66]. The dominant source for the Ruhr Basin was the Variscan Mountains [67] [68], but some sediment was probably also sourced from the Baltic Shield [68]. By the Westphalian (Bolsovian) the Variscan source dominated almost the entire area, but this did not reach the Pennine Basin or UK North Sea in the period covered by this study [52] [53].

4. Upper Carboniferous Cyclothems and Deltaic Sequences

Large parts of the western European Namurian and early Westphalian successions can be divided into cyclothems dominated by fluvio-deltaic sediments. The cyclothems are bounded by flooding surfaces which in many areas are overlain by black mudstones commonly containing thick-shelled goniatites (known as marine bands) and in more marginal areas by shales with *Lingula*, or shallow water limestones with marine fauna. The rapidly evolving nature of their goniatite fauna enables most cyclothems to be recognized across most of the west European sedimentary basins, and to a lesser extent into east Europe [69] [70] [71]. In parts of basins which had not yet been filled with deltaic sediments, the cyclothems within basinal mudstones are typically only a meter or two thick, sometimes less [46] [72] [73]. Where deltaic sequences were deposited, the cyclothems are commonly tens of meters in thickness and locally over 100 m. In this paper each recognized cyclothem has been numbered; so the first cyclothem in the Pendleian is P1 and the second cyclothem in the Arnsbergian is AR2 etc. (Section 5).

4.1. Caledonian River System, Northern England & North Sea Basins

Amongst the various cyclothems supplied by the Caledonian River System in Northern England up to three distinctive fluvial and deltaic sequences have been recognized (**Table 2**, **Figure 5**, **Figure 6**). Each developed at a different time in the evolution of the cyclothem [74]. This classification is slightly different from an earlier classification [75], which was based more on the depth of water into which the deltas prograded.

1) Type 1 delta sequences formed from lobate deltas developed during the earliest phases of delta progradation and are locally present in almost all of the observed cyclothems (see [76] (Pendleian) and [77] (Westphalian B) for more detailed sedimentology descriptions). Other descriptions are given in [74] [78]-[83]. Many of the delta sequences are dominated by mouth bar deposits and are predominantly composed of very fine to medium-grained sandstones. In the Pennine Basin their lithology is commonly referred to as 'flagstones' (or 'flags' as in Rough Rock Flags, Beacon Hill Flags, Scotland Flags, Elland Flags, etc.). There is a wide variety of morphological sub-types defined by variations in the mouth bar facies (**Figure 5**, Types 1a-1e). Only a few mouth bar sequences are dominated by wavy, hummocky or wave ripple lamination (Type 1a) eg. Lower Middleton Grit [12]. Parts of the Beacon Hill Flags (Type 2b) (Cyclothem M8, R2b5) have wavy lamination towards the top with parallel and current current ripple lamination with rare small scale trough cross-beds lower down [74]. Many Type 1 sequences show coarsening upwards grain size profiles with current ripple lamination passing up to cross-bedding at the top (1c). Some form multiple stacked units (eg.) parts of the Wards Stone Sandstone, Cyclothem Ar6-E2a [84]. In others such as the Uldale Sill and stratigraphic equivalents (Cyclothem P5-E1b) the mouthbar facies sit almost directly on the underlying

Table 2. Main features of the three deltaic sequence types in the Northern England/North Sea Caledonian fluvial system.

Main Features	*Type* 1	*Type* 2	*Type* 3
Sst. Grain Size	Mainly fine-medium, occ. coarse (Channels) vf. to medium (Mouthbars)	Fine to coarse, occ. very coarse, pebble lags	Mainly coarse to very coarse with common scattered pebbles
Cross-bedding	Mainly trough (Channels)	Mainly trough	Mainly planar tabular
Mouthbar	Commonly well-developed, but occasionally limited	Absent or very limited, except in deep water deltas	Usually absent, but seen in some deep water deltas
Planform	Narrow (c1km) channels, much wider mouthbars	Channel belts 8 - 50 km	Narrow (2 - 4 km) channels up to 70 km wide sheets
Lateral accretion surfaces (*Meandering*)	Rare	Absent	Absent
Palaeocurrent range	Highly variable	Narrow in channel, highly variable in different belts	Narrow
Incision	None	Sometimes	Very common
Position in cylothem	Early to Middle	Late	Very late (after eustatic min.)

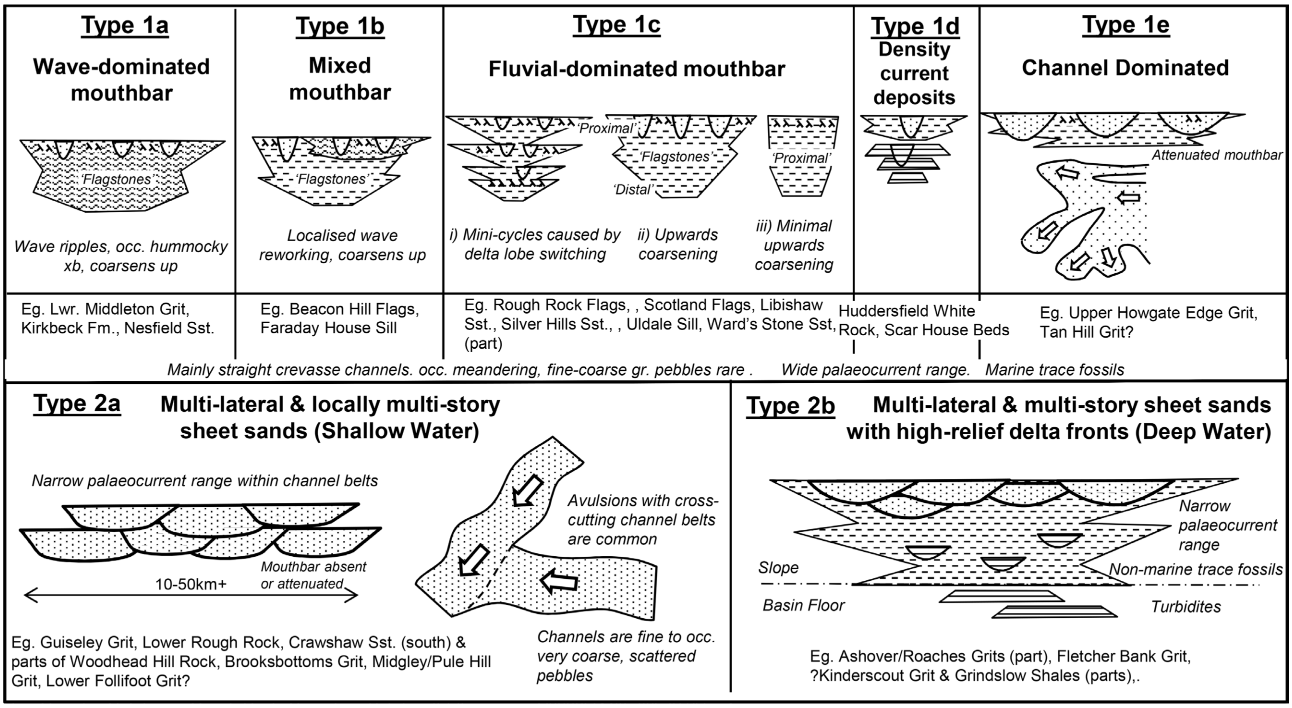


Figure 5. D ifferent Type 1 and Type 2 delta sequences in the Caledonian River System, Pennine Basin.

cyclothem [85]. In the Scar House Beds (Cyclothem Ar11-E2b3) [12] and parts of the Huddersfield White Rock (Cyclothem M10) [46], the mouth bar is dominated by density current deposits. In rare cases (Type 2e) the mouth bar facies is poorly developed, and channel deposits predominate [86]. Trace fossil variety and abundance varies greatly; some mouth bar sequences such as the Beacon Hill Flags showing a wide variety of marginal marine types [74] whereas others are dominated by *Pelecypodichnus* (a.k.a *Lockeia*), the resting and escape traces of non- marine bivalves [87]. Distributary channels in Type 1 delta sequences typically form sandbodies at least 1km wide which may show highly divergent paleocurrent orientations [74] [76] [78] [88] [89], suggesting a radial distributary pattern.

The sedimentology of mouth bars is influenced by the interaction of fluvial, wave and tidal processes [90] as well as by sea-level and sediment supply variations. In the Pennine Basin tides were probably very weak [91] [92], but mouth bar sequences described above have both wave-dominated and fluvial-dominated end members. The former may have been deposited during static or very slowly rising sea levels when delta advance was slowed down, giving more time for reworking to varying extent by waves. Delta sequences dominated by channel deposits, or where proximal mouth bar facies sit directly on the underlying cyclothem, suggest probable forcing during periods of more rapidly falling sea-level than when mouthbar dominated sequences were deposited.

2) Type 2 delta sequences consist of multi-lateral and commonly multi-storey, fluvial channel sandstone sheets, typically 10 km wide or more (**Figure 5**). Their grain size ranges from fine to very coarse grained sandstone with quartzitic pebble lag deposits (**Table 2**). Trough cross-bedding, with a narrow paleocurrent range, is commonly present. Lateral accretion surfaces are absent. They have very little interbedded mud and are regarded as sandy, braided channel deposits formed by laterally shifting and commonly avulsing river channels. They equate with some of the sheet-deltas previously recognized [75]. Examples include the Guiseley Grit (Cycle M8-R2b5) [74] and Brooksbottoms Sandstone (Cycle M11-R2c2) [46]. The Fletcher Bank, Pule Hill and Midgley Grits (Cycle M5-R2b3), large channel fills with larger cross-beds [81] [93] [94] and Lower Rough Rock (Cycle Y4-G1b1) [78] [95] [96], also belong to this category, although previous sedimentological interpretations differ from those adopted here. Mouth bar sediments formed during deposition of Type 2 deltas are usually thin or absent. Coarsening-upwards progradational sequences found below many Type 2 sequences are now mostly regarded as Type 1 mouth-bar dominated delta sequences deposited earlier in the same cycle, as seen in Cycle M8 [74]. In rare cases, Type 2 channel fluvial channels fed deltas which prograded into underfilled deeper water areas (**Figure 7**, Type 2b). The best documented example is in parts of the R2b5 cycle (M8) [11] [74] [97]. Here a thick muddy delta-slope sequence is developed, locally dominated by current ripple-laminated sandstones with *Pelecypodichnus* (a.k.a. *Lockeia*) [87]. The overlying fluvial channel fills are typically up to 1km wide, but amalgamate to form wider sheets.

3) Type 3 delta sequences are dominated by very coarse-grained and commonly pebbly fluvial channel sandstones (the classic "*Millstone Grits*" of the UK Pennines). These developed high in the cyclothems and incise into deltaic sediments of Types 1 and 2 [74], or even into deposits of underlying cyclothems. The dominant sedimentary structures are cosets of planar-tabular cross-bedding [98] with individual sets up to 3 m. Like the deltas forming the Type 2 sequences, they

are interpreted as sandy braided river deposits. A variety of channel types is recognized (**Figure 6**), distinguished mainly by lateral extent and degree of incision.

Type 3*a* (**Figure 6**). In shallower parts of the basin, the delta sequences comprise variably incised channel belts, typically 8 to 30 km wide. The Chatsworth Grit (R2c2-M14) [46] a wide channel belt of about 20 km, can be traced up-current for over 500 km across the North Sea through wells in Quadrants 47 and 48, to Block 43/24 (**Figure 2**) where it is developed as the Lower Trent Sandstone [99]. The middle lobe of the Crawshaw Sandstone (Cycle L1) [100] and parts of the coeval Woodhead Hill Rock and Ousel Nest Grit form a narrower, but similar type of channel (Section 4.2.3). Many of the late Kinderscoutian (R1c) very coarse grained delta channels such as the Addingham Edge and Lower Brimham Grits [89] also fall into this category.

Type 3*b* (**Figure 6**). Some very coarse channel deposits such as the late Yeadonian Upper Rough Rock (see Section 4.2.2) form exceptionally wide sheet sand bodies with only limited incision.

Type 3*c* (**Figure 6**). These are narrow and deep (10 - 40 m) fluvial channel deposits, the channels being repeatedly cut and filled by erosion during annual flood events [74]. In addition to planar-tabular cross-beds, identical to those found in Type 3a and 3b delta channels, the more deeply eroded parts are filled with very large scale (5 - 40 m) cross-beds together with massive or faintly laminated sandstones [9] [74] [101]-[106]. They are restricted to only three stratigraphic intervals:

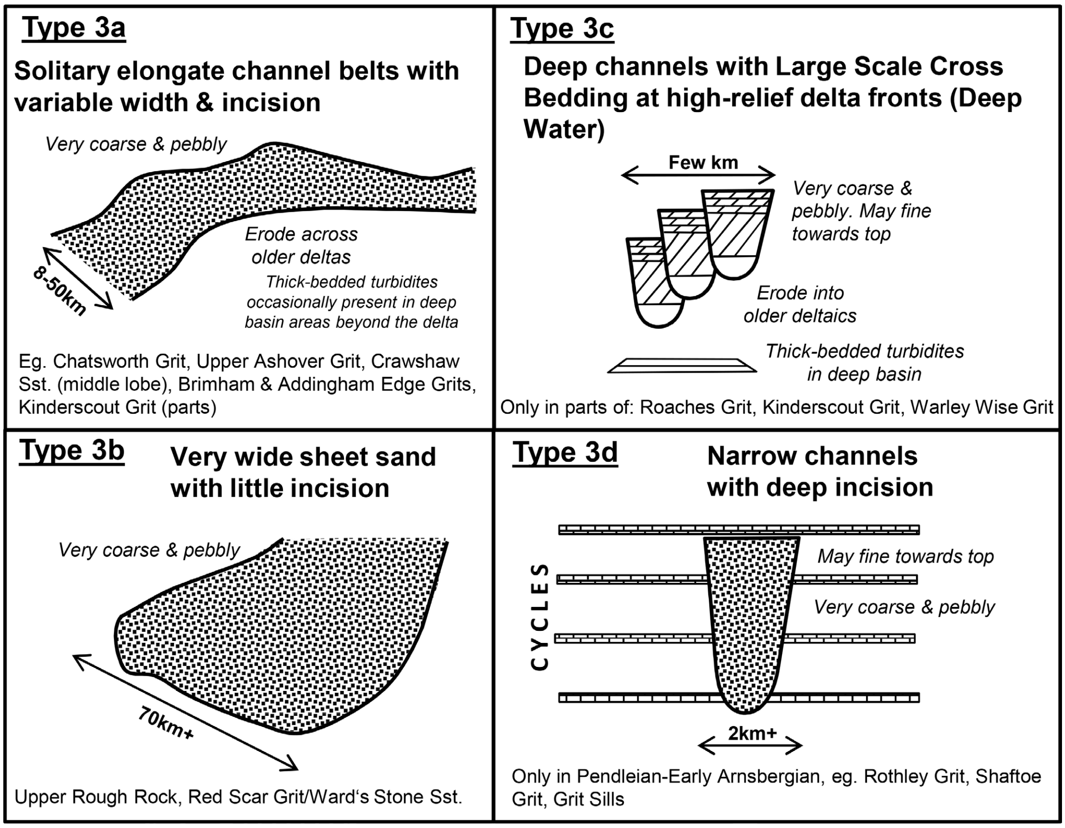


Figure 6. Type 3 delta sequence variations in the Caledonian River System, Pennine Basin.

late Pendleian (E1c), late Kinderscoutian (R1c) and late Marsdenian (R2b5). These channels all developed near the progradational limits of deep-water deltas, marking the first appearance of deltas in previously under-filled deep-water parts of the basin [106].

Type 3*d* (**Figure 6**). Much narrower (c2-4 km) channel fills of middle Pendleian to early Arnsbergian age occur mainly in the Northumberland Trough and adjacent Alston Block (**Figure 2**). Examples include the Grit Sills, Shaftoe Grit and Rothley Grit [45] [107] [108] [109] [110]. These channel fills are also deeply incised but unlike Type 3c, they are not deep water delta deposits and where exposed are clearly some distance back from the original delta fronts.

4.2. Origin and Classification of Sedimentary Cyclothems

The sedimentary succession in northern England has been subdivided into 81 cyclothems (71 in the Namurian), mostly defined by marine bands. This is a slightly higher number than commonly seen in the literature [111] [112], because some of the additional cyclothems recognized in this study are not delineated by marine bands with goniatites. It is now widely accepted that these Northern Hemisphere cyclothems were principally caused by glacio-eustatic sea-level fluctuations [12] [96] [111]. Average cyclothem duration in the interval from Top Serpukhovian (**Table 1**) to Top Namurian (43 cyclothems), using the age dates from [21] (**Table 3**) is 109 Ky. Comparison with the Pleistocene glacial cycles (**Figure 3**) suggests a correlation with 4th order short-eccentricity orbital forcing. Average cyclothem duration for the older interval down to base Namurian again using dates from [21] (28 cyclothems) is 214 Ky. This does not equate to any known orbital forcing periods (**Figure 3**, **Figure 4**), but there may be missing cyclothems in the Pennine and other NW European successions in this interval. It has been suggested [19] that some of the cyclothems in the Serpukhovian are of 400 Ky duration (long-eccentricity). However, other basins with greater subsidence, such as parts of the Midland Valley in Scotland [113] and the West Silesian Basin (**Figure 1**) [114] [115] [116] have additional cyclothems in

Table 3. Recent most likely age estimates for early Upper Carboniferous stratigraphic boundaries (Ma).

	Peterson (2011) *[117]*	*Pointon et al.* (2012) *[118]*	*Davydov et al.* (2012) *[21]*	*Jirásek et al.* (2018) *[116]*	*Cohen et al.* (2018) *[119]*	*Menning* (2018) *[120]*
Top Namurian		319.9	318.5	-	-	-
Top Serp./Miss.	324.42	323.9	323.2	323.2	323.2	320
Base Namurian		-	329.2	330.9	-	
Base Serpukhovian	331.96	-	330.0	330.9	330.9	326.5

this interval,with radiometric dates in the latter indicating an average duration of 92.5 Ky; also consistent with short eccentricity cyclothem lengths.

The relationship between 4th order glacio-eustacy and cyclothem development is complicated by several factors. Preservation of cyclothems is greatest in basins with higher rates of subsidence [121] [122]. Additional cyclothems may result from shorter period 5th order glacio-eustacy (precession and obliquity, **Figure 3**), as well as from autocyclic processes (delta-switching), although the latter tend to be thin and more locally developed. It has been argued that tectonic events may also lead to cyclothems [123], although the author thinks this is uncommon in the Upper Carboniferous.

In the Pennine and adjacent North Sea Basins (**Figure 2**), where sedimentation is dominated by the Caledonian fluvial system, there are two main types of sedimentary cyclothem, simple and complex. All of the cyclothems contain Type 1 deltaic sequences; whilst a third of the cyclothems are complex containing two or three types of sequences (**Figure 7**). The stratigraphic distribution of the simple and complex cyclothems for the entire Namurian and early Langsettian is discussed in detail later in Section 5. Three of the best exposed and best documented complex cyclothems which contain all three delta sequence types are described below.

1) R2b5 Cyclothem (**Figure 8**)*.* The sedimentology of various parts of this cyclothem with later revisions discussing evidence for glacio-eustatic sea-level changes has been described by Jones and Chisholm (1997) [11] Jones (2014) [74] and Jones and McCabe (1980) [104]. The early Type 1 delta sequence (Beacon Hill Flags) was abandoned (sea-level rise?) and succeeded by a Type 2 delta sequence

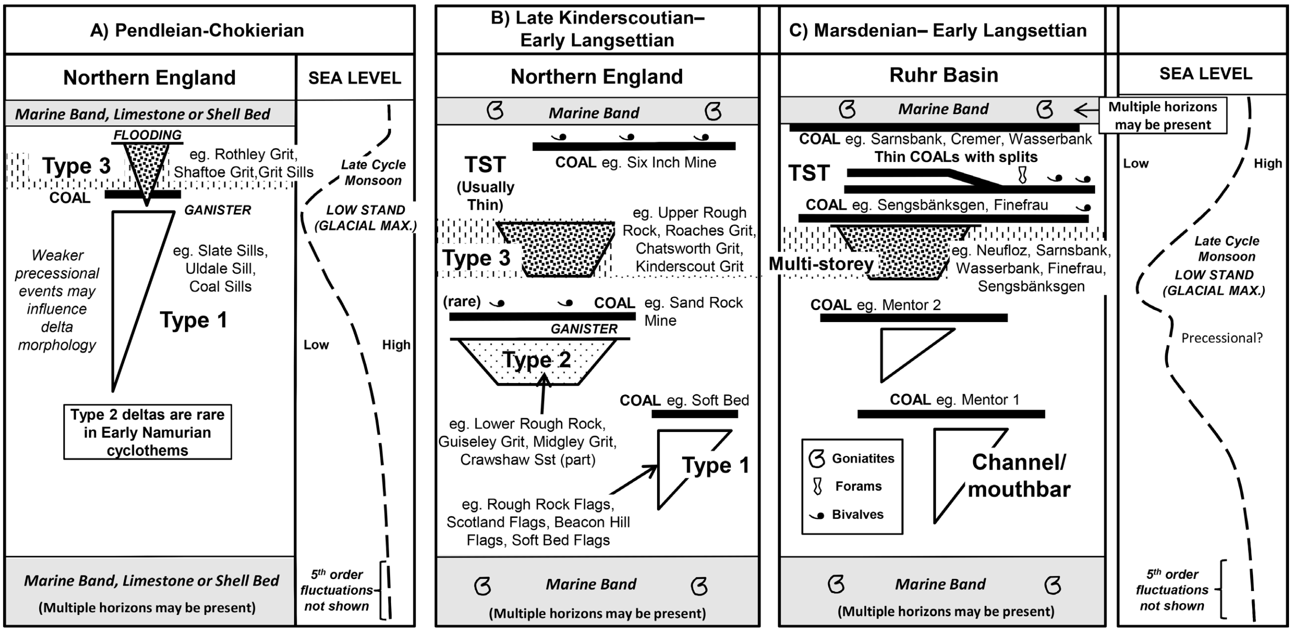


Figure 7. Complex cyclothems of Namurian to Early Langsettian age in the Pennine and Ruhr Basins showing positions of delta sequence types and coals in relation to inferred sea-level fluctuations. (A) and (B) after Jones (this paper) and Jones 2014 [74]. (C) after Hampson *et al.* 1999b [14] and Süss *et al.* 2000, 2002, [15] [16].

(Guiseley Grit). This was interpreted as a forced regression with channels pulled out into the basin during falling sea-level. The sea-level fall led to ganister formation on the previously abandoned Beacon Hill Flags. The overlying Lower Meltham Coal then formed above both the ganister and the Guiseley Grit [124], suggesting another brief sea-level rise. A major avulsion then diverted the delta into the southern Pennine Basin (**Figure 8**) to form a Type 2b, deep water forced-regression delta filling in the remaining basinal areas in Derbyshire (Widmerpool Gulf) and north Staffordshire. A second sea-level fall is inferred and further north a second ganister formed above the Lower Meltham Coal [124]. The coarse and pebbly Upper Roaches and Ashover Grits form Type 3a and 3c channel-dominated delta sequences (**Figure 6**). The thickest parts of this sandbody, preserved near the southern limits of the Roaches and Ashover Grit outcrops (**Figure 8**) were interpreted to be part of an 80 m thick incised valley fill eroded during the lowstand (glacial maximum) [11]. The current view is that the main phase of incision occurred a little later during the ensuing post-glacial sea-level rise, as a result of increased rainfall in the catchment area (see Section 6.2 and [74]). A thick sequence of very coarse sediments was then deposited as a result of accommodation space produced by a combination of fluvial incision, eustatic sea level rise and localized high rates of subsidence caused by sediment loading and compaction of the thick sediment pile at the delta front.

2) G1b Cyclothem (Y4) (**Figure 9**, **Figure 10**) is extensively exposed across the Central Pennine Basin [8] [13] [66] [78] [79] [95] [125] [126] [127]. Previous interpretations of this cyclothem are shown in **Figure 9**. In spite of its complex nature, the same types of deltaic sequences as seen in the older R2b5 cyclothem can be recognised. The Rough Rock Flags (**Figure 9(A)**, **Figure 10**) represent the earliest phase of progradation into the Pennine Basin [78] [79]. This is interpreted as a Type 1 delta sequence, similar to the Beacon Hill Flags described above. Earlier phases in this sequence have been cored in the North Sea in the Trent Field (Quad 43) [128] and other released well data (**Figure 2**). The delta was then abandoned and the overlying flooding surface onshore is overlain (where preserved) by mudstones known locally as the Rough Rock Shale.

The next component of the cyclothem is the Lower Rough Rock, which normally overlies the Rough Rock Flags or Shale [66] [129], but rests unconformably on the Upper Haslingden Flags of the underlying cyclothem in parts of Lancashire [66]. An unconformity is also seen locally in Yorkshire [130] and below the Aqueduct Grit in North Wales [127] This was widespread in NW Europe, being also seen in South Wales [65] [131] and offshore boreholes west of Ireland [132] and unpublished well data. The Lower Rough Rock shows a complex palaeocurrent pattern [78] [79] suggesting a number of mutually eroding channel bodies, their precise order of deposition being uncertain. The channels forming the Lower Rough Rock are interpreted here as a Type 2a (forced regression) delta complex (**Figure 9(B)**). The multi-story nature of the delta channels seen in the Elland Road Cutting (**Figure 9(B)**, **Figure 9(D)**; **Figure 10**) and locally in Lancashire requires either a later sea-level rise or increased subsidence. The culmination of this led to the deposition of the Sand Rock Mine Coal which extensively overlies the Lower Rough Rock in Lancashire. Further east this coal is largely eroded by

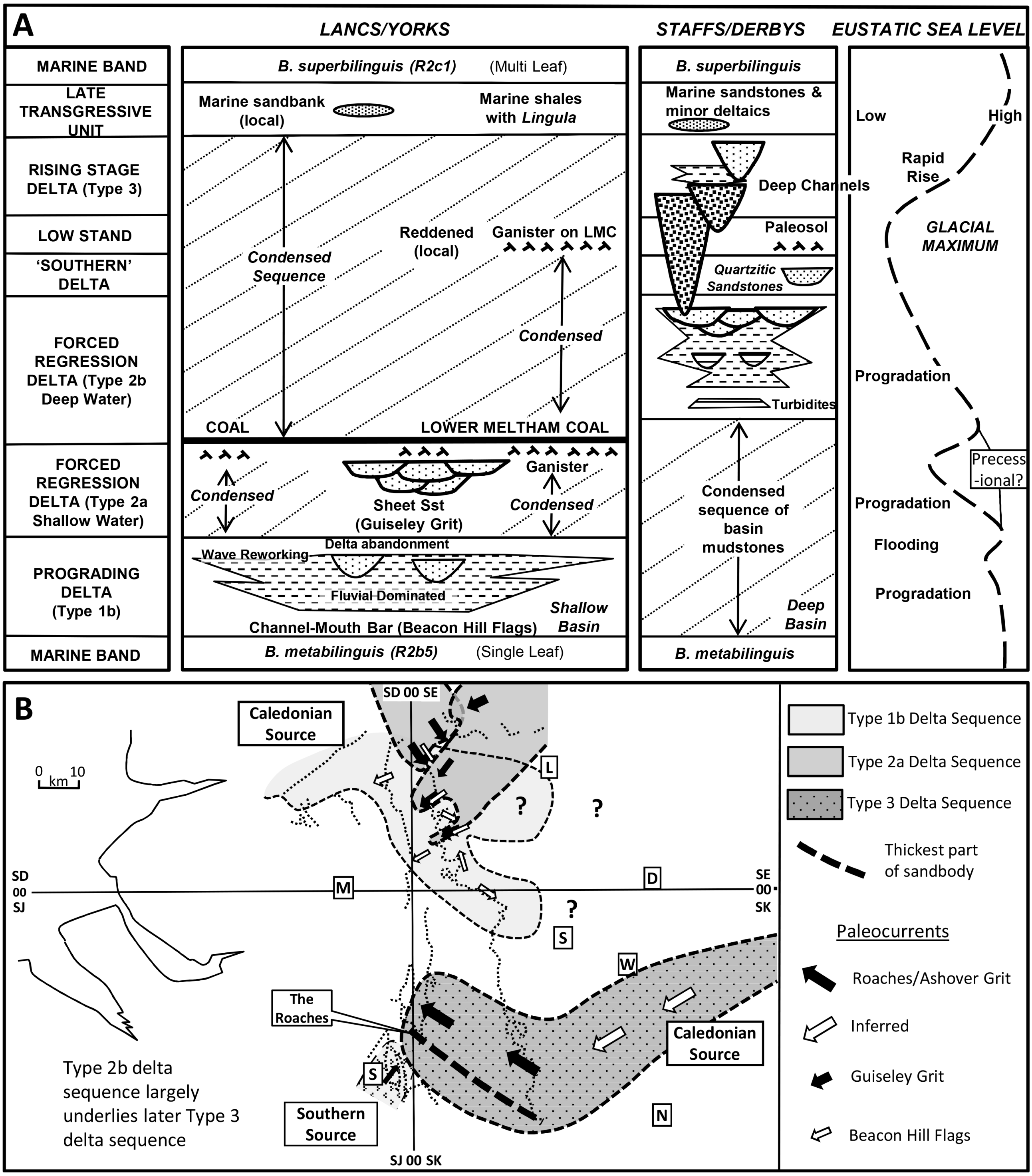


Figure 8. (A) Stratigraphy and delta sequence types in Cycle M8 (R2b5), with inferred sea-level curve. (B) Distribution of delta sequence types in Cyclothem M8 (R2b5) in the Pennine Basin, L-Leeds, D-Doncaster, S-Sheffield, W-Worksop, N-Nottingham, St-Stoke, M-Manchester. Modified from Jones (2014) [74].

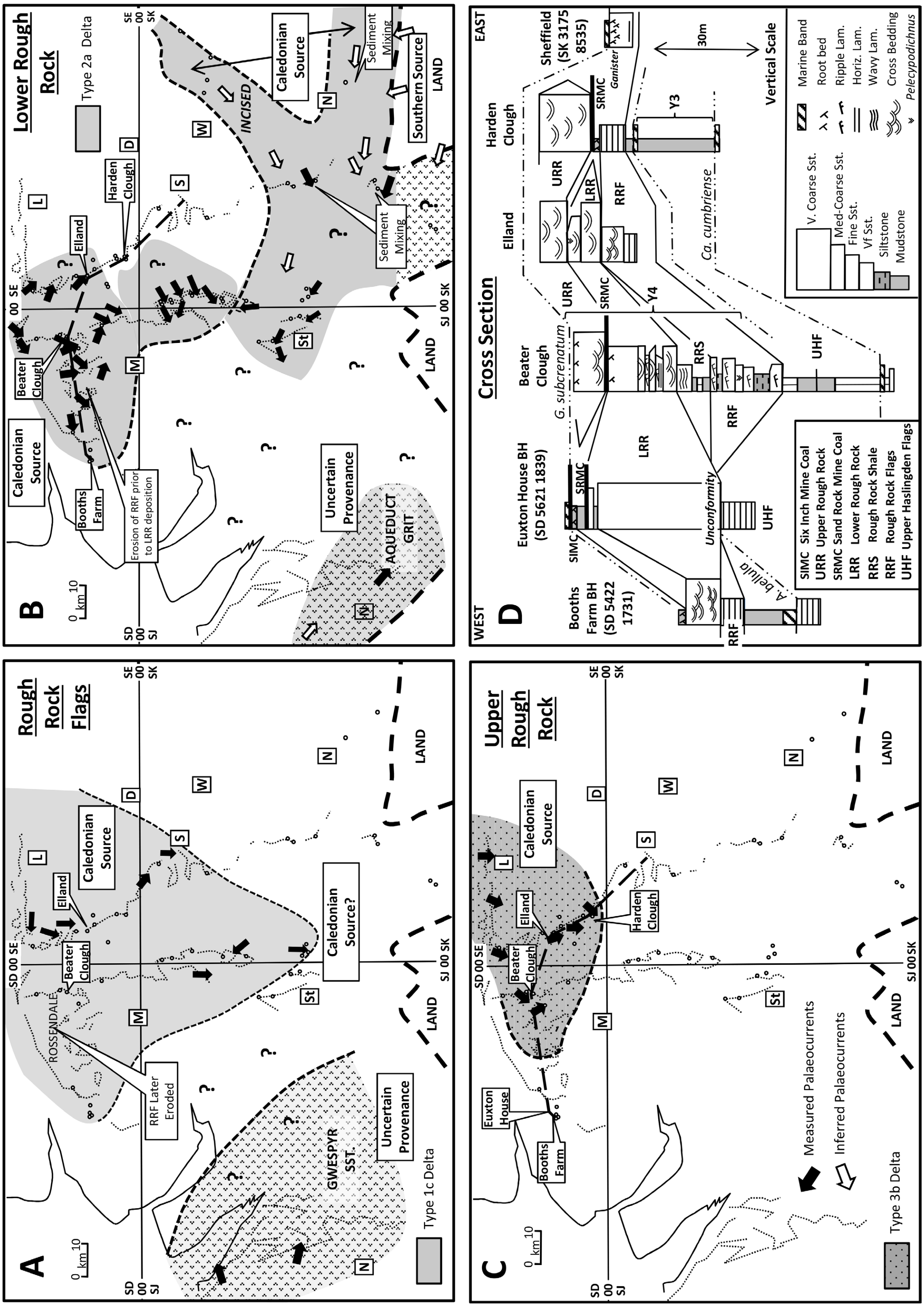


Figure 9. Revised interpretation of the Rough Rock Cyclothem (Y4) showing distribution of delta sequence types in the Central Pennine Basin. Data from Hallsworth and Chisholm (2008, 2017) [54] [61], Morton *et al.* (2014) [62], Bristow (1988) [78], Bristow and Myers (1989) [95], Percival (1983b) [125], Steele (1988) [126], Jerrett and Hampson (2007) [129]. Locations as **Figure 8**.

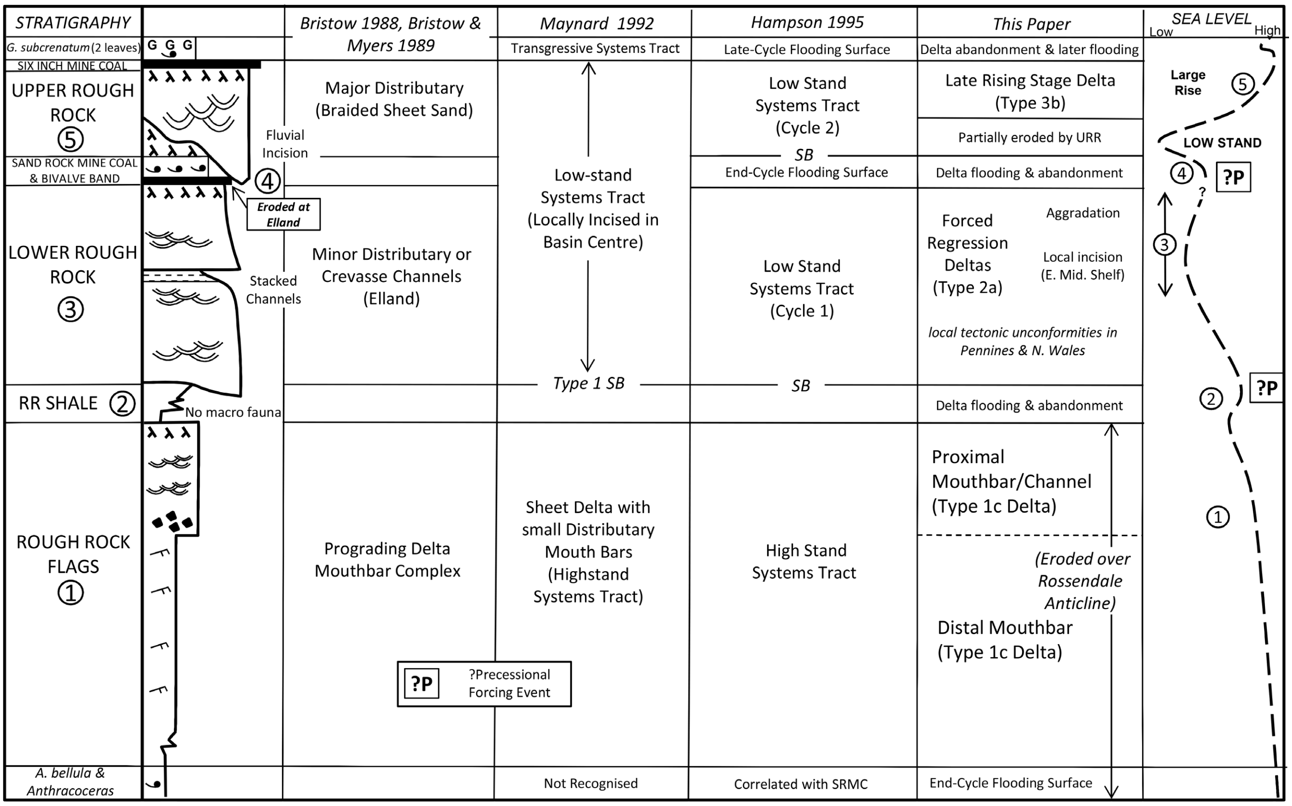


Figure 10. Changing interpretations of the Rough Rock Cyclothem (Y4).

later channels except at Harden Clough in Yorkshire (**Figure 9(D)**). The Lower Rough Rock is commonly exceptionally coarse-grained and pebbly for a Type 2 delta and this could result from the tectonic event seen in the basin also being responsible for uplift in the source area, although climatic effects cannot be excluded.

A mature seat-earth is locally developed above the abandoned delta lobe of the Rough Rock Flags near Sheffield (**Figure 9(D)**) [125]. This is correlated with the eustatic minimum. The Upper Rough Rock, commonly seen to overlie the Sand Rock Mine Coal (**Figure 9(D)**, **Figure 10**) is the coarsest of all the channel systems. This is a sheet-sand 70 km wide and dies out to the south without any significant associated mouth bar (**Figure 9(C)**, **Figure 9(D)**). It is the youngest of the fluvial channel deposits and is interpreted here as a Type 3 delta deposited late in the cyclothem. Following abandonment of this channel the Six Inch Mine coal and its characteristic overlying non-marine bivalve band (**Figure 9(D)**) was deposited during the final stage of the sea level rise.

3) Early Langsettian Cyclothem (L1). The sedimentology of part of this cyclothem in the eastern outcrop area (Crawshaw Sandstone) was first described in [100] which recognized three separate delta lobes. Applying the model discussed earlier suggests a different order of deposition from previously proposed. The northern lobe (Soft Bed Flags) is interpreted here as a Type 1 delta sequence forming the first phase of progradation into the Pennine Basin (**Figure 11**). In Lancashire the mouth-bar dominated Margery Flags which may be of western

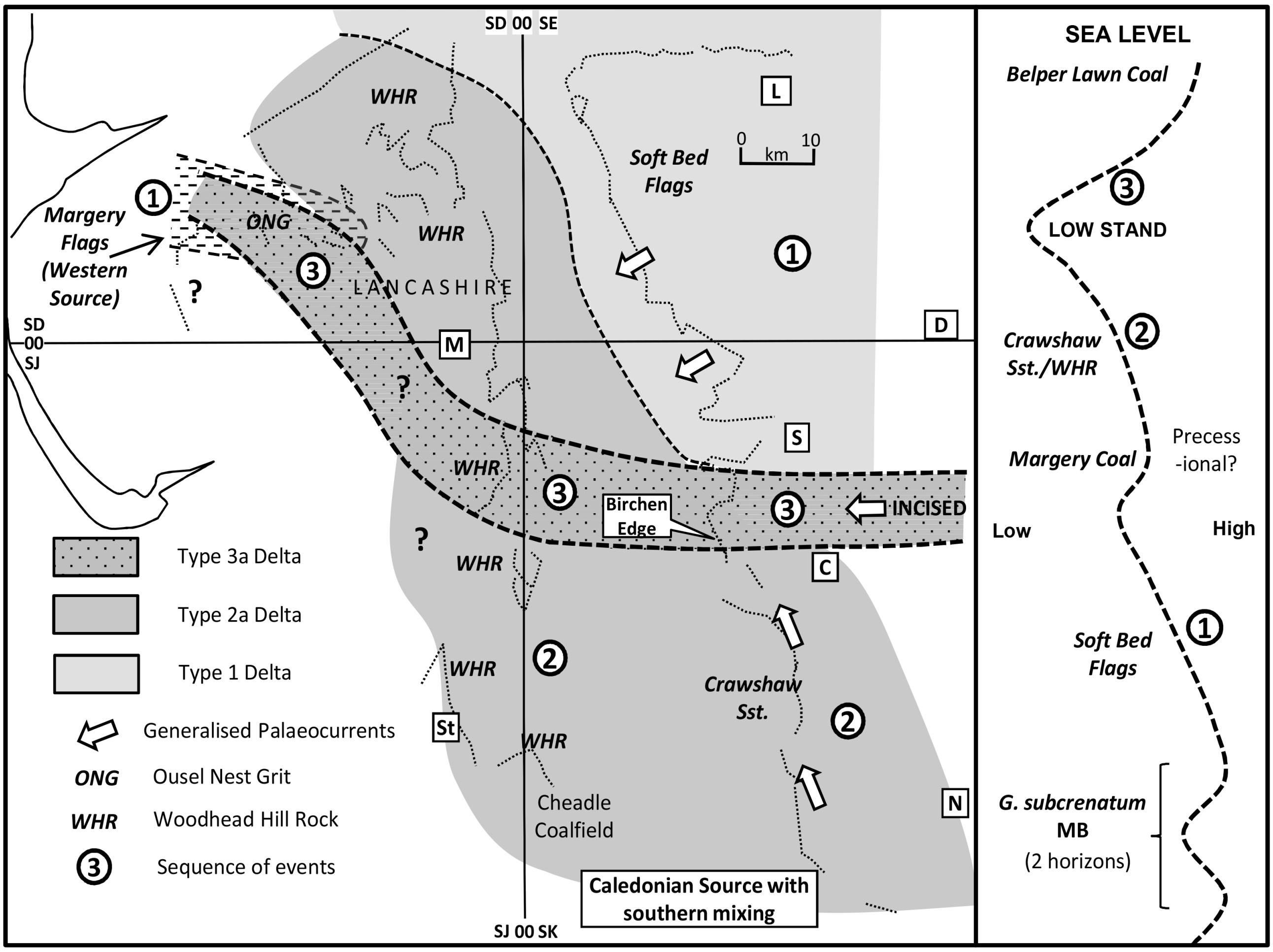


Figure 11. Distribution of delta sequence types in Cyclothem L1 in the Central Pennine Basin. After Guion and Fielding (1988) [100], Hampson *et al.* (1999a) [10], Flint *et al.* (1995) [133] and unpublished field work by the author and J.I. Chisholm. Locations as in **Figure 8**.

provenance (J. I. Chisholm, pers. com.) are probably contemporary. These deltas were abandoned, followed by the deposition of the Margery Coal in Lancashire and possibly the Soft Bed Coal in Yorkshire, although this could, in places be later.

This was followed by the southernmost of the three lobes in the Crawshaw Sandstone [100], medium to coarse grained fluvial channel sandstones, lacking any underlying mouth bar deposits. They are interpreted here as a Type 2a delta sequence. Similar fluvial channel deposits are extensively developed as the Woodhead Hill Rock around the Cheadle Coalfield in Staffordshire and probably in Lancashire (**Figure 11**). The same channel system is probably also seen in the North Sea where an extensive medium grained fluvial sheet-sand forms the main reservoir of the Cavendish gas field (43/19) [134] [135] (**Figure 2**). A later fluvial channel is represented by the very coarse and pebbly middle lobe of the Crawshaw Sandstone, well exposed at Birchen Edge (**Figure 11**) [100] (their **Figure 10**). This is correlated with similar coarse-grained channel sandstones in Lancashire (Ousel Nest Grit), which overlies the Marjery Flags (**Figure 11**).

This fluvial channel fill appears to be deeply incised over the East Midlands Shelf [10] [133] but less so in the basin. It is interpreted as a Type 3a delta sequence.

Complex cyclothems in the earlier Namurian (pre-Kinderscoutian) have been less studied and the main published accounts of their sedimentology are given in [12] [45] and [84]. Further discussion is given in Section 5.

4.3. Ruhr Basin Cyclothems and Deltaic Sequences

The fluvio-deltaic sequence in this basin is Marsdenian and younger [28] [29]. Few palaeocurrent data are available, but the sandbody distribution and pebble types suggest there were probably two sediment sources [14] [68] (**Figure 1**). The dominant source was the evolving Variscan Mountains to the south [15] [16]. These lay in a young fold belt which underwent major late Visean tectonism [67] [136].

Two types of delta sequence are recognized [15] [16]. Mouth-bar dominated delta sequences, not dissimilar to the Type 1 delta sequences in the Caledonian fluvial system, are the primary progradational features (**Figure 7(C)**). These form coarsening-upwards sequences with either proximal mouth-bar or distributary channel fills towards the top. Most are capped by root beds and coals [27] [28]. In addition, many cyclothems contain more extensive coarse-grained and often pebbly multi-story fluvial channel sheet-sands, some of which show significant incision. There have been two theories for the origin of these: 1) Accelerating sea-level fall prior to the low-stand caused the fluvial distributary channels to incise [14]. The channels were then filled during the lowstand; as sea levels stabilised. 2) The channels were both cut and filled during the lowstand [15] [16]. This would allow a possible break between the mouth-bar dominated deltas and later incised channel fills (**Figure 7(C)**). Further discussion is given in Section 6.2.

There are two types of cyclothem; the first containing only mouth bar dominated delta sequences, whilst the second type also contains extensive coarse-grained, multi-story channel deposits as discussed earlier (**Figure 7(C)**). Prograding mouth bar dominated deltas were active earlier within the longer (4th order) cyclothems, the coarser channel fills, seen in some cyclothems, being deposited later. In the Ruhr Basin, where subsidence rates were generally higher than in the Pennine Basin [121], there is commonly a well-developed transgressive sequence deposited in the later part of the cyclothem. These contain thin deltaic sequences capped by coals.

4.4. Marine Bands in NW Europe

Marine bands are commonly highly condensed [137] [138] [139] [140], but internally complex, and are named after the dominant thick-shelled goniatite fauna. Although a majority contain only one thick-shelled goniatite interval, others can have two, eg *G. subcrenatum*, [140]; three, eg *Ca. cancellatum*, [141] and locally up to four intervals with goniatites, eg *B. gracilis*, R2a1, **Figure 12**; [142] [143] [144]. These are interbedded with horizons which are either unfossiliferous, or contain inferred lower salinity faunas [63] [144] [145] [146].

The marine bands formed after the sea level rises caused by end-glacial ice melting flooded the deltas which then retreated back to the basin margins. Thick-shelled goniatites then occupied deeper water areas which developed over regions of greater subsidence (**Figure 2**). The internal faunal complexity of many marine bands is probably related to intra-cycle (5th order?) sea-level fluctuations. The distribution of the four intervals with goniatites within the complex *B. gracilis* band (**Figure 12**) suggests precession (c20Ky in the Carboniferous), or obliquity (35 Ky in the Carboniferous) [38] [147] as possible causes for these sea-level fluctuations, assuming the whole cycle (R2a1) took approximately 100 Ky to deposit (as discussed in Section 4.2). Comparisons with the Pleistocene (Section 2, **Figure 4**) show a much closer correlation between sea-level changes and precession. The marine bands and limestones largely lacking goniatites formed in more slowly subsiding areas with shallower water (**Figure 2**).

The cyclothems in the Ruhr Basin (Section 4.3) contain marine bands with thick-shelled goniatites each of which normally has the same number of thick-shelled goniatite horizons with similar fauna as their counterparts in the UK basins [148] [149].

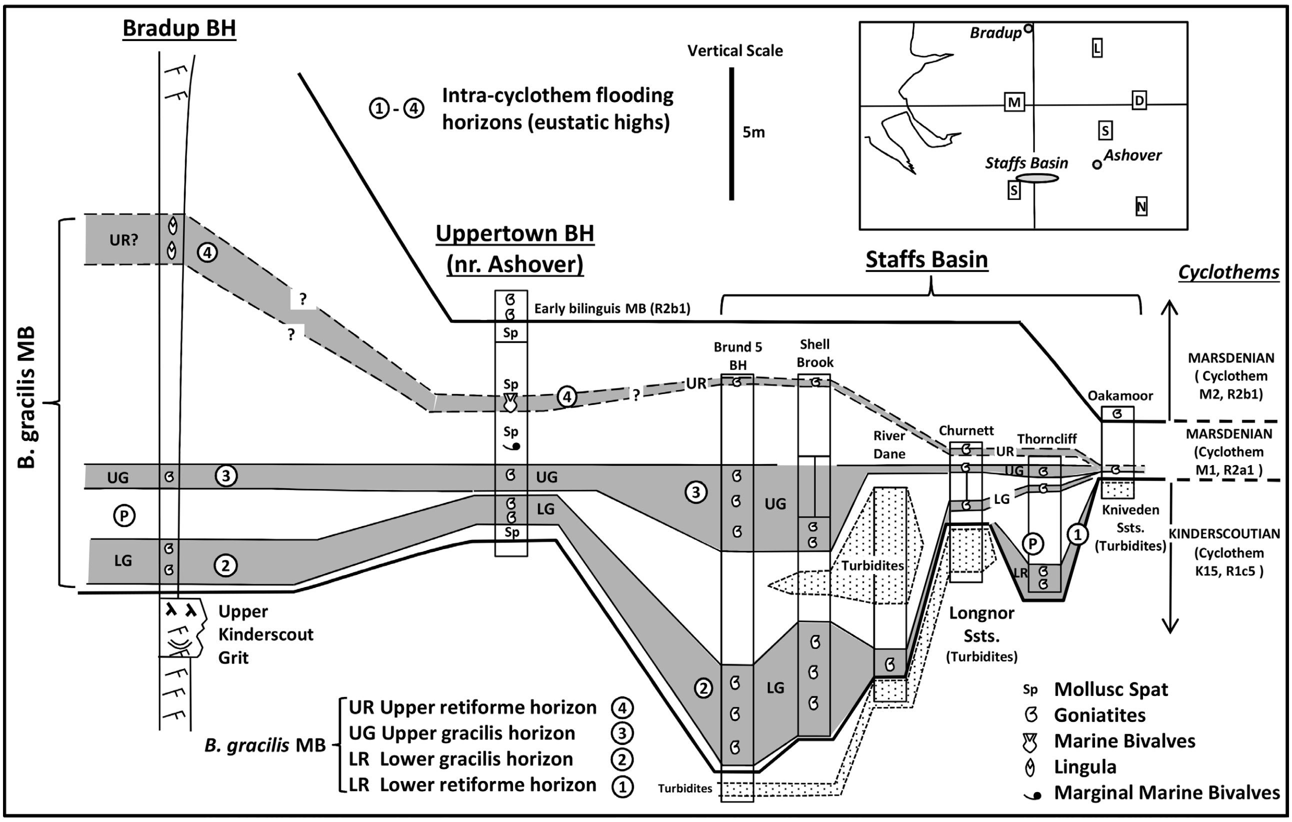


Figure 12. Sections through the *B. gracilis* MB and Cyclothem M1 (R2a1) in northern England; after Aitkenhead and Riley (1996) [142]; Ramsbottom *et al.* (1962) [72]; Ramsbottom (1969) [144]; Ashton (1974) [143].

5. Namurian to Early Langsettian Sedimentary Succession in Northern England and Adjacent Areas of NW Europe

The stratigraphic distribution of cyclothem types is not random and allows the succession to be divided into eight longer period intervals each dominated by either simple or complex cyclothems (**Figure 13**). These intervals are not the same as the mesothems previously described [145], but do have some common boundaries. Additional useful data come from the stratigraphic distribution of goniatite faunas in the condensed pro-delta offshore sequence on the Ashover Shelf in Derbyshire (**Figure 2**). This was described in great detail in three continuously cored boreholes which penetrated most of the Namurian [72] [111]. Later in Section 6.2 it is argued that the eight longer period intervals relate to

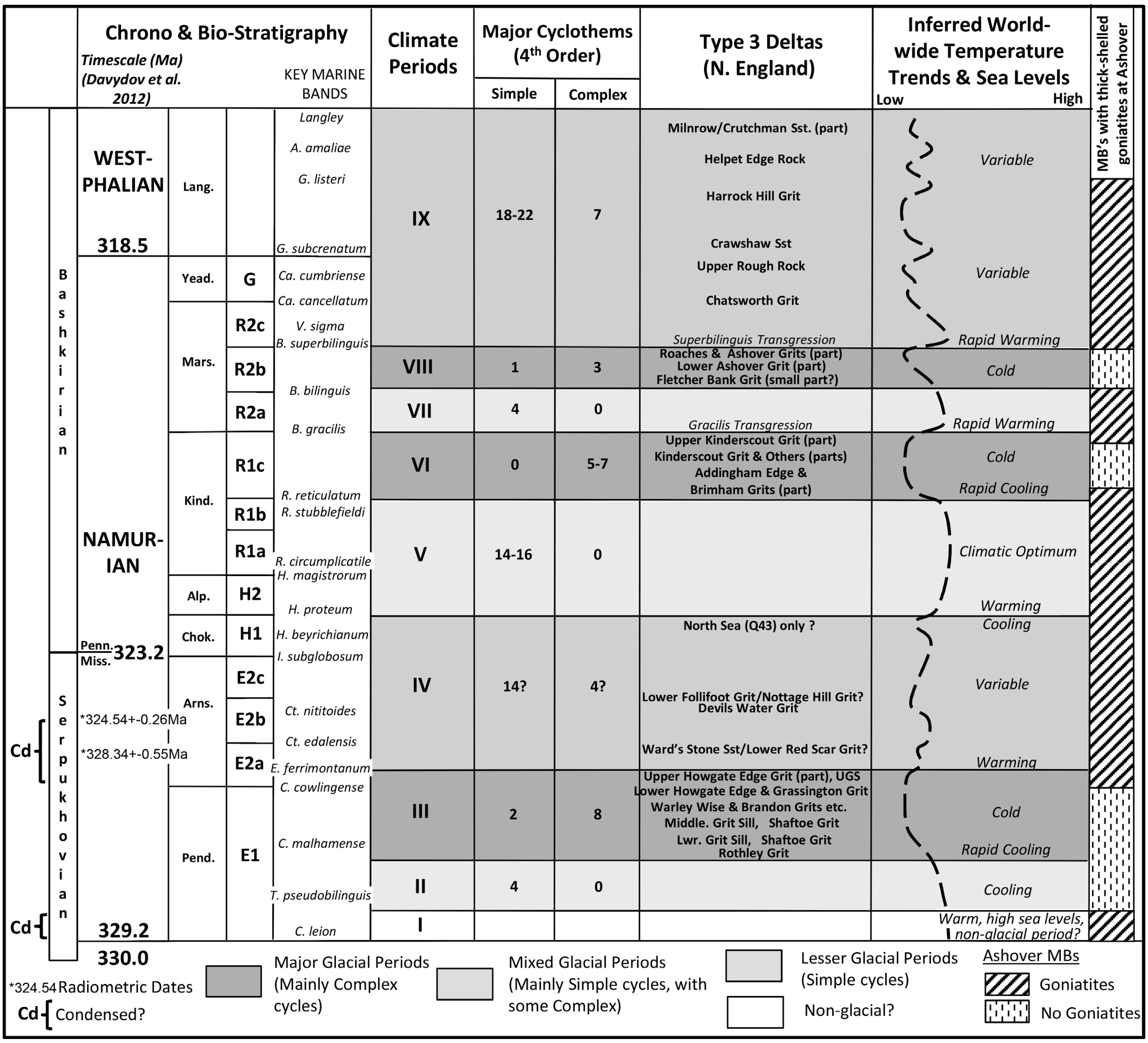


Figure 13. Suggested major climate periods and generalized sea-level curve for the Namurian-Early Langsettian, based on the stratigraphic distribution of simple and complex cyclothems. (Abbreviations as in **Figure 14**).

climatic variations and sea-level fluctuations over longer time periods than those associated with individual glacial cyclothems.

5.1. Pendleian (Figure 14; Cyclothems P1-9)

The base of the Pendleian is here taken at the base of the *Cravenoceras leion* MB in basinal areas and at the base of the Great Limestone north of the Craven Fault (**Figure 2**) [150]. In [151] the base of the Serpukhovian is placed a little lower at the base of the underlying Four Fathom Limestone on the basis of the foraminiferal data in the Seal Sands well in the Stainmore Trough (**Figure 2**).

In the early Pendleian only one cyclothem is traditionally recognized between the *C. leion* and the overlying *C. brandoni* marine bands [152] [153]. However, radiometric dates from the East Silesian and Donetsk Basins [21] [116] suggest a probable time span of c1-2 My for the Lower Pendleian. Therefore, the *C. leion* MB (**Figure 14**) and equivalent Great Limestone further north is likely to be a condensed sequence deposited over a considerable time period [154]. Above the Great Limestone, two prominent early cyclothems are represented by the Lower and Upper Coal Sills [155]. These are interpreted as Type 1 delta sequences.

The most completely exposed section in this interval is seen on the Northumberland coast near Alnwick (**Figure 2**, **Figure 14**) [156]. Additional cyclothems are seen here, but their status remains uncertain. The overlying cyclothems (P3-4) are possibly partly represented in basinal areas by the complex *T. pseudobilinguis* MB. The basinal marine bands rarely contain any interbedded coarser clastics, although in the Duffield borehole (**Figure 2**) turbidites derived from the Anglo-Brabant Massif occur between two of the *T. pseudobilinguis* leaves [157].

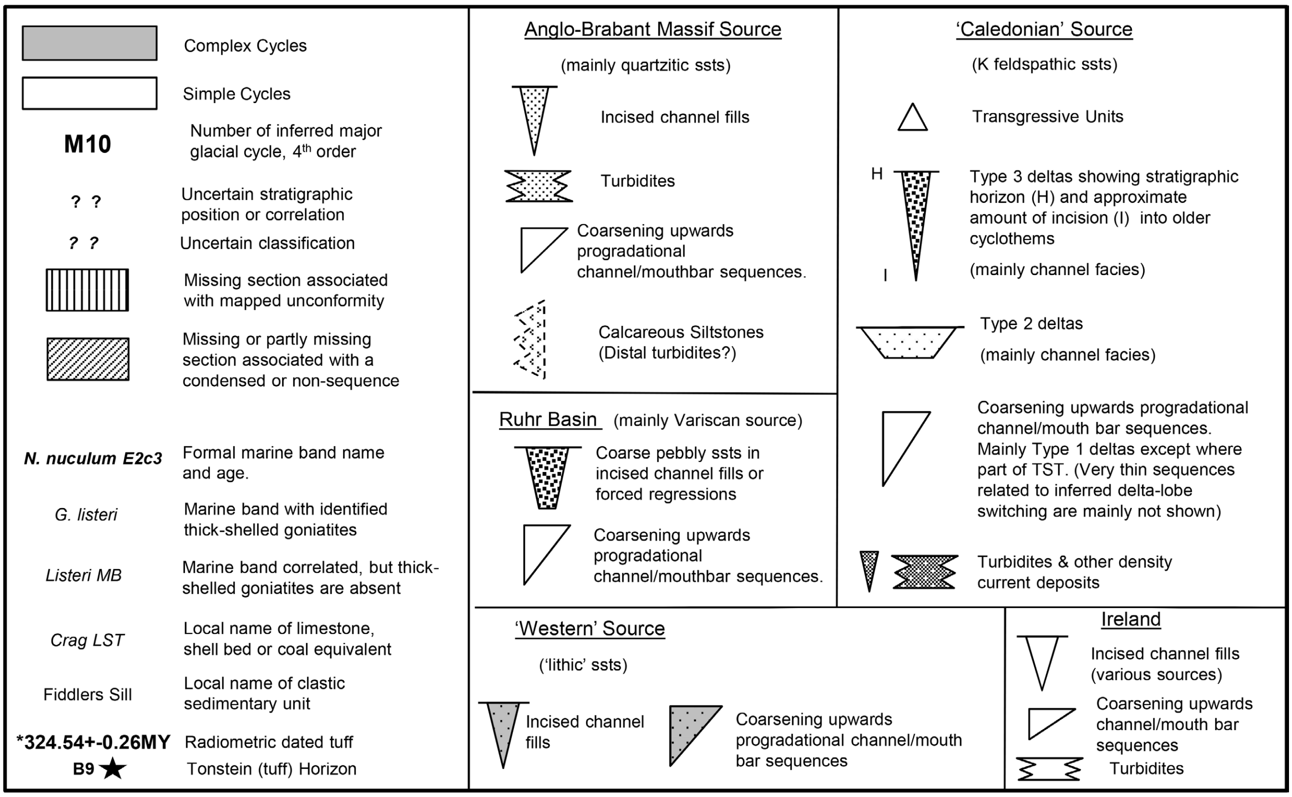
Cyclothem P5 (**Figure 14**) begins with the Uldale Sill and Jackdaw Crags, its stratigraphic equivalent in the Northumberland Trough [85]. On the Askrigg Block the Uldale Sill sits almost on top of the underlying Faraday House Sill, the two sandstones collectively known as the Ten Fathom Grit [158]. A similar situation is seen in the Haltwhistle Burn section in the Northumberland Trough [85] where proximal mouth-bar facies of the Jackdaw Crags sit directly on the Leeshall Quarry Coal from the underlying P4 cyclothem. Cyclothem P5 is the first complex cyclothem seen in the Namurian and the narrow Type 3 delta channel at the top of the cyclothem, the Rothley Grit [108] incises down into a number of older cyclothems (**Figure 14**) [109] [110] [159].

The remaining cyclothems in the Pendleian (P6-12) are also mainly complex. On the Alston Block and Stainmore Trough (**Figure 2**), Type 3 delta sequences are represented by the various Grit Sills (**Figure 14**), which form narrow deeply incised channels cut into earlier Type 1 delta sequences represented by the Slate Sills [45] [107]. Further north in Northumberland; the Shaftoe Grit [45] [108] [109] [110] is composed of at least two narrow incised channels, also interpreted as Type 3 delta sequences. The precise stratigraphic range of this multi-cyclic channel complex is unclear. During this time, thick turbidite sands (Pendle Grit, P6-7) started to fill the deep-water Bowland and Craven Basins [101] [102] [160].

Abbreviations used: in Figures 14-20.

AEG Addingham Edge Grit, AQ Aqueduct Grit, BBG Brocka Bank Grit, BBM Barncroft Bank Member, BBS Brooksbottoms Sst., BES Brown Edge Sst., BHF Beacon Hill Flags, BG Brimham Grit, BHG Botton Head Grit, BLES Blackstone Edge Sst., BS Brockholes Sst., CCG Caley Crags Grit, CG Chatsworth Grit, CL Crag Lst., CMS Cloughton Moor Siltstones, CoG Corbar Grit, CQ Cumbriense Quartzite, CrS Crawshaw Sst., CS Cheddleton Sst., DCS Dure Clough Silstones, DFS Dun Fell Sst., DWG Devils Water Grit, ECG East Carlton Grit, FBG Fletcher Bank Grit, FC Finefrau Conglomerate, FCS Five Clouds Sst., GIF Gull Island Fm., GG Guiseley Grit, GR Ganister Rock, GrG Grassington Grit, GS Grit Sill, GSh Grindslow Shales, HBG Holcombe Brook Grit. HER Helpet Edge Rock, HFS Hack Falls Sst., HHF Howells Head Flags, HHG Harrock Hill Grit, HR Heydon Rock, HWR Huddersfield White Rock, IR Inch Rock, KG Kinderscout Grit, KS Kniveden Sst. LAG Lower Ashover Grit, LCS Lower Coal Sill, LER Loxley Edge Rock, LES Lum Edge Ssts., LHEG Lower Howgate Edge Grit, LHF Lower Haslingden Flags, LFG Lower Follifoot Grit, LFW Lower Farewell Rock, LHEG Lower Howgate Edge Grit, LLQ Lower Leasehall Quartzite, LMC Lower Meltham Coal, LPG Lower Plompton Grit, LRR Lower Rough Rock, LRSG Lower Red Scar Grit, LS Ladgill Sill, LSG Lower Shaftoe Grit, Ment. Mentor, MG Midgley Grit, MiG Middleton Grit, MrG Marchup Grit, MTB MamTor Beds, ONG Ousel Nest Grit, PEG Pickersett Edge Grit, PHG Pule Hill Grit, PS Pendle Shales, RDF Readycon Dean Flags, ReG Revidge Grit, RRF Rough Rock Flags, RR Rough Rock, RSG Red Scar Grit, RG/AG Roaches/Ashover Grit, RoG Rothley Grit, RS Ross Sst., Sarnsb. Sarnsbank, SC Sharpcliffe Conglomerate, Sch. Schieferbank, Schg Schieferbanksgen Sst., Schs Schmiedestrasse Sst., SellS Sellenberg Sst., SG Shaftoe Grit, SHG Shale Grit, SS Sheen Sst., TG Todmorden Grit, THG Tanhill Grit, UBG Upper Brimham Grit, UCS Upper Coal Sill, UGSh Upper Grindslow Shale, UHF Upper Haslingden Flags, UHEG Upper Howgate Edge Grit, UKG Upper Kinderscout Grit, UPG Upper Plompton Grit, URR Upper Rough Rock, URSG Upper Red Scar Grit, WBG Walker Barn Grit, WFG Waddington Fells Grit,, WH White Hazle, WHR Woodhead Hill Rock, SF Scotland Flags, WSS Ward's Stone Sst., WWG Warley Wise Grit.

The latest Pendleian (P9-P11, late E1c) contains a series of very coarse-grained and pebbly Type 3 delta channels, the Warley Wise and Grassington Grits plus local stratigraphic equivalents (**Figure 14**) [101]. Both [12] and [102] interpreted this sequence as a major incised valley complex. However, the present author follows [150] and many earlier publications which showed that there is a major tectonic unconformity caused by uplift between cycles P8 and P9 on the Askrigg Block and probably also in the Bowland Basin to the south (**Figure 2**) [161]. The sequence contains up to three sedimentary cyclothems (P9-11) developed over the southern part of the Askrigg Block [150] and the Craven Basin [101], all



Key to Figures 14-17 & 19-20.

containing very coarse-grained pebbly sandstones interpreted as Type 3 delta channel complexes.. On the northern part of the Askrigg Block only the uppermost of these channels persists, the 15 km wide, Lower Howgate Edge Grit [150], which can be traced northwards into the Stainmore Trough [162] (**Figure 2**, **Figure 14**). Further south, in deeper water areas, this interval is probably stratigraphically equivalent to the very coarse and highly channelised turbidites of the Pendle Grit in the Waddington Fell outlier in the Bowland Basin [163]. The turbidite Minn Sandstones in the Staffordshire Basin [63] [164] [165] were also deposited in part during this period. In the final cyclothem, P12 (**Figure 14**) the Bradley Flags a mouthbar dominated (Type 1) delta sequence is developed in the Harrogate Basin (**Figure 2**).

This interpretation suggests the Pendleian contains more cyclothems than traditionally recognized [19] [111]. Other early Namurian basins with higher subsidence rates such as the Kincardine Basin in the Midland Valley Scotland [113] (**Figure 1**) and the West Silesian Basin [116] (**Figure 1**) contain even more cyclothems.

5.2. Arnsbergian (Figure 14, Figure 15; AR1-15)

The first cyclothem (AR1) (**Figure 14**) includes the Upper Howgate Edge Grit, interpreted by [12] as an incised channel complex. Isopachs of this interval [86] suggest a series of separate channels with variable orientations. These cut into an attenuated mouth-bar sequence and the grit overall is interpreted as a Type 1

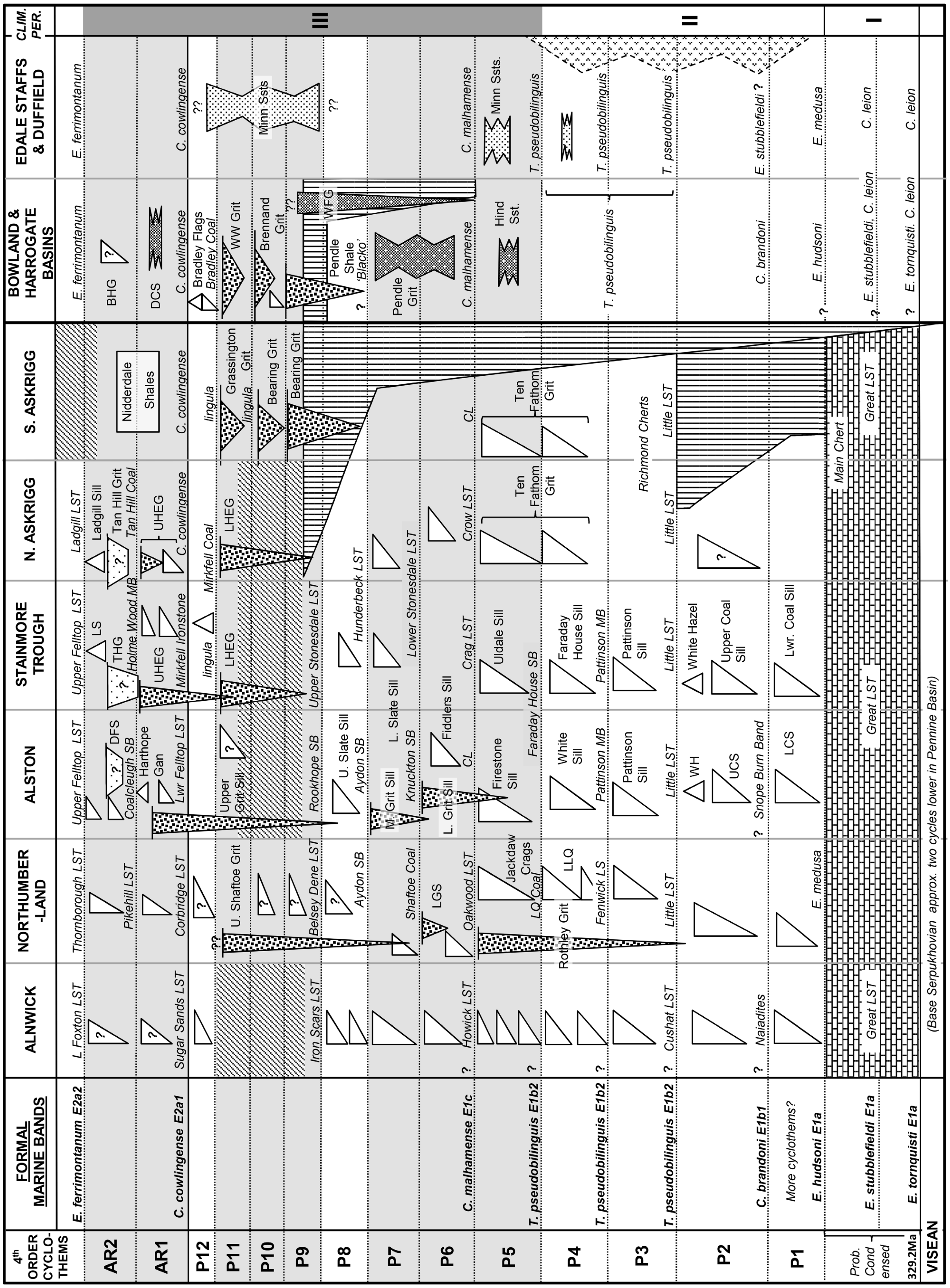


Figure 14. Cyclothems in the Pendleian and early Arnsbergian. Marine band stratigraphy for this and succeeding Figs. largely based on: Ramsbottom *et al.* (1962) [72]; Ramsbottom (1979) [145]; Ashton (1974) [143]; Holdsworth & Collinson (1988) [111]; Brandon *et al.* (1998) [84].

delta sequence. On the Alston Block (**Figure 2**), another very coarse channel in the same cyclothem (Upper Grit Sill) incises through the Lower Felltop Limestone, the basal Arnsbergian flooding surface [45] [107] [166] [167]. These last two channels are also interpreted as probable Type 3 sequences. In the overlying cyclothem (AR2) the Tan Hill Grit on the Askrigg Block is a fluvial channel sheet-sand [12]. This is another forced regressive deltaic sequence (Type 1d or 2a).

The rest of the Arnsbergian succession in northern England contains predominantly simple cyclothems (**Figure 15**, AR3-5, 7-10, 13-15). There are only three complex cyclothems in this interval, the Lower Red Scar Grit and lateral equivalents; the Pickersett Edge Grit, and part of the Ward's Stone Sandstone in the Bowland Basin [84] [153]. In [12] this was interpreted these as an incised valley-fill complex, but there is now thought to be a tectonic unconformity below these sandstones [84] [153]. They are coarse, locally very coarse and pebbly, and are interpreted as a probable Type 3 delta sequence.

The succeeding interval (Caton Shales) contains at least four cyclothems, (**Figure 15**, AR7-10) in which deltaic sediments are largely absent from the Pennine Basin [84]. Radiometric dates from the Pennines [19] [118] and stratigraphic equivalent section in the West Silesian Basin (**Figure 1**) [116] suggest a significant time span for this interval (Section 4.2). Compared to the more rapidly subsiding West Silesian Basin, it appears to be condensed in the UK Pennines, with many missing cyclothems. Following on from this episode, in Cyclothem AR11 (**Figure 15**), the Devils Water river section in Northumberland contains a very coarse pebbly sandstone channel [45], interpreted here as another Type 3 delta sequence.

A third complex cyclothem (AR12) contains the Lower Follifoot Grit. This is a coarse-grained fluvial channel sheet-sand that occupies a wide area across the Askrigg Block and Harrogate Basin (**Figure 2**). Further south, the Nesfield Sandstone, a wave-dominated mouth bar [12] is probably in this cycle, forming part of the early Type 1 sequence (**Figure 15**). The rest of the Arnsbergian sequence contains three simple cyclothems (**Figure 15**, Cyclothems AR13-15), including the locally wave-modified mouth bar of the Middleton Grit [12] and the Silverhills Sandstone in Lancashire [84]. The youngest three Arnsbergian marine bands all have *N. nuculum*. North of the Craven Fault this interval is extremely thin or absent due to condensation, believed to have been caused by low rates of subsidence.

5.3. Chokierian to Mid Kinderscoutian (Figure 16, Figure 17; Cyclothems CH1-6, AL1-6, KI-10)

North of the Craven Fault much of the interval is missing or very highly condensed. Not all of the flooding intervals which overlie the deltaic sequences in this area contain thick-shelled goniatites. As a result, correlation across the region is still uncertain and the precise stratigraphic horizon of several of the named deltaic sequences remains unclear. In the offshore North Sea Basin

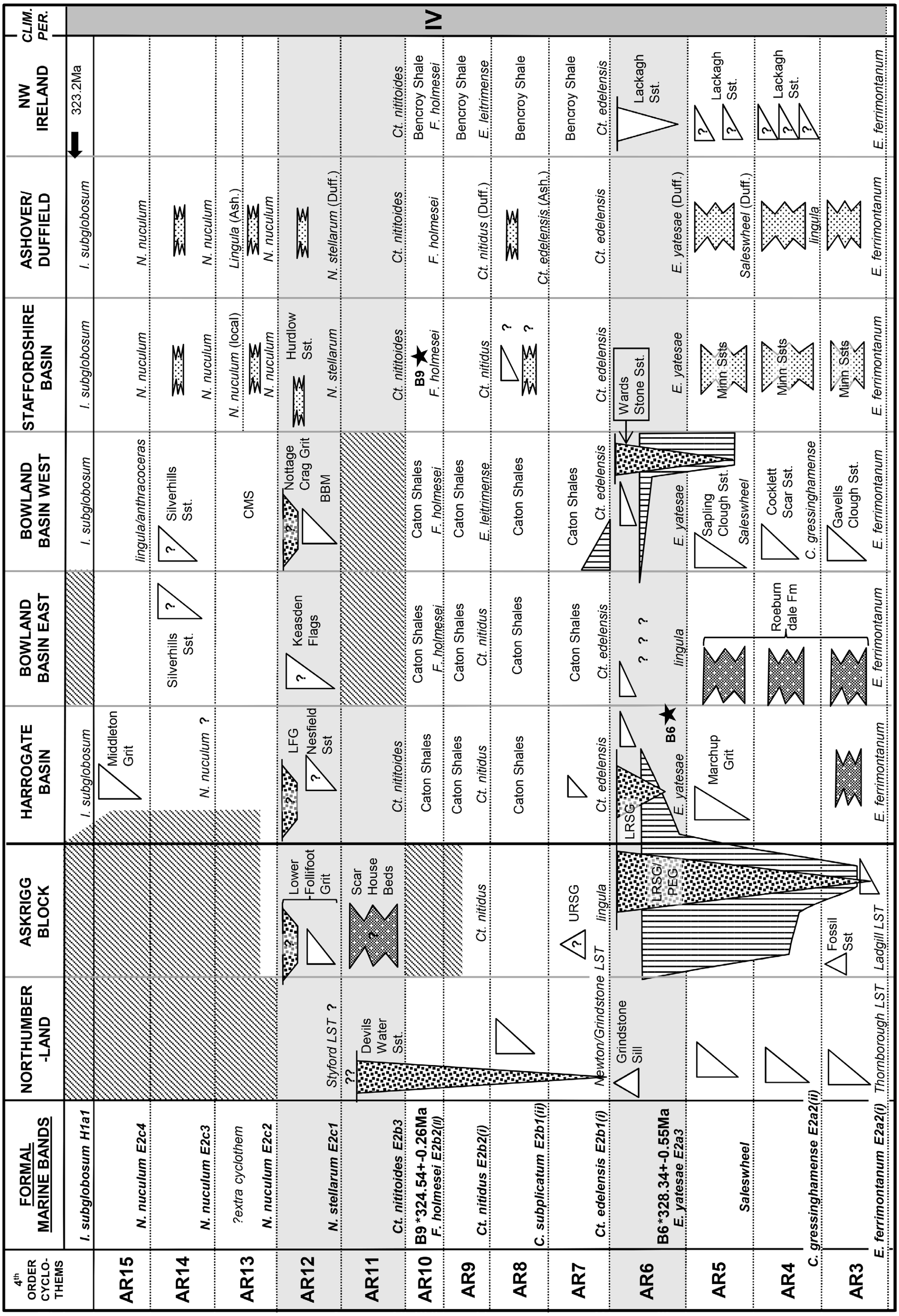
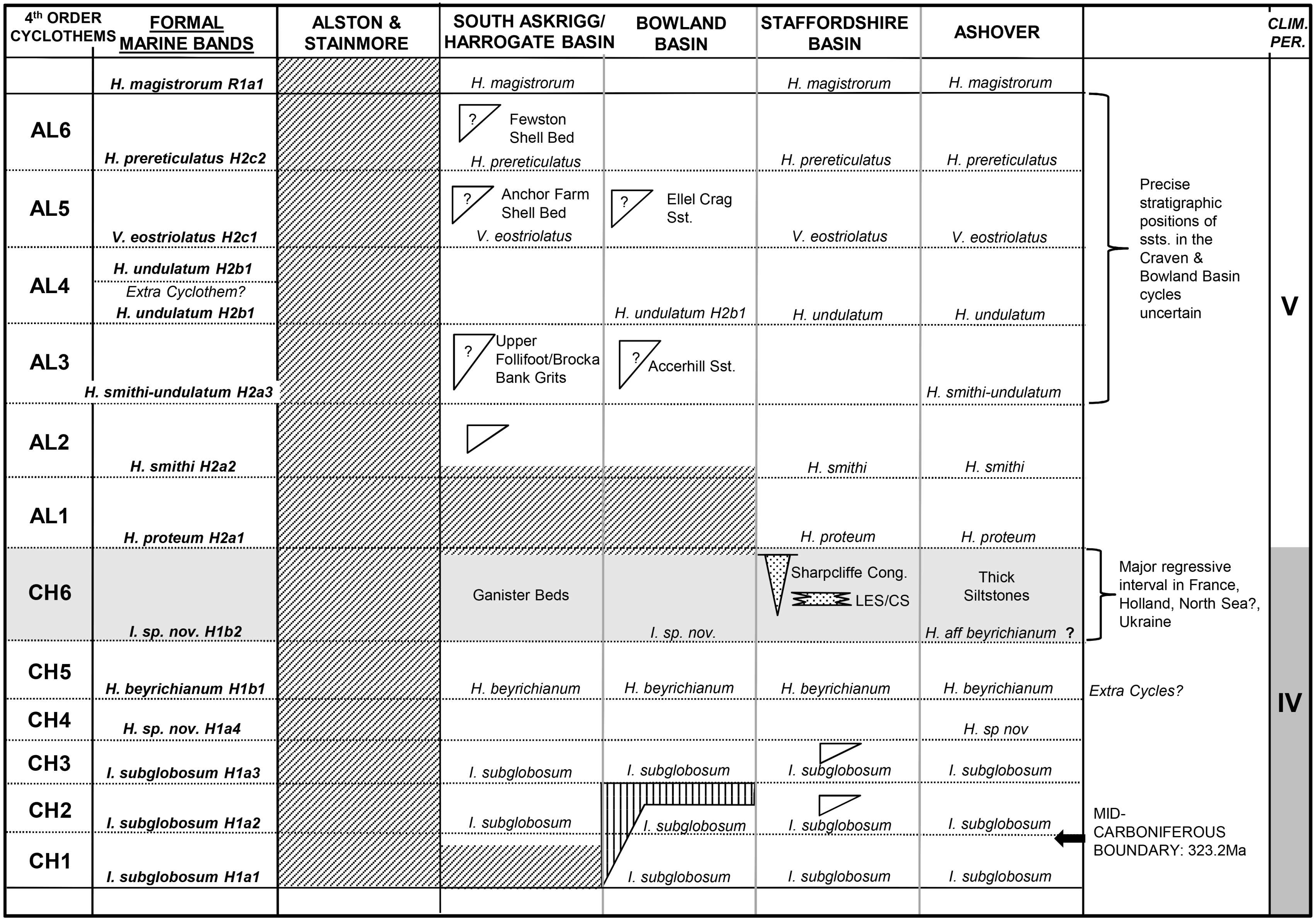


Figure 15. Cyclothems in the Arnsbergian, (see **Figure 14** for abbreviations). Radiometric dates from the B6 and B9 bentonites revised by Pointon *et al.* (2012) [118] and Waters and Condon (2012) [19].



4th ORDER CYCLOTHEMS	FORMAL MARINE BANDS	ALSTON & STAINMORE	SOUTH ASKRIGG/ HARROGATE BASIN	BOWLAND BASIN	STAFFORDSHIRE BASIN	ASHOVER		CLIM. PER.
	H. magistrorum R1a1		*H. magistrorum*		*H. magistrorum*	*H. magistrorum*		
AL6	**H. prereticulatus H2c2**		? Fewston Shell Bed *H. prereticulatus*		*H. prereticulatus*	*H. prereticulatus*	Precise stratigraphic positions of ssts. in the Craven & Bowland Basin cycles uncertain	**V**
AL5	**V. eostriolatus H2c1**		? Anchor Farm Shell Bed *V. eostriolatus*	? Ellel Crag Sst.	*V. eostriolatus*	*V. eostriolatus*		
AL4	**H. undulatum H2b1** *Extra Cyclothem?* **H. undulatum H2b1**			*H. undulatum H2b1*	*H. undulatum*	*H. undulatum*		
AL3	**H. smithi-undulatum H2a3**		? Upper Follifoot/Brocka Bank Grits	? Accerhill Sst.		*H. smithi-undulatum*		
AL2	**H. smithi H2a2**				*H. smithi*	*H. smithi*		
AL1	**H. proteum H2a1**				*H. proteum*	*H. proteum*		
CH6	**I. sp. nov. H1b2**		Ganister Beds	*I. sp. nov.*	Sharpcliffe Cong. LES/CS	Thick Siltstones *H. aff beyrichianum* **?**	Major regressive interval in France, Holland, North Sea?, Ukraine	**IV**
CH5	**H. beyrichianum H1b1**		*H. beyrichianum*	*H. beyrichianum*	*H. beyrichianum*	*H. beyrichianum*	*Extra Cycles?*	
CH4	**H. sp. nov. H1a4**					*H. sp nov*		
CH3	**I. subglobosum H1a3**		*I. subglobosum*	*I. subglobosum*	*I. subglobosum*	*I. subglobosum*		
CH2	**I. subglobosum H1a2**		*I. subglobosum*	*I. subglobosum*	*I. subglobosum*	*I. subglobosum*	MID-CARBONIFEROUS BOUNDARY: 323.2Ma	
CH1	**I. subglobosum H1a1**			*I. subglobosum*	*I. subglobosum*	*I. subglobosum*		

Figure 16. Cyclothems in the Chokierian and Aportian, (see **Figure 14** for abbreviations).

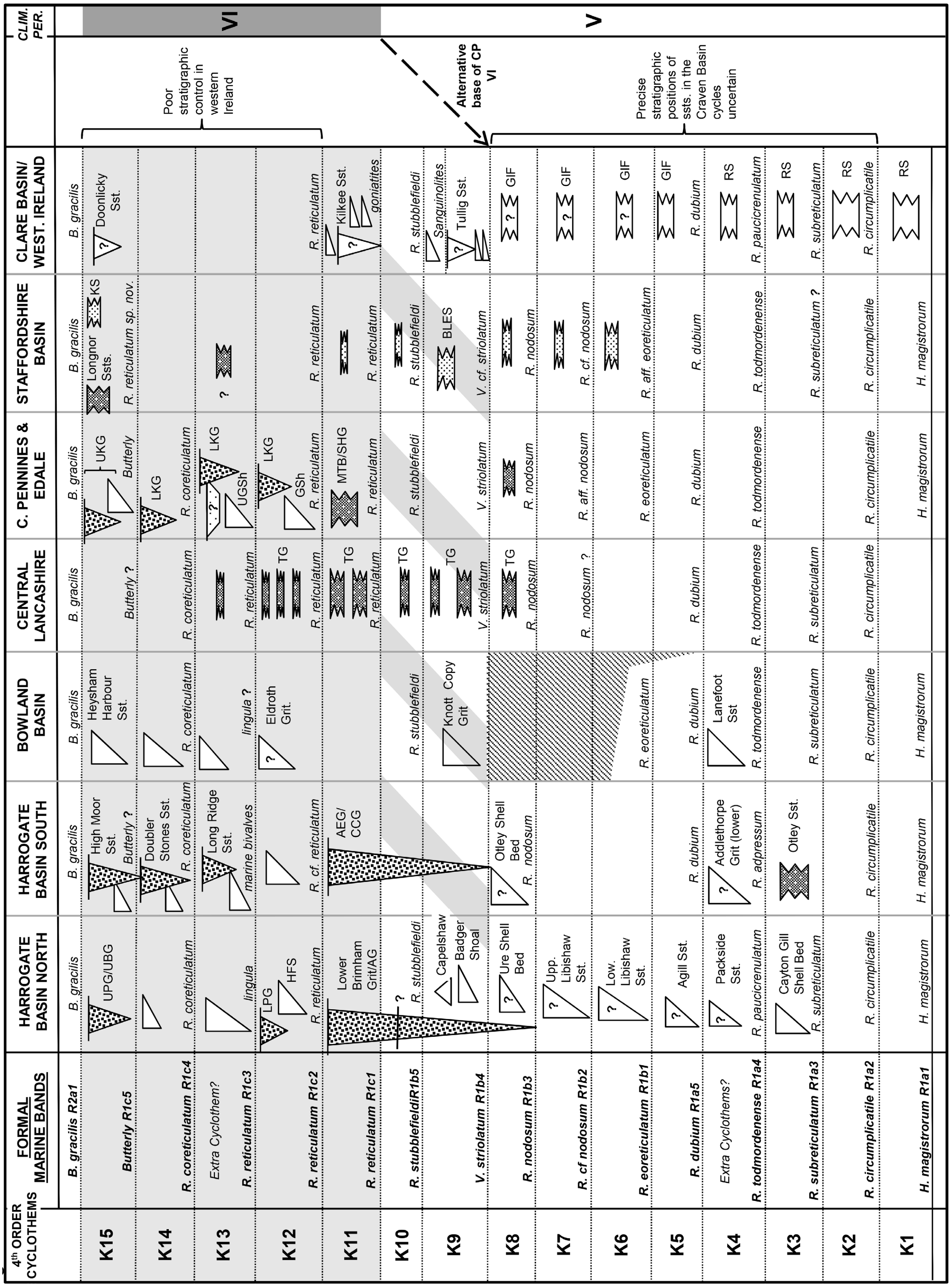


Figure 17. Cyclothems in the Kinderscoutian, (see Figure 14 for abbreviations).

(**Figure 18**), most cyclothems cannot be dated precisely because of the scarcity of goniatite information. However, the limited well log and core data suggest that the cyclothems are not significantly different; in particular, as in the onshore succession there is a shortage of thick channel sandstones that are characteristic of Type 2 and Type 3 delta sequences.

All but one of the twenty two cyclothems in this interval in the Pennine Basin contain only Type 1 sequences. However, the last cycle in the Chokierian (CH6) is unusual, with widespread evidence for a significant sea-level drop [111] (**Figure 16**) in the Staffordshire Basin, where a deltaic sequence, the Sharpcliffe Conglomerate is present [168]. This is one of the most extensive of all the Namurian deltas derived from the Anglo-Brabant Massif. In the Ashover boreholes (**Figure 2**) succession, the cyclothem contains a lithologically unusual sequence of siltstones, 5 - 7 m thick, containing several horizons with *Posidonia* [72]. These are regarded as a shallower water interval than most of the Ashover succession. No Type 3 delta sequence is seen, but well developed soil horizons, the "ganister beds" [169] occur on the Askrigg Block, suggesting a period of incision somewhere in the basin.

A major regressive sequence is also seen in this cycle in northern France, represented by the Grés de Suchmont and Zone des Murs [170]. In the Aachen Basin (**Figure 1**) this regressive interval is represented by the Burgholzer Conglomerate [171]. In the Donetsk Basin (**Figure 1**) an extensive erosive fluvial channel sandstone [20] may be of the same age. In the Pennine Basin, the overlying cyclothems (**Figure 16**, **Figure 17**; AL1-6, K1-10) up to the Late Kinderscoutian are all simple.

5.4. Late Kinderscoutian (Figure 17; Cyclothems K11-15)

This interval contains at least five complex cyclothems, which in the Pennine Basin are dominated by laterally extensive and commonly deeply incised Type 3 delta channels known as the Kinderscout Grit and local stratigraphic names (**Figure 17**). In the Irish Clare Basin (**Figure 1**, **Figure 17**) the first incised channel-fill (Tullig Sst.) appears in Cyclothem K9 [172]. Therefore, the major sedimentological change associated with the appearance of these major incised channels and associated turbidites probably took place in late R1b, but incised channel fills did not appear in the Pennine Basin until two to three cycles later. In the North Sea (Quads 43 & 44) the incoming of these thick and coarse channel sands is very obvious in gamma ray logs from wells such as 43/21-2, 43/24-1 and 43/25-1 (**Figure 18**). However, because of the absence of goniatite data the precise cyclothem in which these are first seen cannot be determined.

After late Kinderscoutian Cyclothem K12 (**Figure 17**) the delta then migrated southwards from Yorkshire into Derbyshire (**Figure 2**) as the deep Central Pennine Basin was filled by thick deltaic slope sequences [9] [80] [173] [174] [175]. Many of the Type 3 delta channels in this progradational phase contain very

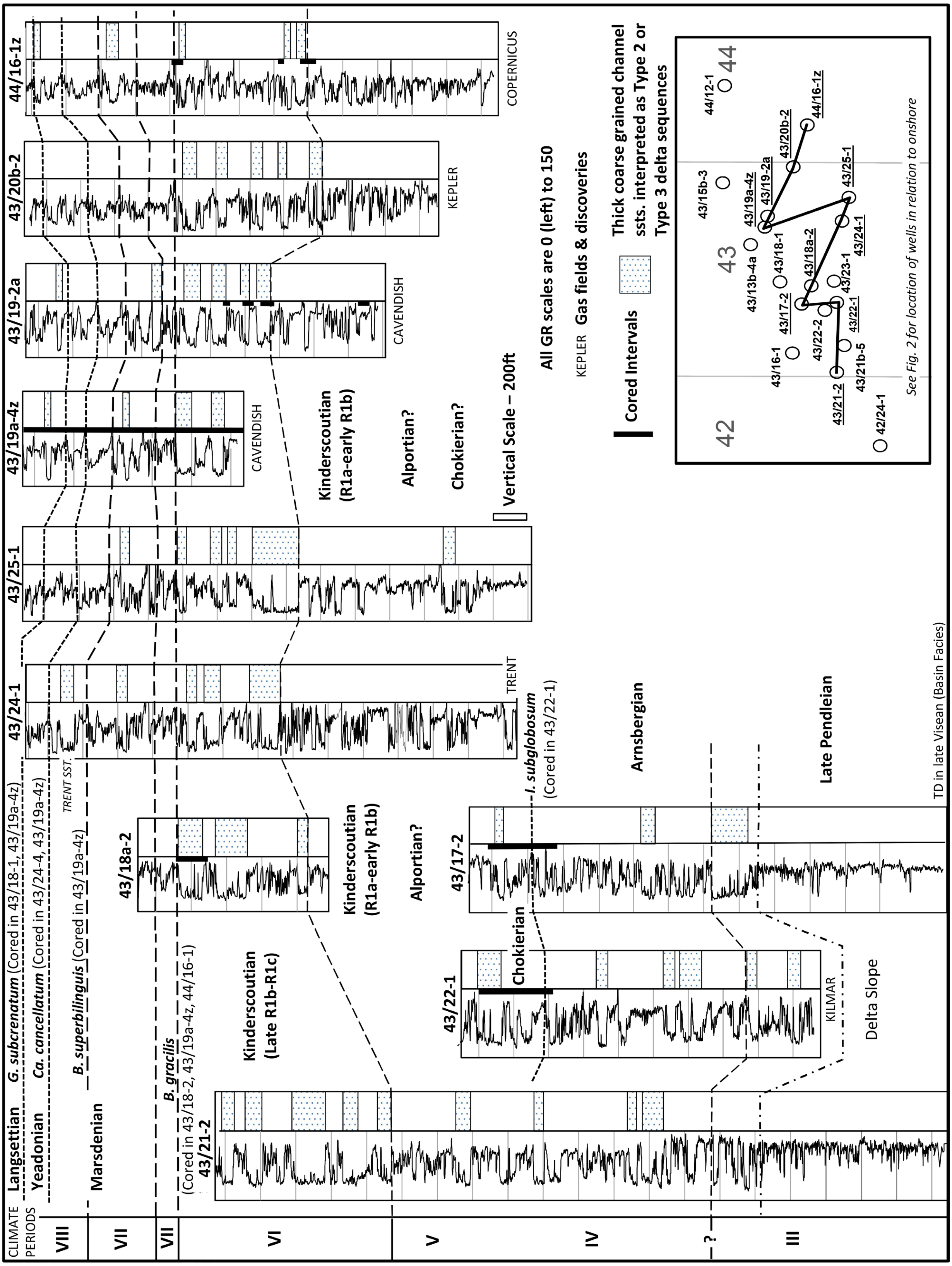


Figure 18. Namurian gamma ray log correlation through wells in Quads 43 and 44, UK North Sea, showing the distribution of the thickest and coarsest channel sand bodies (inferred Type 2 and Type 3 delta channels) in relation to the major climatic intervals identified in the correlative onshore sequence.

large cross-beds [103] [104]. Type 1 delta sequences, developed in the earlier parts of the cyclothems are seen in the Grindslow Shales in Derbyshire [80], plus references cited above; and in the Bowland Basin [84] [142]. Similar sequence types are also seen offshore in wells marginal to the main channel belt such as 44/16-1 (**Figure 18**). No Type 2 delta sequences have yet been recognized, their preservation potential being low due to the extensive Type 3 delta channels developed towards the ends of the five late Kinderscoutian cycles.

In Belgium this regressive interval is represented by thick fluvial conglomeratic sandstones of the Grès d'Andenne [176] [177]. In the Aachen Basin (**Figure 1**), the Gedauer Conglomerate, which contains very large reworked chert boulders, is also within R1c [171]. At Ashover (**Figure 2**) [72] goniatites are lacking in the R1c2, 3 and 4 marine bands (**Figure 13**). The final cyclothem above the Butterly MB (K15-R1c5) contains a Type 1 delta sequence with *Olivellites* (a.k.a. *Psammichnites*) in the mouth-bar facies [178] and a later Type 3 delta sequence of the Upper Kinderscout Grit [9].

5.5. Marsdenian and Yeadonian (Figure 19, Figure 20; Cyclothems M1-13, Y1-4)

The major late Kinderscoutian coarse grained interval (**Figure 18**) ends with the complex *B. gracilis* MB [143] [144] (Section 4.4; **Figure 12**) at the base of the Marsdenian. The four succeeding cyclothems (M1 to M4) in the early Marsdenian (**Figure 19**) are all simple. A similar transition is very obvious from gamma ray logs through Quad 43 and 44 wells in the North Sea (**Figure 18**). Cyclothem M5 (**Figure 19**) is dominated by an extensive series of thick sheet channel-sands represented by the Fletcher Bank Grit in Lancashire and the Midgley and Pule Hill Grits in Yorkshire, plus local stratigraphic names [82] [93] [94] [179] [180]. This cyclothem (M5) also sees significant progradation further west into the previously under-filled basin in central Lancashire [179]. Cyclothem M6 is a simple cycle of uncertain status.

The last two complex cyclothems, M7 and M8 (**Figure 19**) include the very coarse grained Type 3 deltas forming parts of the Ashover and Roaches Grits, (see Section 4.2). In M8 (R2b5) there was major progradation into the Staffordshire Basin towards the end of the deposition of this cyclothem [74]. In the Ruhr Basin there are two coarse-grained channel sands, the Kaisberg Conglomerate in M7 and Sengsbänksgen Conglomerate in M8, the latter interpreted as an incised valley fill [15] [16].

A major flooding surface, the *B. superbilinguis* MB marks the end of this coarse grained interval (**Figure 19**). The succeeding interval consists of nine cyclothems (**Figure 19**, **Figure 20**; M9-13, Y1-4). The oldest, cyclothem M9 contains five locally developed simple cyclothems in high subsidence parts of the Ruhr Basin [15] [28]. Each contains coarsening upwards delta mouth-bar sequences and a sedimentology log through the youngest, where it is 28m thick, is given in [181]. The cyclothems are not seen elsewhere, the equivalent interval (M9) in Quad 43, (43/19a-4z) (**Figure 2**) being only one centimeter thick [74]

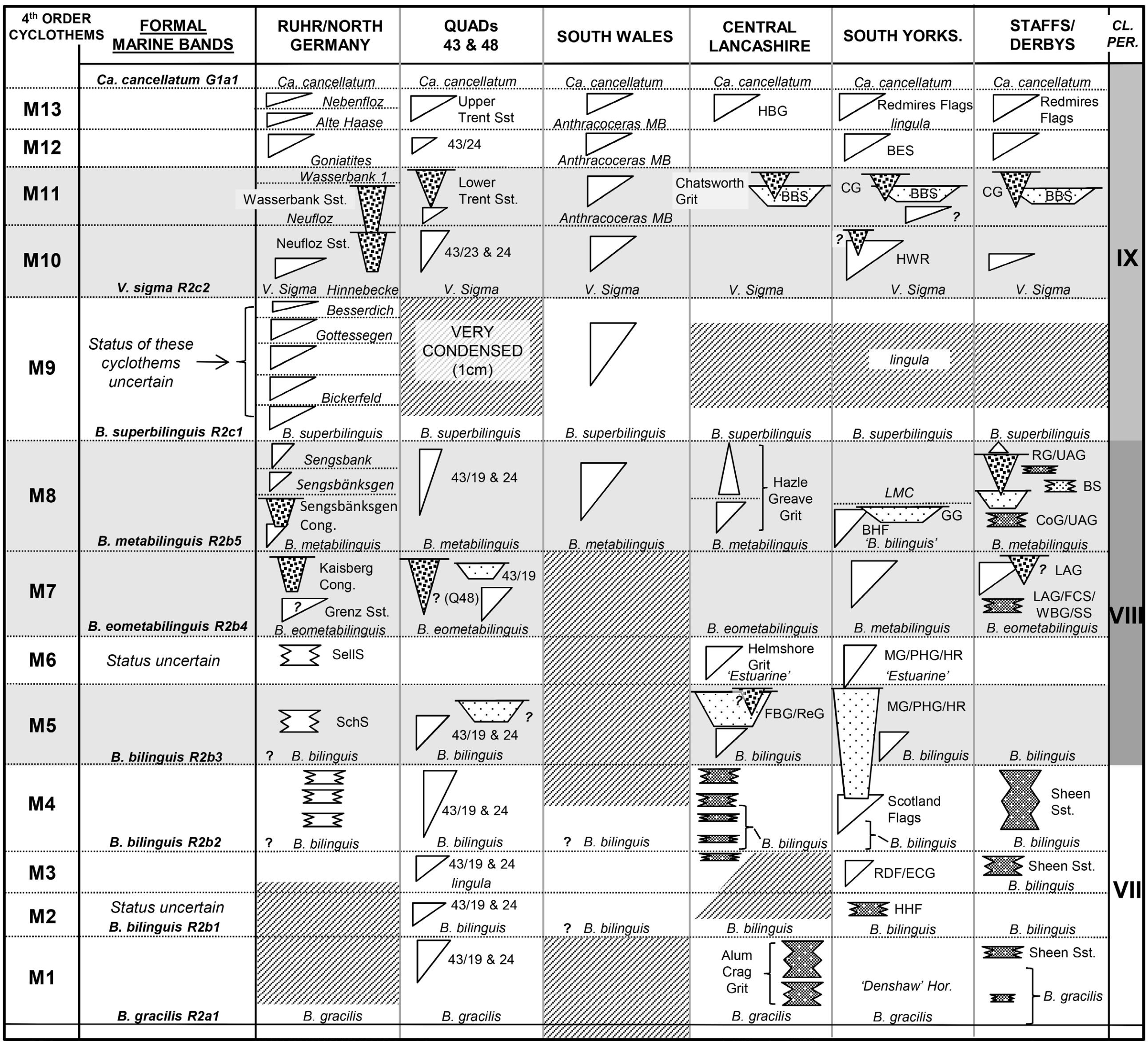


Figure 19. Cyclothems in the Marsdenian (see **Figure 14** for abbreviations).

[182] and in the Central Pennine Basin the interval consists of a mainly mudstone sequence only a few metres thick [73]. In South Wales only a single cyclothem is present [130].

The remaining Namurian interval (**Figure 19**, **Figure 20**; M10-13, Y1-4) contains both simple and complex cyclothems. Two of the latter are M11 which contains the Chatsworth Grit (**Figure 19**) and Y4 which contains the Rough Rock (see Section 4.2, Figs. 9, 10). In cycle Y4, incised channels from two separate sediment sources also occur in South Wales (**Figure 1**) [65] [130]. A third major regressive channel sand, the Raleigh Sandstone from a probable Variscan source, occurs in the Culm Basin (**Figure 1**) [130]. In cyclothem M11 the incised Lower Trent Sst. occurs in the North Sea (**Figure 18**) (well 43/24-1, [99], plus unpublished well data which includes the cored *Ca. cancellatum* MB in the

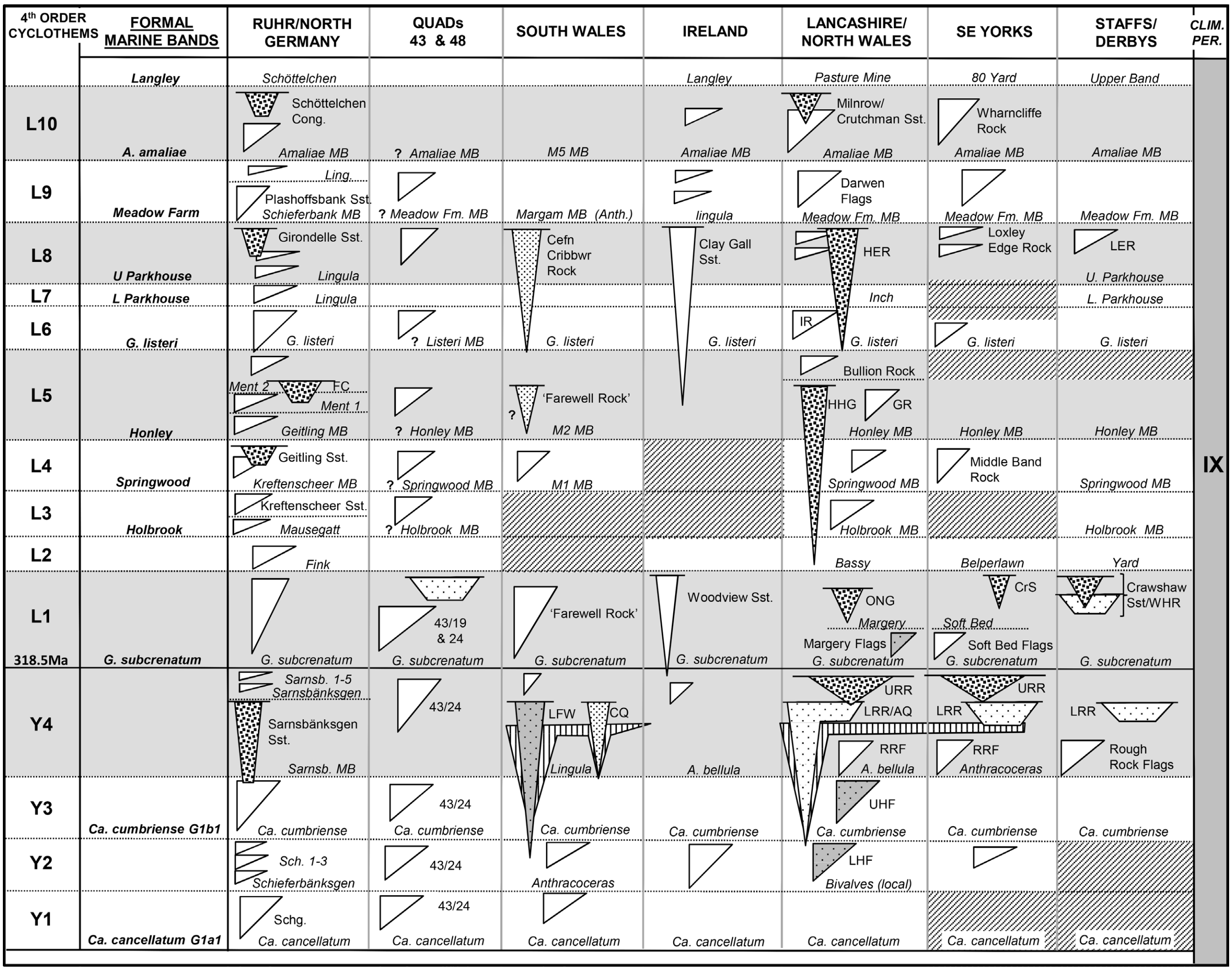


Figure 20. Cyclothems in the Yeadonian and Early Langsettian. (see Figure 14 for abbreviations).

Trent Field) (Figure 2, Figure 18); suggesting this is the up-current equivalent of the Chatsworth Grit. In the Ruhr Basin, both cyclothems are also complex, M11 containing the Wasserbank Sst. interpreted as an incised valley fill [15] and Y4 the coarse-grained Sarnsbänksgen Sst which locally erodes through the underlying marine band [14] [28] [183]. Cyclothem M10 (Neuflöz Sst.) contains a thick multi-story channel sandstone [28].

5.6. Early Langsettian (Figure 20; Cyclothems L1-9)

This interval is similar to the late Namurian and contains both simple and complex cyclothems. Altogether, four complex cyclothems have been recognized. The first of these in the Pennine Basin (L1) contains the Crawshaw Sst., (Section 4.2; Figure 11). The Woodview Sst. in the same cyclothem in the Leinster Coalfield incises through the *G. subcrenatum* MB [184]. The second complex cyclothem (L5) contains coarse-grained, commonly incised channels in four separate fluvial systems; the very coarse Harrock Hill Grit in the Pennine Caledonian system [185]; the upper Farewell Rock in South Wales [186], derived from the

Anglo Brabant Massif; the Variscan sourced Finefrau Conglomerate in the Ruhr Basin [15] [27] [28] and the Late Ransart Member in the Campine Basin (**Figure 1**), sourced from the Anglo-Brabant Massif [187]. The third complex cyclothem (L7) also contains incised channel fills in four separate systems. In the Pennine Basin there is the Caledonian sourced Type 3 delta channel in parts of the Helpet Edge Rock [185]. In South Wales the Cefn Cribbwr Rock incises through two older cyclothems into the Listeri MB [188]. In southern Ireland the Variscan sourced Clay Gall Sandstone is widely developed in three of the small coal basins and also locally incises through the Listeri MB [184] [189] [190]. In the Ruhr Basin the multi-storey, coarse-grained Girondell Sandstone [15] is from a separate Variscan source. The fourth complex cyclothem (L9) in the Pennine Basin in Lancashire contains a narrow coarse-grained Type 3 channel from the Caledonian river system which incises into a thick mouth bar sequence, which together form the Milnrow/Crutchman Sst. [185] and in the Ruhr the coarse, pebbly Variscan sourced Schöttelchen Sst. is probably in the same cyclothem [28] [121].

In the Pennine Basin all of these coarse-grained channel fills incise into finer grained sandstones mainly representing earlier Type 1 delta sequences. Type 2 delta sequences are represented by parts of the Crawshaw Sandstone in L1 (described in Section 4) and probably the Loxley Edge Rock in cycle L7.

In the Ruhr Basin, between the *G. subcrenatum* MB and the Schottelchen Coal (Langley Coal in the Pennines) fourteen cyclothems have been recognised [14] compared to only ten in the Pennine Basin [185] (**Figure 20**). Many of the Ruhr Basin cyclothems are defined by coal seams. The widespread development of these additional cyclothems suggests they do not result from delta-switching, but are either 5th order events, or possibly 4th order cyclothems which are not developed in the more slowly subsiding Pennine Basin.

6. Climate Change Indicators during the Namurian-Early Langsettian

6.1. Northern England

This area contains the most complete succession through the Namurian and early Langsettian. Sediment input was dominated by the Caledonian system (**Figure 1**). It responded to changes in subsidence, catchment area elevation, sediment supply and glacio-eustatic sea-level fluctuations. Climatic change was affecting the latter two of these, but unraveling all the variable contributions is difficult. Modeling studies have shown that the same outcome can be achieved by variable inputs from each of the above four [191] [192]. In flume experiments variations in fluvial discharge (sediment yield) produced facies patterns that resembled those attributed to sea-level changes in conventional sequence-stratigraphic models [193]. Possible controls on the initiation and abandonment, plus varying sedimentary facies of the three delta types have been briefly discussed in Section 4 and are summarized in **Table 4**.

Table 4. Possible controls on initiation, abandonment and facies variation in various delta sequences of the Caledonian fluvial system.

Delta Type		*Autocyclicity*	*Tectonism*		*Climate*	
			Source Area Uplift (Sed. Supply)	Basin Subsidence	Fluvial Discharge (Sed. Supply)	Sea-level Rise/Fall
Type 3	Abandonment	Yes	No	Possible	Yes	Yes
	Grain Size	No	Yes	No	Yes	Possible
	Superimposed Bedforms	No	No	No	Yes	No
	Stacked Channels	Yes	No	Yes	No	Yes
	Initiation	Yes	Possible	No	Yes	Yes
Type 2	Abandonment	Yes	No	No	Yes	Yes
	No Mouth Bar	No	No	Possible	Yes	Yes
	Stacked Channels	Yes	No	Yes	No	Yes
	Initiation	Yes	No	Yes	Possible	Yes
Type 1	Abandonment	Yes	No	No	Yes	Yes
	Wave Reworking	No	No	Possible	Yes	Yes
	Limited Mouth Bar	Possible	No	Possible	No	Yes
	Parasequencies	Yes	No	Yes	No	Yes
	Initiation	Yes	No	Yes	Possible	Yes

A key component of the complex cyclothems is the intra-cycle abandonment of the Type 1 deltas. There are two possible explanations for this.

1) Delta switching. Type 1 deltas in the Pennine Basin represent a late stage of delta progradation out of the North Sea basinal area. In rare cases where there is adequate stratigraphic control (eg Cylothem Y4, **Figure 18**, **Figure 20**) separate delta lobes can be recognized in offshore well data. This shows that delta switching was occurring.

2) Intra-cyclothem sea-level rises. The late Pleistocene geologic record shows that in most glacial cycles, intra-cycle sea-level variability was related to ice volume fluctuations caused by short period, precession and obliquity orbital forcing events (Section 2; **Figure 3**, **Figure 4**). If the Carboniferous glacial cycles had the same types of climate variations, then similar sea-level fluctuations are a likely cause of delta abandonment. The marine bands with multiple thick-shelled goniatite horizons (Section 4.4) provide additional evidence of intra-cyclothem (5th order) sea-level fluctuations.

Complex cyclothems also contain Type 2 and 3 delta sequences (Section 4). The Type 2 sequences are characterised by the sheet geometry of the fluvial channel fills and the virtual absence of mouth bar deposits in parts of the basin previously filled by Type 1 deltas active earlier in the cyclothem [74] (Section 4.2). Given their stratigraphic position later in the cyclothems closer to the eustatic minimum, it was probably a combination of limited accommodation space and rapidly falling sea level which influenced delta sedimentation. This supports their interpretation as the deposits of highly forced regressions [46] [74].

The common element in most of the Type 3 deltaic sequences is the very coarse and commonly pebbly nature of much of the channel fill sediments. Many also show significant incision, greater than could result by normal channel erosion processes (Section 4.1). The deeply incised channel fills associated with deep water deltas; late Pendleian (**Figure 14**); late Kinderscoutian (**Figure 17**) and Mid Marsdenian (**Figure 19**); have previously been interpreted as incised valley deposits, eroded close to the eustatic minimum [7] [9] [11] [102]. The current view is that the deep incision may relate to a combination of deep water at the delta front and very high discharge rates. However the mechanism for deep incision is still poorly understood and the deeply incised channels in the older Rothley and Shaftoe Grits and Grit Sills (Section 5.1; **Figure 14**) were formed well back from the delta front.

There are a number of possible explanations for the variable development of the different cyclothem types in the Caledonian fluvial system.

1) The coarser grained channel fills in the Type 2 and Type 3 delta sequences may have developed as a result of tectonic uplift in the source area. Because coarse grained fills are also commonly seen in different fluvial systems in different sedimentary basins (Section 5.6), more than one source area would have to have been uplifted at the same time; perhaps possible if the uplift was related to widespread plate movements. Another difficulty is the stratigraphic distribution of the complex cyclothems. For instance, it may be possible to correlate the incoming of complex cyclothems in the late Kinderscoutian (Section 5.4) with tectonic uplift of the sediment source area, but why the sudden termination at the end of the Kinderscoutian? This could not be explained by tectonic processes, but could possibly result from delta switching. From late Marsdenian through into the Langsettian there is a repeated alternation of complex and simple cyclothems (Section 5; **Figure 19**, **Figure 20**). A tectonic explanation seems unlikely. Another difficulty is that it fails to explain why the coarsest sediments (Type 3 deltas) only occur towards the ends of the cyclothems. Clearly some other factor must be at play.

2) Northern England forms the western extension of a more extensive sedimentary basin which occupied the greater part of the present day North Sea area (**Figure 1**). The absence of coarser (Types 2 and 3) delta deposits in the simple cyclothems seen in Northern England could result from delta switching into a part of the basin which underlies the present offshore area. This was suggested by [12] as a possible explanation for the predominantly finer grained interval (simple cyclothems) spanning the Chokierian up to the beginning of the late Kinderscoutian (Section 5.3; **Figures 16-18**). There is only limited well penetration through this interval in the North Sea area, and hardly any detailed stratigraphic control because of the scarecity of cored marine bands with goniatites. The data available (**Figure 18**) shows that some wells do have a more sandy se-

quence, but overall, the gamma ray log data do not show an abundance of thick channel fill deposits which are characteristic of complex cyclothems. The contrast with the very coarse grained late Kinderscoutian succession and the underlying one is readily apparent. Other possible areas for delta switching include the Dutch and Danish sectors of the North Sea (**Figure 1**); there is little well penetration through this interval, but what there is shows no evidence for diversion [194]. The deltas could have been restricted to an area further north known as the Mid North Sea High (**Figure 2**), where any Namurian and early Westphalian sediments previously deposited have been eroded. This remains possible, but seems unlikely.

3) The variable development over time of the two cylothems types is related to changes in climate. Two climate models for the tropical late Paleozoic (late Carboniferous to early Permian), have been proposed. Either the tropics experienced a wetter and less seasonal precipitation regime during glacial (lowstand) intervals than during interglacial (highstand) intervals [20] [195], or a drier and more seasonal precipitation regime during glacial (lowstand) intervals than during interglacial (highstand) intervals [18] [196] [197]. The climatic evidence from the older northern England succession is closer to the latter model.

The NW European Namurian-early Langsettian succession was deposited close to the equator (**Figure 1**); contains coals throughout and lacks evidence of aridity, suggesting an ever-wet climate. The catchment area of much of the Greenland Caledonides, c7.5˚ - 20˚ North [30] probably had a different climate. The northern England succession with its multiple complex cyclothems demonstrates that there must have been significant rainfall in the Caledonian mountains. During the glacial maximum, when greenhouse gas levels and sea level decreased, it may have been much drier in that area, in which case the Caledonian river system could have been largely inactive [74]. This is supported by late Carboniferous climate modeling which suggests that glacials were drier than interglacials in most areas, as both relate to moisture availability [198]. During the succeeding deglaciation rainfall increased but was highly seasonal.

The Pangean supercontinent was prone to large seasonal changes in heating that may have driven intense monsoons [199]. Climate modeling studies [198] [200] [201] have demonstrated the possibility of very strong summer rainfall over Pangea in the northern hemisphere tropics. In most of the model simulations, changes in the Pangaean monsoon are the primary control on the spatial pattern of tropical precipitation variability, and thus of tropical precipitation away from the Equator. Changing orbital forcing can significantly enhance or diminish monsoon intensity [47]. High summer insolation strengthens the monsoon, while low summer insolation suppresses it. The impact of sub 100Ky orbital parameters was modeled by [200]. With an eccentric orbit (enhanced precession) and the longitude of perihelion around southern summer, the ITCZ was located at 20^0 north. Strong south easterly winds drew moisture from the Paleo-Tethys across north-eastern Pangea. The Greenland catchment area lay 4000 km from that ocean and the inferred elevated rainfall area was much further west than in the climate models of [198] and [200]. However, these models were based on an early Permian palaeogeography, by which time the equator had shifted well to the south of its Namurian position (**Figure 1**) and the climate over Greenland would have been more arid [30] [197]. Detailed climate models for the Namurian are not yet available.

This interpretation of the Carboniferous climate suggests similarities with the end of the last Pleistocene glacial cycle, where orbital forcing parameters can be reliably back-calculated and rainfall variability is better documented. Strong monsoon rainfall relates to summer insolation maxima during a strong precession period [202] [203]. More recent studies on variability of Indian summer monsoon rainfall [204] [205] suggest that as summer insolation increased at the end of the LGM there was an accompanying increase in rainfall. A similar pattern is seen over the Sahara which is at comparable latitude to the paleo-latitude of a significant part of the catchment area of the Caledonian deltas (**Figure 1**). After the peak of the last glaciation (21Ka, **Figure 3(A)**, **Figure 4**) there were changes to the pattern of monsoon circulation leading eventually to the onset of the African humid period at about 12Ka [206], with accompanying major changes in vegetation. This also triggered the reactivation of a large river system in the Western Sahara [207]. These rainfall patterns are seen in spite of the post LGM deglaciation coming at the end of a long-eccentricity cycle with weaker eccentricity and precession (**Figure 3(B)**, **Figure 3(C)**).

6.2. Detailed Climate History

The climatic interpretation of different cyclothem types outlined above allows the stratigraphic distribution of these to be used to provide evidence of possible climatic variation over longer periods of time (**Figure 13**). The underlying assumption is that the complex cyclothems were deposited during climates with more ice accumulation, greater fall in sea level, and greater rainfall variability.

The earliest part of the Pendleian represented by the Great Limestone and in basinal areas by the complex *C. leion* MB (**Figure 14**) (Climate Period 1) is a possible non-glacial interval. Following an inferred relatively warm period with simple cyclothems (Climate Period II), evidence for further cooling is first seen in late E1b (P5) with the forced Type 1 delta, represented by the Uldale Sill and Jackdoor Crags [85] (**Figure 14**). The Firestone Sill [208], a thick ganister, on the Alston Block (**Figure 14**) is further evidence for a significant sea-level fall. This is followed by a number of complex cyclothems (Climate Period III). The Ashover succession (**Figure 2**, **Figure 13**) [72] lacks thick-shelled goniatites in the middle to late Pendleian interval. This is possibly because lower world sea-levels during this inferred cold period of more extensive ice accumulation, resulted in too shallow waters for goniatite survival in this shelf area.

The suggested evidence for a colder interval (Climate Period III) from late Pendleian to early Arnsbergian contradicts the oxygen isotope work of [209]. They examined brachiopods from the Woodland Borehole on the Alston Block (**Figure 2**) over a late Pendleian stratigraphic interval from the Faraday House

Shell Bed up to the Rookhope Shell Bed (**Figure 14**) and concluded, from the negative values obtained that there were no widespread ice-caps during this period. This contradiction between the decrease in equatorial isotope values and evidence of extending southern hemisphere glaciations in the Serpukhovian has been noted elsewhere [48] who suggested that tropical epicontinental seaways may not have been as well mixed as the open oceans. Another factor to consider in the Pennine Basin is that the Alston Block was subject to extensive late Carboniferous mineralization with probable elevated associated heat flows [210]. Other isotope analyses in northern England [211] led to the conclusion that elevated heat flows associated with this mineralization could have led to the overprinting of earlier sea-water derived isotope values.

In Climate Period IV, (Cyclothems AR3-CH6), nineteen cyclothems are recognized in Northern England and only four of them are complex (**Figure 15**, **Figure 16**). The succession is interpreted as a predominantly warm period punctuated by a few more extreme glacial cycles. In Climate Period V, (Cyclothems AL1-K10), all sixteen cyclothems are simple (**Figure 16**, **Figure 17**). This succession is interpreted as a prolonged period when glacial-related cyclicity continued, but sea-level fluctuations were modest and probably had the warmest climate since the early Pendleian.

The beginning of Climate Period VI (Cyclothems K9 or K11-K15) marks a major climatic change. The five cyclothems in the late Kinderscoutian are all complex. Regressive sequences are also seen in Ireland and mainland Europe (Section 5.4). The absence of thick-shelled goniatites in the R1c2, 3 and 4 marine bands of the Ashover boreholes (**Figure 2**, **Figure 13**) succession [72] is again regarded as evidence that water depths over the Ashover shelf were too shallow for goniatites, during a period of inferred lower world sea levels. The sedimentology of this interval also suggests a significantly colder than average climate. Climate Period VII (Cylothems M1-M4) (**Figure 13**, **Figure 19**) starts with the *B. gracilis* transgression and was warmer; whilst Climate Period VIII, with mainly complex cyclothems, M5-M8 and with goniatites again absent over the Ashover Shelf area (**Figure 13**) marks a return to the colder climatic conditions of the late Kinderscoutian. The *B. superbilinguis* transgression delineates the start of Climate Period IX. This is a more variable interval with alternating simple and complex cyclothems (**Figure 19**, **Figure 20**).

The similarity in the development of coarse and commonly incised channel fills in the late Namurian and early Langsettian sequences in different sedimentary systems and fluvial sources (**Figure 19**, **Figure 20**; **Table 5**) is a strong indication of a global climatic control. This does not just relate to variable sea-level fluctuations, but also suggests synchronous climatic variation in different fluvial catchment areas. Major marine bands from *G. cumbriense* in the late Namurian to *A. amaliae* in the Langsettian, the majority of them with two or three thick-shelled goniatite horizons, occur in every fourth cyclothem, suggesting a possible long eccentricity beat, as also proposed by [16] and [19].

Table 5. Stratigraphic distribution of major coarse channel sandstones.

Complex Cyclothems in the Pennine Basin (Include Type 2 & 3 delta sequences)	Number of other basins with incised & major coarse channels in same cycle
Milnrow/Crutchman Sst	1 (Ruhr)
Helpet Edge Rock	3 (Ruhr, Ireland, S. Wales)
Harrock Hill Grit	3 (Ruhr, Belgium, S. Wales)
Woodhead Hill Rock/Ousel Nest Grit/Crawshaw Sst.	1 (South Wales)
Rough Rock	3 (Ruhr, Cornwall, South Wales, 2 systems)
Chatsworth Grit	1 (Ruhr)
Roaches & Upper Ashover Grits	1 (Ruhr)
Lower Ashover Grit	1 (Ruhr)
Kinderscout Grit (5 cycles)	3 (Belgium, Aachen, Clare)

The suggested climatic history outlined above is complex, not surprising over a period of at least 12 My. There were clearly a number of influences, some as yet unknown. The interpreted sea level curve presented (**Figure 13**) differs from previous curves, such as that by [212] [213] [214] which is reproduced in several later climate studies. Their curve shows a prolonged period of eustatic low sea level beginning at the base of the Chokierian and extending until Westphalian D. This includes the interval described above (Alportian to base late Kinderscoutian, Climate Period V) which is interpreted in this study as the Namurian climatic optimum (**Figure 13**, **Figure 16**). The Ross and Ross curve for the Namurian [212] [213] [214] is largely based on papers by Ramsbottom, [71] [145] [146] [170] who believed that non-sequences in this interval over the northern part of the Pennine Basin; Stainmore, Alston and Northumberland (**Figure 2**, **Figure 13**, **Figure 15**, **Figure 16**) represented long periods of low sea levels. These were correlated with other stratigraphic gaps worldwide [71] [215]. The current interpretation is that the non-sequences in the northern part of the Pennine Basin are caused by very low rates of subsidence which severely reduced accommodation space and are unrelated to sea levels. An unconformity is commonly seen at this horizon in other basins, such as the Upper Silesian Basin, [116].

A possible climate model for the complex cyclothems suggests they commonly correspond to periods when eccentricity modulated precessional orbital forcing was stronger. These were associated with enhanced precession related, seasonal rainfall during deglaciation (Type 3 delta sequences). This then declined and during the ensuing marine bands there was little delta progradation. As ice accumulation started again, falling sea-levels began to pull the deltas (Type 1 sequences) into the basin, but later strong (precessional?) forcing events produced sea-level rises sufficient to flood them. Accelerating sea level falls close to the eustatic minimum pulled the deltas (Type 2 sequences) back into the basin. Aridity of the catchment area during glacial maximum then starved these deltas of sediment supply.

The coarser incised channel fills in the Ruhr succession [14] [16] (Section 4.3) could have a variety of origins. The basin may have been close enough to the main catchment area (Variscan Mountains, **Figure 1**) for knick point recession during the eustatic minimum of colder cyclothems to increase the fluvial gradient back into the source area, allowing a coarser bedload to be transported. An alternative explanation is provided by the climate model of [200] which suggests high precipitation over the Variscan Mountains in association with strong monsoons at times of strong precession. However, these same monsoons could also have been supplying high seasonal rainfall to the Caledonian fluvial catchment area further to the north (**Figure 1**). In this scenario there would have been contemporaneous deposition of the coarser grained channel sediments from the different catchment areas; in which case, the Ruhr coarse grained channel deposits accumulated during the early deglaciation period (**Figure 7(C)**), a little later in the cyclothem than suggested by [14] [16]. Conversely simple cyclothems in the later Namurian and Langsettian were deposited during less cold periods of low eccentricity and lesser modulation of precession. Sea level fluctuations were more modest and climate changes in the catchment area less extreme, although rainfall in the Caledonian catchment area (**Figure 1**) was probably still seasonal, as in the same latitudes in the present. The simple and complex cyclothems would have varied systematically through long-eccentricity (400Ky) cycles, in response to variations in orbital forcing (**Figure 3(B)**, **Figure 3(C)**).

This climate change model best fits Climate Periods VII to IX (**Figure 13**, **Figure 19**, **Figure 20**) where regular alternations of complex and simple cyclothems occur. This pattern is not seen, or is poorly developed, in the earlier Namurian. The late Kinderscoutian (Climate Period VI) (**Figure 13**, **Figure 17**), which contains five recognized cyclothems, must have been deposited over more than one long eccentricity (400 Ky) cycle. Climate Period V (**Figure 13**, **Figure 16**, **Figure 17**) with sixteen cyclothems had a more stable climate. Changes in orbital forcing alone cannot explain these longer term climatic trends.

7. Comparison between the Southern Hemisphere and the North West Europe Successions

Known Namurian glacial deposits in the Southern Hemisphere are quite restricted (**Figure 21**); there were probably multiple glaciated areas at times, but their full extent remains unknown because of gaps in the stratigraphic record and no exposure. No Namurian glacial deposits have yet been discovered in present-day Antarctica and at least part of the continent (Trans-Antarctic Mountains) is believed to have been ice free [49]. The early Namurian is missing in South Africa and the age of the earliest glacial deposits remains uncertain [216]. The extensive Upper Carboniferous glacial sequences in Brazil (**Figure 21**, **Figure 22**) have

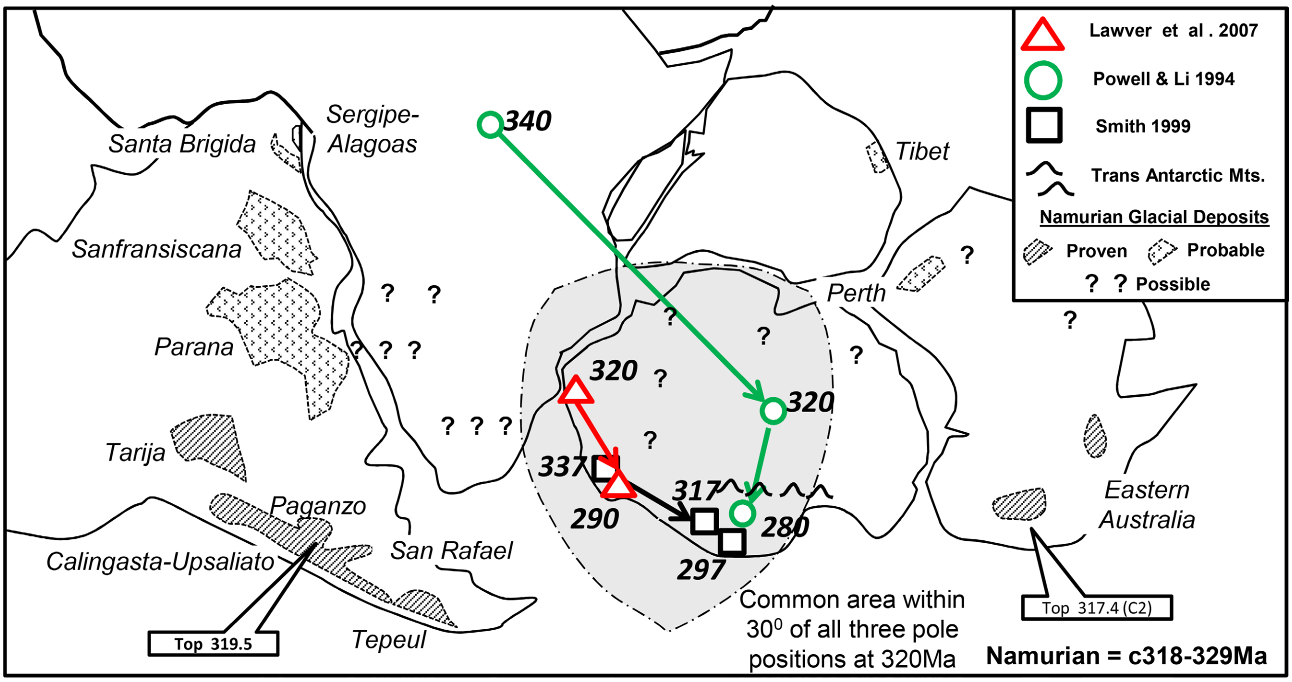


Figure 21. Distribution of known Namurian glacial deposits in Gondwanaland. After Fielding *et al.* (2008a) [3], Garzanti and Sciunnach (1997) [226], Montañez and Poulsen (2013) [227]. Estimated positions of the South Pole after 340 - 280 Ma; after Lawver *et al.* (2007) [228], Smith (1999) [229]; Powell and Li (1994) [230].

radiometric and palynological ages suggesting they are probably all younger than the Namurian to early Langsettian sequence discussed in this paper [217], although the age of the oldest deposits again remains uncertain [218]. Further away from the various possible polar positions, late Namurian glacial sediments, with associated *Levipustula* brachiopod fauna, are known from a number of basins in south-western South America (**Figure 21**) [49] [219] [220], although many of these are interpreted as valley glacier deposits [218] [221] [222] [223] [224], and the western Australian Perth Basin [225], although their age is poorly constrained. In Tibet glacigenic sediments underlie shales with a *Levipustula* fauna and are probably Namurian in age [226], although they could be Visean.

The best documented Namurian glacial deposits so far discovered are found in eastern Australia (**Figure 21**, **Figure 22**) [3] [4]. These allow a detailed southern hemisphere glacial chronology for the Upper Carboniferous and a number of correlations have been proposed with the UK (Pennine) succession [19] [231] and also with the Donetsk Basin succession [20]. The area had a relatively distal location from the Pole (**Figure 21**) and the Australian successions probably record major ice-age periods when glaciations were more extensive. A new correlation between the Southern Hemisphere and NW Europe is proposed (**Figure 22**). It is not possible, at present, to accurately correlate the Southern Hemisphere and European sequences using biostratigraphy. The oldest Australian ice-age period (C1, **Figure 22**) is represented by the Spion Cop Conglomerate, the restricted nature of the sequence suggesting deposition by valley glaciers [3]. An age range of 325.5 - 326.5 Ma, on the year 2000 time scale of [232], or slightly

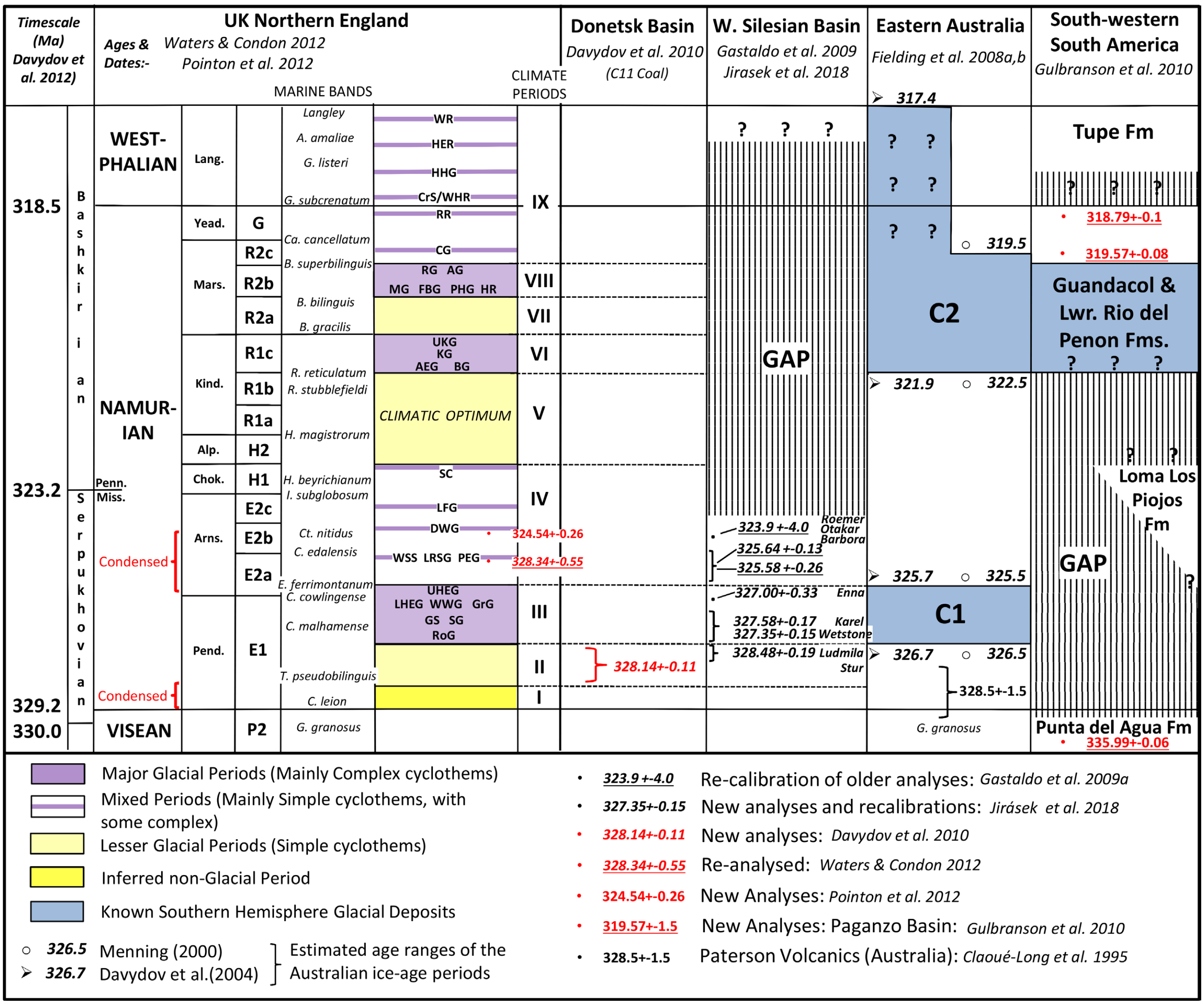


Figure 22. Suggested correlation between the known Southern Hemisphere ice-age periods (with estimated age ranges after Fielding *et al.* (2008a) [3] and Gulbranson *et al.* 2010 [220]) and the inferred colder periods seen in the NW Europe stratigraphy (dated after Davydov *et al.* 2012) [21]. Recent isotopic age dates are also shown for comparison. There is no precise biostratigraphic correlation between the southern hemisphere and European successions. (Abbreviations: same as **Figure 14**).

older using the year 2004 time scale of [233] has been suggested [3] [4]. This placed it in the early Pendleian, assuming the base of the Pendleian is dated at about 326 my. However, a more recent U-Pb age date from the West Silesian Basin of 328.84 Ma [116] (**Figure 22**) has goniatite control which probably places it in Pendleian Zone E1b, although *C. malhamense* (Base E1c) has not been recorded in this basin. A U-Pb radiometric date from a Pendleian aged tuff in the Donetsk Basin (**Figure 22**) is dated at 328.14 ± 0.11 Ma [234]. These dates push the base of the Pendleian back to at least 329.2 Ma in the year 2012 timescale of [21], (**Table 3**) and possibly older. If these new dates are reasonably accurate, and they have been questioned [120], then the currently published radiometric dates suggest the Spion Cop Conglomerate is probably younger than basal Pendleian and more likely correlates with the first of the Namurian major colder periods (III), suggested in this paper, which can be accurately dated as late Pendleian to early Arnsbergian (**Figure 13**, **Figure 22**). Two tuffs which lie just below and just above the Enna MB in the Upper Silesian Basin (**Figure 1**), which is probably the *C. cowlingense* MB (=early Arnsbergian, E2a1), have dates [116] at 327±0.33Ma and 325.58±0.26Ma (**Figure 22**).

The second ice-age period (C2) lasted for 3 My, using the year 2000 time scale of [232] three times as long as C1, or 4.5 My using the year 2004 time scale of [233]. These deposits are also more extensive. The period has been placed largely in the Arnsbergian period of the European succession [3] [4]. However, their suggested age ranges; 317.4 Ma to 321.9 Ma or 319.5 Ma to 322.5 Ma (**Figure 22**) depending on which time scale is used, indicates correlation with a younger part of the European Namurian succession using the more recent time scales of [21] [234] and ICS time scale of [119] (**Table 3**). It seems more likely that C2 correlates, at least in part, with the major NW European colder periods (VI, VIII, IX) identified in this paper as being within the stratigraphic interval which ranges from late Kinderscoutian to early Langsettian. The age of the top of C2 (317.4 Ma or 319.5 Ma) is fairly close to the age of the top Namurian (318.5 Ma or 319.9 Ma) in the time scales of [21] and [118] (**Table 3**). If this correlation is correct, then the European evidence suggests that the C2 ice-age period may have contained considerable variations in the intensity of glacial cycles and included a number of climatic ameliorations.

In South America glacial deposits in the Guandacol and Rio del Penon Formations [220] (**Figure 22**) overlie an unconformity and the timing of the beginning of the glaciation is close uncertain. It probably correlates with part of the C2 glacial episode in Australia. The overlying non-glacial sequence has late Namurian Pb/U ages of 318.79 Ma in the Paganzo Basin and 319.57 Ma in the Rio Blanco Basin. This correlates with parts of Climate Period IX in NW Europe (**Figure 13**, **Figure 22**) which has alternating complex and simple cyclothems, and is inferred to be slightly warmer overall, than the earlier Period VIII.

The C3 ice-age period in Australia (315 - 317 Ma) is probably younger than the stratigraphic interval discussed in this paper and appears to correlate with the mid to late Langsettian of the European stratigraphy.

The continuous cyclical sequence in NW Europe suggests glaciations, with their associated eustatic sea-level fluctuations, persisted for most of the Namurian and early Langsettian interval discuused here (**Figure 13**, **Figure 22**) with the possible exception of the early Pendleian. The shaded area in Gondwanaland (**Figure 22**) occurs within a latitude of 30˚ for all three possible pole positions in the late Namurian (320 Ma), but none of the currently known Namurian glacial deposits lies within it. It has been questioned whether the Namurian ice sheets were extensive enough for their fluctuations to provide sufficient sea-level variation to account for the equatorial cyclothems [49]. Climate modeling suggests sea-level fluctuations of ≤50 m are possible with this ice-sheet distribution [227]. Some of these areas were ice-free at times, eg. East Australia and western South

America, but there may have been waxing and waneing ice sheets in other parts of Gondwanaland, their deposits having yet to be discovered, not exposed or removed by later erosion. The different climatic periods inferred from the NW European succession, therefore probably relate to the variable development of glaciations in different areas of Gondwanaland. There were probably more glaciated areas during inferred colder periods; eg III, VI and VIII, than during inferred warmer periods, such as periods I II and IV.

Climatic Change and Basin Filling

The Namurian deep-water Pennine Basin has four major phases of fill each associated with turbidite-fronted deltas [106]. These phases appear to be all related to major glacial periods. The first (E1c-E2a) mainly corresponds to Climate Period III (**Figure 13**) which correlates with the C1 Glaciation in Australia. The second (R1c), correlates with Climate Period VI (**Figure 13**), the earliest phase of the C2 glaciation in Australia. The third and fourth periods (R2b) occur during Climate Period VIII, within the middle part of the C2 glaciation. During the last period (R2b4-R2b5) there was also a major progradation of the Ruhr deltas [26]. These were all caused by a combination of factors related to the colder climate conditions; namely, larger than normal sea-level fluctuations and climate changes in the catchment areas. All of these basin fill phases experienced an influx of large volumes of sediment, so that the deltas were able to fill and prograde out into the previously under-filled deep-water basins. This was possible because of increased run-off brought about by a number of possible climate-related factors, as discussed earlier.

8. Summary

1) The Western European (Namurian to early Langsettian) sedimentary basins contain well correlated widely developed cyclothems. Recent age dates indicate average durations of c100Ky, comparable to cycle durations during the Pleistocene glaciations, which relate to short-eccentricity orbital forcing (**Figure 3**).

2) Cyclothems in the UK Pennine Basin (**Figure 2**) contain up to three types of deltaic sequences which develop at difference stages during delta progradation, before and after the inferred eustatic minimum (**Figure 8**). Many (complex) cyclothems contain two or three delta sequence types, but in the majority (simple cyclothems) there is only one.

3) The stratigrapic distribution of simple and complex cyclothem types is not random. In the Namurian, the latter group together into three longer periods: late Pendleian, late Kinderscoutian and mid Marsdenian. These are associated with periods of major delta progradation in the UK Pennine Basin.

4) From the mid Marsdenian onwards there is a good correlation between complex cyclothems in the Pennine Basin and deltaic sequences in the same cyclothem in other West European sedimentary basins that show evidence of coarse grained fluvial input, commonly accompanied by incision. (**Figure 19**, **Figure 20**).

5) A revised correlation between the Western European and Southern Hemisphere shows that European stratigraphic intervals dominated by complex cyclothems are approximate age equivalents to known Southern Hemisphere glacial sequences.

9. Conclusions

1) Four independent factors can be interpreted to suggest that the Namurian to Early Langsettian climate varied systematically between more and less extreme glacial periods. These are: the stratigraphic distribution of coarse-grained delta channels; the timing of the major periods of delta progradation; the presence of depth-related goniatite faunas in a shelfal part of the Pennine Basin and the stratigraphic distribution of glacial deposits in the Southern Hemisphere

2) Many of the cyclothems deposited during these colder periods contain evidence for significant rainfall variability in the fluvial catchment area (Greenland and Scandinavia?) of the Caledonian system, with intense, seasonal rainfall towards the end of the cyclothems. In the later Namurian and Langsettian, there is also evidence for increased run off in other fluvial catchment areas in Europe. Carboniferous climate modeling and comparisons with the late Pleistocene, has related this to strong precessional forcing.

3) Alternations between complex and simple cyclothems in the later Namurian and early Langsettian suggest a possible correlation with long eccentricity orbital forcing. This is not seen in the older Namurian and a long period with a relatively warm, more stable climate is inferred from the Alportian to the beginning of the late Kinderscoutian.

4) Within many cyclothems, shorter-period sea-level fluctuations are inferred from the flooding of early progradational deltas, variations in their sedimentology and marine bands with complex faunal variations. These are attributed to shorter period glacio-eustacy; comparisons with the late Pleistocene again suggests a possible relationship to precessional (c20Ky) orbital forcing.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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