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The Influence of Variable (Monsoon) Rainfall on Sedimentation in the Roaches Grit and Other Upper Carboniferous Delta Sequences in the UK Pennine Basin

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Abstract

The Roaches Grit in the UK Pennine Basin was a complex deep water deltaic sequence deposited during the Late Carboniferous glacial period. The channels of the upper part of the Roaches Grit, deposited towards the end of the cyclothem after the eustatic minimum, contain evidence for very high seasonal discharges related to strong monsoon rainfall in the catchment areas. In some channels, intense turbulence near the delta front, led to knick point recession and deep incision. These channels were filled with sediments during reduced discharge, including very large sets of cross-bedding up to 16 m thick. Channels were short-lived with frequent avulsions. Over time slightly lower discharges formed laterally migrating channels dominated by bar forms. Different discharge-controlled processes operated on the reactivated delta slope. Incised channels generated turbidity currents during floods which transported sediments directly into the basin far from the delta. Migrating channels built mouth bars; resedimentation during floods formed density currents which then deposited sediment on the lower parts of the slope.

Keywords

Carboniferous, Delta, Climate, Monsoon, Rainfall, ITCZ, Precession

1. Introduction

The Roaches Grit and associated sediments form a deltaic sequence developed in the latter stages of the late Marsdenian R2b5 Cyclothem (**Figure 1**). Along with the coeval upper Ashover Grit in the East Midlands, it represents one of a small number of major Namurian deep water basin fill events seen in the UK Pennine

Basin [1] [2] (**Figure 2**). The complete cyclothem is believed to correlate with an episode of short-eccentricity orbital forcing (c100ky) [2]. The cyclothem is complex; with earlier phases of delta sedimentation occurring in parts of Yorkshire and Lancashire (**Figure 2(A)**), and also in the offshore North Sea Basin [3].

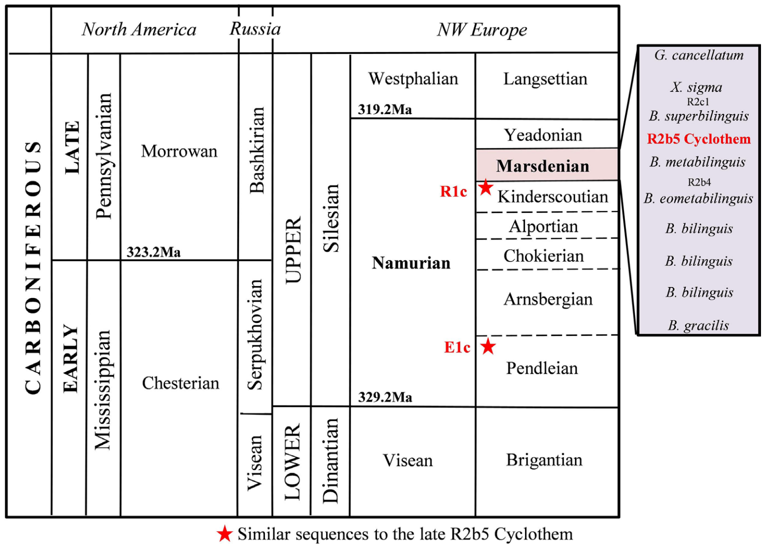

Figure 1. Stratigraphy of the early Upper Carboniferous showing positions of the R2b5 Cyclothem (320 ma) and other similar deltaic sequences.

The Roaches Grit succession is dominated by thick alluvial channel sediments exposed in natural escarpments, stream sections and rare quarries. In addition, there are finer grained delta plain facies, plus delta slope sediments exposed mainly in stream sections. The best exposures lie along the natural 'gritstone' escarpments of Ramshaw Rocks, Hen Cloud and the Roaches, and the stream section in the Dane Valley, 4 km to the west (**Figure 2(B)**). Detailed facies analysis has been carried out on these exposures and a detailed alluvial stratigraphy can be deciphered. A separate area of outcrop lies to the north and west of Leek (**Figure 2(B)**), where exposure is much poorer and the detailed alluvial stratigraphy is unknown, although it appears to be relatively simple. A third area comprises a number of outcrops developed northwards from The Roaches and Ramshaw Rocks towards and beyond Buxton (**Figure 2(B)**). The alluvial stratigraphy in this area contains fewer events and cannot be directly correlated with that around the Roaches.

This paper builds on over forty five years of sedimentology research [1]-[7] on the Roaches Grit during which the interpretation has evolved with the application of new approaches in sequence stratigraphy [6] [8]-[12] and advances in the understanding of the Upper Carboniferous climate [2] [3] [13]-[16]. The aims of this new paper are to: 1) provide a more detailed account of the evolution of the delta; 2) provide a revised interpretation of the lithofacies deposited within the channels and delta slope and 3) discuss how facies variations and different channel types provide evidence for large fluvial discharge variations believed to be caused by rainfall (monsoon) variability in the catchment area. Stratigraphic names of the various sandstone units mapped by the British Geological Survey are shown in Table 1.

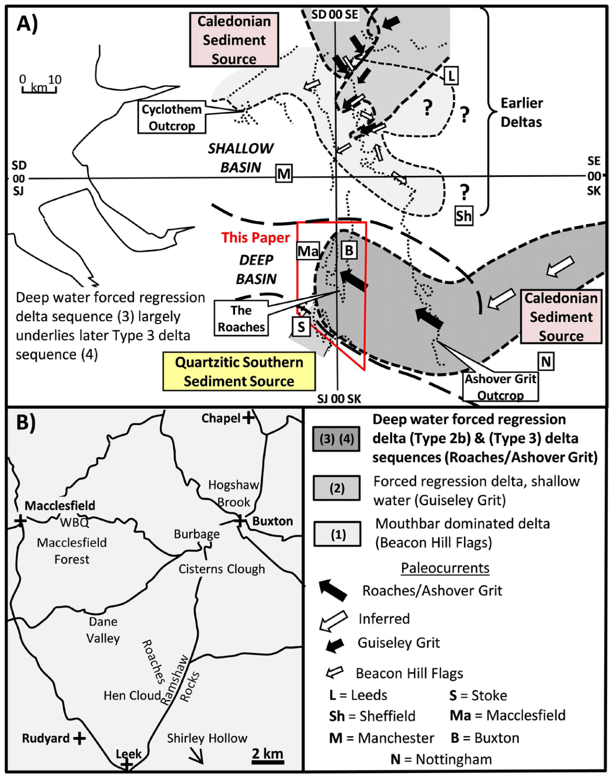

Figure 2. (A) Location of the R2b5 Cyclothem delta sequences in Northern England (modified from Jones 2014 [3]); (B) Area discussed in this paper.

Table 1. Stratigraphic names of mapped sandstone units and marine bands [17]-[19]. A = marine band absent, P = marine band present. Shaded area marks R2b5 Cyclothem.

Facies Unit	Macclesfield Forest	Buxton/Chapel	Roaches area & Dane Valley	Shirley Hollow/Leek (Basin Margin)
B. superbilinguis MB (R2c1)	P	P	P	P
Wave reworked fine sst. with marine trace fossils			Roaches Grit	
Coarse fluvial channel deposits (Type 3 Delta)	Roaches Grit	Roaches Grit	Roaches Grit	
Reactivated Slope (Type 3 Delta)	Roaches Grit	Roaches Grit	Roaches Grit	
LOWSTAND		ROOT BED		ROOT BED/COAL
Forced Regression Delta (Type 2b)	Roaches Grit	Roaches Grit	Roaches Grit/Five Clouds Sandstone	Shirley Hollow Sandstone/Roaches Grit
B. metabilinguis MB (R2b5)	P	A	A	A
Basin Floor Turbidites	Walker Grit/ Corbar Grit	Corbar Grit	Five Clouds Sandstone	

2. Delta Sequences

The main phase of deep water (>100 m) delta progradation occurred late in the cycle during falling sea-level, prior to the inferred eustatic minimum (see [2] [3]). In the western Roaches area the delta constructed a predominately fine grained slope sequence averaging about 80 m thick (post compaction), which was fed by delta distributaries of variable size and orientation (**Figure 3**). This delta was then abandoned, the seaward limit of the delta top lying to the west and northwest of Leek and Buxton (**Figure 2(B)**).

Following abandonment, root beds and a thin coal developed near the southern margin near Leek [20] (**Figure 2(B)**) and at Shirley Hollow south-east of Leek [4], where subsidence and hence sediment thicknesses were significantly reduced. A poorly developed root-bed also occurs in a central area at Cisterns Clough south of Buxton (**Figure 2(B)**). These developments show the delta top was vegetated for a short time. In other areas the top of the deltaic sequence is unexposed. The delta was then flooded because of high rates of subsidence probably caused by sediment loading and compaction of the earlier slope sequence. The delta was then reactivated during a later eustatic sea-level rise. A combination of rising eustatic sea-level, compaction, and subsidence led to sediment loading, creating significant accommodation space. This led to a complex alluvial stratigraphy with successive fluvial channel sediments associated with a series of successively higher base levels.

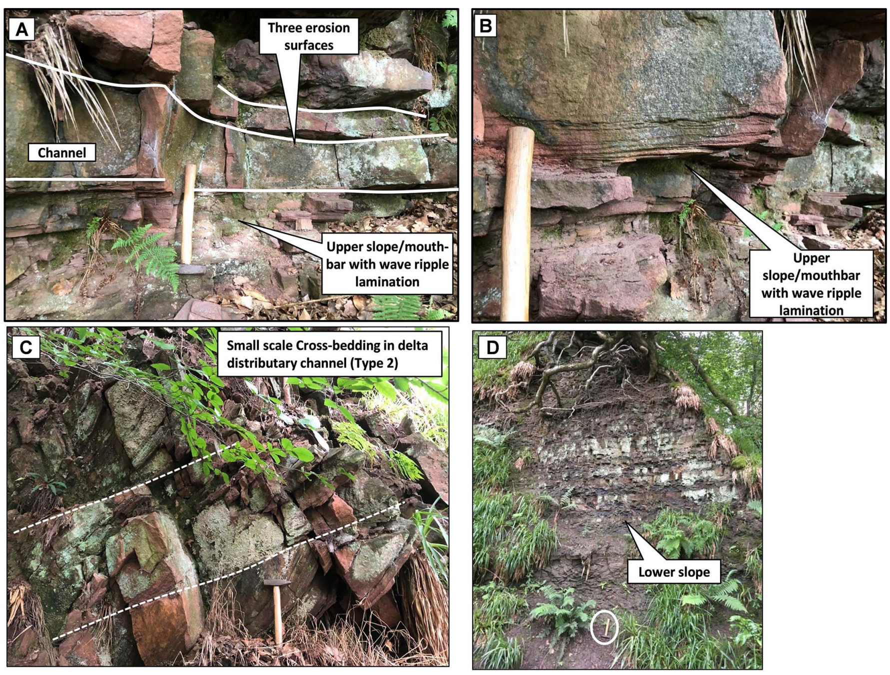

Figure 3. Forced Regression Delta (2b) exposed in the Dane Valley: (A) & (B) contact between upper slope/mouth bar and distributary channel; (C) Distributary channel cross-bedding; (D) Lower part of the slope sequence a few meters above the base of the cyclothem.

3. Channel Facies and Bedforms

The channel fills of the upper part of the deltaic sequence are dominated by three distinctive sedimentary facies [1] [3] [5]-[7], and brief descriptions, with additional observations and updated interpretations are given below. Very similar facies were first identified in the upper Grindslow Shales and Kinderscout Grit (Namurian R1c) in Derbyshire [21] [22], another deep-water delta succession, and are also observed in the Warley Wise Grit and stratigraphic equivalents (Namurian E1c) (**Figure 1**) in Yorkshire [23]-[25].

3.1. Medium-Scale Cross-Bedding (MSXB)

This facies is the dominant channel-fill facies in many Namurian delta sequences in the Pennine Basin [2] and forms the major part of what was previously referred to as sheet deltas [26]. It comprises medium to very coarse-grained and pebbly sandstones forming cosets of planar-tabular cross-bedding (**Figure 4(A)**) and is interpreted as the product of migrating bars with sinuous, possibly linguoid shaped slip faces [5]. A feature of this facies is the very uniform nature of the cosets. Apart from rare trough cross-bedded sets, no other facies occur. Superimposed smaller bed forms and rare bar front erosion (reactivation) surfaces within the MSXB provide evidence for fluctuations in discharge [5].

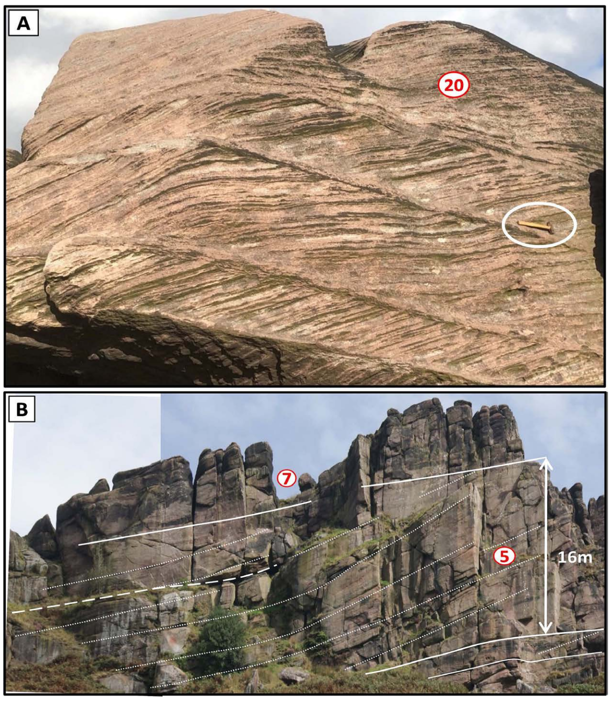

Figure 4. (A) The Roaches: Medium-Scale Planar-Tabular Cross-Bedding Coset (MSXB) within a sheet channel (Type 3a). Hammer (circled) gives scale; (B) Hen Cloud: Large Scale Cross Bedding with tangential foresets in a 16m set within an incised channel (Type 3c). A sheet-channel with MSXB overlies it. Red numbers in circles delineate depositional sequence in the alluvial stratigraphy discussed in Section 6.

3.2. Large-Scale Cross-Bedding (LSXB)

This is a very unusual lithofacies and appears to be unique to Namurian deep-water successions of the Pennine Basin. In the Roaches Grit it comprises mainly solitary sets of cross-bedding in coarse-grained to very coarse and pebbly sandstones, from 6 m to at least 16 m in height (**Figure 4(B)**). Detailed descriptions are given in previous papers [7] [27]. Three main variants occur (**Figures 5(A)-(C)**): angular foresets without intrasets, tangential foresets with intrasets of variable orientation and locally associated with undulatory bedding developed in front of the main slipface [7], and tangential foresets which merge with structureless or faintly laminated sandstones (FLCS facies see below). In rare cases small pods of structureless sandstone filling scoop shaped erosion surfaces occur within the large foresets (**Figure 6**). Internal erosion surfaces, broadly concave upwards are very common (**Figure 5(D)**) [7]. At the Roaches LSXB is overlain by MSXB which merges with it down dip over a series of convex upwards reactivation surfaces (**Figure 7**) [7]. A similar relationship has been described in the Kinderscout Grit (Namurian R1c), where even thicker large scale cross-beds are present [21] and also observed by the present author in the Warley Wise Grit (Namurian E1c), proving a sometime genetic link between the two facies. The origin of this very unusual facies is controversial. There have been a variety of different sedimentological interpretations over the years, including Gilbert-type deltas [12] [21] [25]; alternate bars [7] [27], and sedimentation across a knick-point [3].

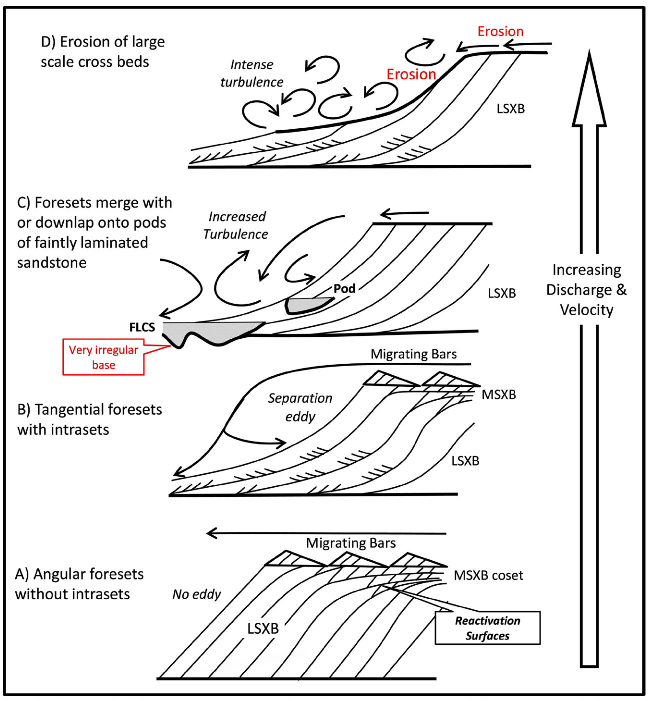

Figure 5. Different types of Large Scale Cross Bedding present in the Roaches Grit, interpreted to be related to changes in discharge and current velocity.

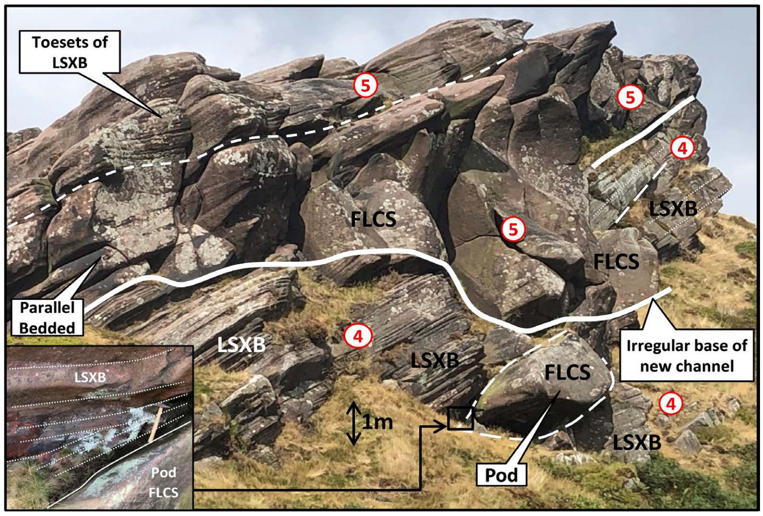

Figure 6. Ramshaw Rocks: Relationship between LSXB toesets and FLCS. The tectonic dip to the left exaggerates the inclination of the LSXB. A pod of FLCS fills an erosional hollow cut into the LSXB toesets of Channel (4). The base of Channel (5) is very irregular over several hundred meters. Structureless sandstone passes up to poorly defined horizontal bedding and then up into the well laminated toesets of LSXB. Inset: relationship between FLCS pod and overlying LSXB.

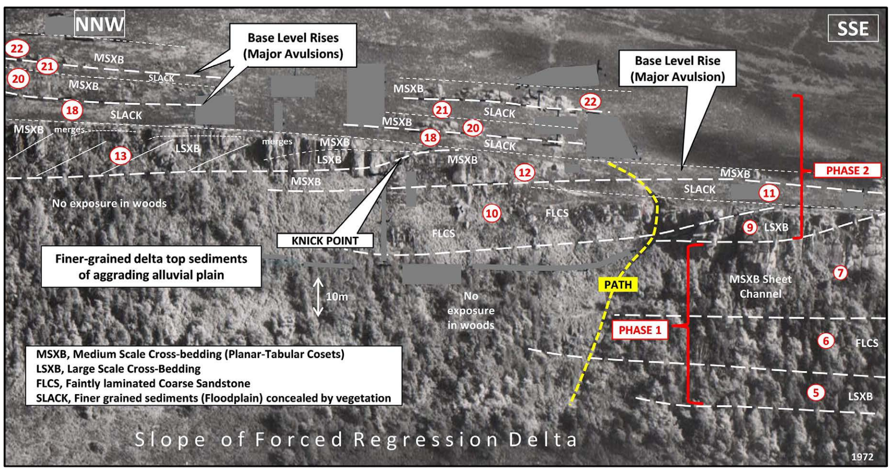

Figure 7. Oblique aerial photograph (1972) of the central part of The Roaches outcrop; showing the junction between Phases 1 & 2. In Event (13) MSXB in a shallow part of the channel merges with LSXB across a knick-point.

3.3. Structureless and Faintly Laminated Coarse Sandstone

This unusual lithofacies comprises coarse to very coarse and pebbly sandstones. Although commonly appearing to be completely structureless, with favourable weathering, faint cross-cutting and undulatory lamination is visible [1] (**Figure 8**). Two associations occur. At Ramshaw Rocks where the facies is closely associated with overlying LSXB, underlying channel bases are commonly extremely irregular with very steep sides forming scoop-shaped erosive hollows ([1], Plate 2) (**Figure 6**). Within the hollows the lamination indicates lateral fill and the steepness of the sides (locally up to 80˚) suggests sedimentation followed immediately after erosion. In some channel fills weak parallel lamination (Figure 6) and undulating lamination, 2 - 4 m in relief occurs at a slightly higher level above the hollows [1]. FLCS is also seen within the toesets of LSXB at both Hen Cloud [7], and the Roaches. In the second association, an identical facies comprises the entire fill of channels up to 40 m thick (see Section 5). Although mainly deposited in the deepest parts of the channels; one example of FLCS with lower amplitude undulating lamination (<1 m) (Figure 8(B)), has a solitary set of MSXB sandwiched within it. This unit was probably deposited in a shallower part of the channel.

Figure 8. (A) FLCS with faint inclined lamination and internal erosion surface (arrowed); (B) FLCS with faint undulating lamination (1) and erosion surface (2). The Roaches.

The mode of deposition of these sandstones has always been problematic. In the Warley Wise Grit delta top sequence (Namurian E1c, Figure 1), a very similar facies to the FLCS has been interpreted as density current deposits [25]. These could occur within a channel if there was slumping of sediment down a knick point or the foresets of the LSXB. However, the style of the lamination and the presence of scoop shaped erosion surfaces; are not very supportive of this explanation. The undulating lamination could be evidence of antidunes, which form in supercritical flows defined by a *Froude Number*: of 1 or greater. Possible antidune structures in the same facies were described from the late Kinderscoutian in a very early paper [28]. However, the predominance of the facies in the deepest parts of the channels does not support an upper flow regime origin. Channel (1) (Figure 9) entirely filled with FLCS was over 40 m deep. The FLCS at the base of Channel (5) at Ramshaw Rocks (Figure 6) is overlain by a LSXB set 15m thick. To achieve upper flow regime at these water depths would require impossibly high velocities.

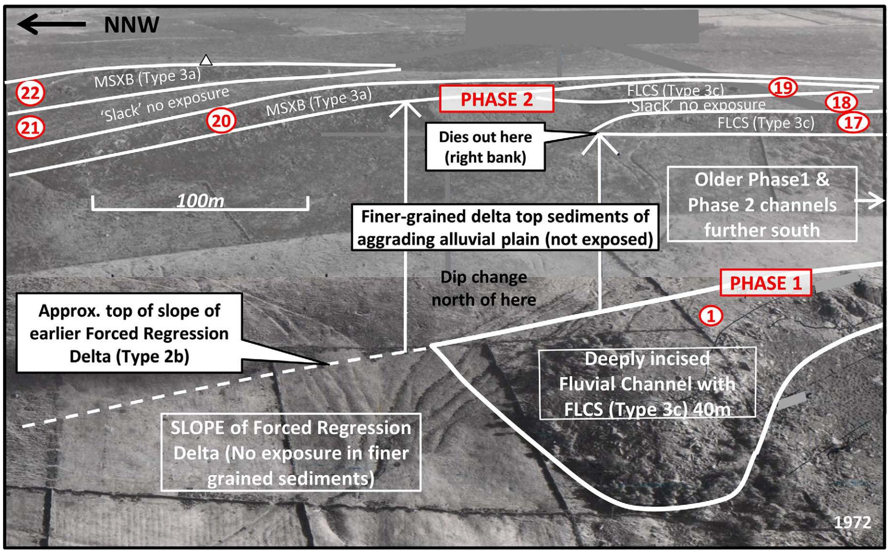

Figure 9. Oblique aerial photograph (1972) showing revised interpretation of the delta top sequence at the northern end of The Roaches. (Compare to [1] Plate 3). Foreshortening exaggerates the thickness of the Phase 1 channel. MSXB = Medium Scale Cross-Bedding coset. FLCS = Faintly-laminated coarse sandstone (Type 3c channels).

FLCS in the Roaches Grit was originally interpreted as being deposited within powerful and very turbulent currents in the lower flow regime but outside the dune and bar stability fields [1]. This is still the favored explanation for the FLCS deposited in the deeper parts of the channels. It would be unusual however, if some upper flow regime deposits were not present in channels with periodically high discharges, as they are common in many channel deposits of this origin [29]. The low amplitude undulating lamination (**Figure 8(B)**) seen in association with MSXB in a nearby exposure in the same channel fill appears to be deposited in a shallower part of the channel. This could be evidence of antidune deposition.

4. Description and Interpretation of Channel Types

The Roaches Grit fluvial channel fills were originally interpreted as the deposits of deep delta distributaries [1]. This interpretation is now only favored for the finer grained channel sand bodies in the early progradational delta sequence (**Figure 3**) [2] [3] [6] and is no longer tenable for the later thick coarse and very coarse grained channel deposits. In delta distributaries, the main feeder channel usually divides at the delta into a number of smaller channels which then distribute the flow between them. However, the field evidence in the uppermost Roaches Grit succession suggests there was probably only one large channel active at any one time. Although there are many channel fills exposed in the Ramshaw Rocks, Roaches and Dane Valley area, nearly all of them are vertically displaced and align with successively high base levels [1]. Also, most of the channels have SE-NW channel orientations showing little variation.

Because of the large scale of the channel deposits and limited size of natural exposures, working out how different lithofacies deposits were organized within the channels has always been problematic. With the adoption of a sequence-stratigraphic approach in the 1990's many of the very coarse grained fluvial channels sand bodies in cyclothems within the UK Pennine Basin, including the Roaches Grit [6] were reinterpreted as incised valley fills. Although this interpretation is still accepted by many [25] [30], this view was challenged by the present author [3], who now believes the complex fluvial channel architecture as described below is inconsistent with an incised valley interpretation.

Two different channel types are now recognized; this follows the classification previously defined in [2].

4.1. Sheet Channels (Type 3a)

Channels of this type are dominated by the planar-tabular cross-bedding facies (MSXB) and cosets are typically up to 20 - 35 m thick. Cross-bedding paleocurrent data [1] [5] suggest the channels were of low-sinuosity. Sand body widths are difficult to determine for reasons cited above. One channel fill (21) is nearly 7km wide, and another (7), slightly wider assuming the sand bodies at Hen Cloud and near Leek (**Figure 2(B)**) are the same, although there is no continuous exposure. The channels were probably relatively stable and constructed wider sand bodies by lateral migration, as also suggested for similar channels in the Kinderscout Grit [21] [22]. With a rapidly rising base level there was time to provide sufficient accommodation space that allowed for aggradation to produce a sand body thicker than the depth of the active channel.

4.2. Incised Channels (Type 3c)

These channel sand bodies can contain all three of the facies described above. Two varieties are recognized. In one, only the structureless and faintly laminated sandstone facies (FLCS) is present. Channel sand bodies range from 10 - 40 m thick and 280 - 500 m wide, and may be either symmetrical or asymmetrical in cross section (**Figure 9**). Where exposed, channel bases are smooth. Similar channels have been described from the upper Grindslow Shales (Kinderscoutian, Namurian R1c) [22] [31].

In the other variant all three facies types are present, although not always observed because of outcrop and exposure limitations. The FLCS facies occupies the lowest part of the channel fill and is overlain by large scale cross bedding (LSXB). This is overlain by sets of medium-scale cross-bedding which at The Roaches (**Figure 7**) are seen to merge down current with the large foresets over a series of convex up erosion surfaces (see also [7]). These medium-scale cross-beds continue further up current, forming thin cosets deposited in shallower parts of the channel identical to those seen in the Type 3a sheet channels.

Channel widths in this variant are difficult to determine because of exposure limitation and many channel fills are mutually erosive. At Ramshaw Rocks two superimposed channel fills (3) & (4) are each c850m wide, and in the upper one the large scale cross beds are exposed across almost the entire channel width;

although there is no exposure near the edges of the channels. An overlying channel fill (5), possibly composite, is at least 1.4km wide (**Figure 6**), with the southern edge extending beyond the outcrop. LSXB in this channel fill can be traced in discontinuous exposures along the dip slope of Ramshaw Rocks for several hundred meters across the width of the channel. The large scale cross beds show variable orientations with respect to the channel edge. In younger channels (9) (13) at The Roaches (**Figure 7**), they build out obliquely from the channel edge [4] [7] but elsewhere orientations can be either normal to or directed towards the channel edge.

It should be noted that these types of deep channels only occur near the delta front. They are not seen in the upper part of the Ashover Grit which contains the deposits of the same fluvial system 50km up current from the delta front (**Figure 2**) [6].

4.3. Discharge Variation

Sedimentological evidence for discharge variations in both the MSXB and LSXB facies at The Roaches was discussed in detail in the late 1970's [5] [7], although this is not accepted by some more recent workers [30]. Variations were all assumed to relate to annual river flooding events. At the time there were few published accounts of sedimentation in large river rivers with fluctuating discharges. Coleman's classic description of the Brahmaputra River [32] was regarded as possible analogue. This river is still regarded as most useful because it is largely fed by annual monsoon rainfall of high intensity and a great deal of information is now available. Summer monsoon rains falling in the SE Himalayas and Tibetan Plateau feed the river, although not all of the catchment area is within the monsoon rain belt and some of the discharge comes from melting glaciers at high elevations [32]-[34] which ameliorates the impact of rainfall variation on discharge. The active channel of the Brahmaputra [32] is also much wider than the channel fills in the Roaches Grit.

Fluvial sequences deposited by rivers fed by irregular rainfall have a number of characteristics [29] [35] [36]. The Roaches Grit channel deposits have several of these (**Table 2**). Although no mud drapes, trace fossils or bedform shapes have been observed, they are known to the author in other channel deposits from the Pennine fluvial system. No in-channel vegetation is observed, but unlike in the Brahmaputra River [34], the Roaches Grit shows no evidence for any large stable braid-bars where in channel vegetation can develop, although these have been postulated in the late Kinderscoutian Brimham Grit [37]. Absence of positively identifiable UFR facies is also noted.

Attempts to identify the catchment area of the Pennine delta drainage system have used a variety of techniques which do not give entirely consistent results. The majority of the studies have used heavy minerals including zircon and monzanite age dating, petrography, and garnet geochemistry [38]-[44]. Another approach has looked at Pb isotopes in K-Feldspars [45]. Earlier workers in the 19th

Table 2. Characteristics of fluvial channel deposits with irregular discharge. After Jones (1977b) [35], Plink-Björklund (2015) [29], Fielding *et al.* (2018) [36].

Parameter	In Roaches Grit	In other Pennine Cyclothems
Frequent Channel Avulsions	Yes	Some
Catchment area within monsoon rain belt latitudes	Yes	Yes
Upper flow regime (Fr > 1) deposits	Possible	Uncertain
Mud drapes in channel fill	No	Rare
Pedogenically modified mud deposits	No	No
Abundant in-channel mudstone clasts (bank collapse)	No	No
Trace fossils in channel fill	No	Uncommon
Soft sediment deformation	Yes	Yes
Lack of base flow sediments	Yes	Uncertain
Bar or dune shape preserved	No	Rare
Growing vegetation in channel	No	No
Evidence for superimposed bedforms in bars	Yes	Yes
Reactivation surfaces in bar cross-bedding	Rare	Not Seen

and early 20th centuries were able to collect very coarse pebbles from numerous working quarries (now filled in), which enabled them to identify a particular rock type, which they could compare with the hinterland geology [46] [47]. A recent multidisciplinary study [48], the culmination of many years work, has concluded that the East Greenland Caledonides were the dominant source area with additional contributions from NE Scotland and western Norway. In the late Namurian these three areas lay between latitudes 4˚ & 15˚ North (**Figure 10(B)** & **Figure 10(C)**) [49].

The Caledonian Mountains are unlikely to have been of Himalayan proportions as previously suggested [47], as they underwent severe erosion during the Devonian and early Carboniferous. However, absence of Namurian and early Westphalian A strata from Kongeborgen in East Greenland (**Figure 10(C)**) suggests possible end Visean uplift [43]. Higher elevations in East Greenland would have resulted in higher rainfall than in the other lower lying catchment areas; as it does not require huge elevation to have a significant orographic effect on rainfall. This could explain why East Greenland, although a relatively small area, has provided the greatest proportion of sediment in the Pennine fluvial system [43]. It is likely that the feldspar rich Caledonian granites intruded into Pre-Cambrian basement are the source of the relatively unweathered K-feldspar grains which are such a common feature of the coarser fluvial channel deposits in the UK Pennines succession. Monzanites with Caledonian ages probably have a similar granitic origin [41].

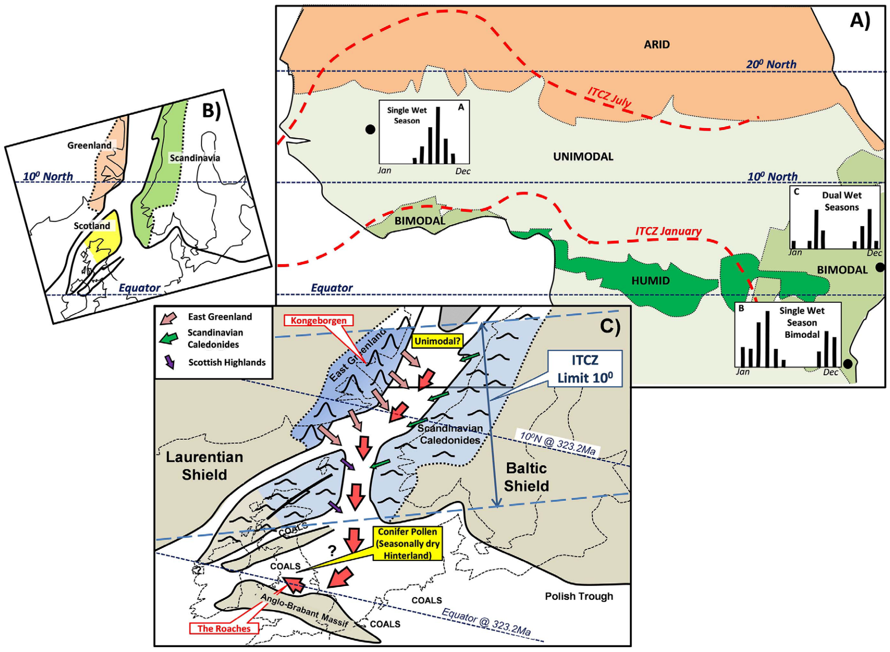

Figure 10. (A) Climatic Zones of North Africa with January and July positions of the ITCZ after Herrmann and Mohr 2011 [50] and Ngeutsop *et al.* 2011 [51]; (B) Caledonian fluvial catchment areas in NW Europe at same scale and equivalent latitudes at 323 ma (Namurian); (C) Detail of catchment areas during deposition of Roaches Grit with the ITCZ related rainfall belt (10˚ Latitude in width) at optimum location to maximise runoff from all three areas.

There were no grasses in the Carboniferous. Palynology and fossilized wood from two late Namurian marine bands in the southern Pennine Basin deposited after the delta plains were flooded suggests the hinterland Upper Carboniferous vegetation comprised gymnosperms; especially cordaites and also tree ferns, and cycads [52] [53]. Cordaites grew in a variety of environments [54]-[57], those without growth rings more likely found in ever-wet environments. The southern Pennine hinterland flora is most likely derived from the nearby Anglo-Brabant Massif (**Figure 10(C)**), a probable ever-wet environment very close to the equator during the Namurian. However, in the central part of the Pennine Basin in Derbyshire a 'super-hinterland' palynology fauna of bisaccate Gymnosperms has been recorded from the *Reticuloceras reticulatum* (R1c3) marine band [58], within the late Kinderscoutian deep water delta succession (**Figure 1** & **Figure 10(C)**). This flora is probably represents early conifer vegetation which is believed to have evolved in the driest upland areas [56] [59] [60], suggesting that seasonally dry uplands must exist not too far distant from the Pennine Basin.

In present day Africa (**Figure 10(A)**), a unimodal summer rainfall with a long dry season and savannah vegetation prevails north of latitudes 5˚ - 10˚ as far north as latitude 20˚ [50] [51]. The greater part of the Caledonian catchment area also lay within these latitudes during the Namurian (**Figure 10(B)**). Sediments in the Roaches Grit are rich in K-feldspar and mica [1] indicative of limited chemical weathering, and suggesting a rapid rate of erosion [38]. This would seem unlikely in a continuously wet highly vegetated tropical environment, which is more likely to source quartzitic sandstones as seen in the Namurian protoquartzites (turbidites) in the Staffordshire basin which were derived from the Anglo-Brabant Massif [61]. In the R2b5 cyclothem, this land area also supplied quartzitic sands along the basin margin near Leek (**Figure 2(A)**) after the abandonment of the forced regression delta (**Figure 2(B)**) [3].

On the basis of the sedimentology data presented above, the climate of most of the catchment area was probably different to that prevailing in the Pennine Basin, which shows limited evidence for significant seasonal drying, although an alternative interpretation has been proposed [30]. The northern catchment area is assumed to be seasonally dry and with different vegetation than the Anglo-Brabant Massif. Forest fires may have reduced vegetation cover in a high oxygen atmosphere [62], although the impact of these has been questioned [54]. Therefore, significant run off could have been possible from this area during periods of intense monsoon rainfall, which could result in a fluctuating discharge regime not dissimilar to the modern Brahmaputra system (**Figure 11**); although the Brahmaputra has a very different type of catchment area in terms of elevation, areal extent and vegetation cover.

5. Variability in Channel Sedimentation

The channels are interpreted to have been straight or low sinuosity with a meandering thalweg and average widths during bankfull discharge typically approaching 1 km (**Figure 12**). Extremely high discharges associated with mega-monsoon rainfall in the catchment area occurred during some summers, and the flow was extremely turbulent. The high slope of the deep water delta allowed for deep erosion where the channel thalweg with highest velocity met the slope. As more sediment was eroded away the zone of maximum erosion began to progressively shift further up the channel creating a knick-point between the deeply eroded area and main channel (**Figure 12(A)** & **Figure 12(B)**). Continuation of this process led to knick-point recession. The eroded channels had steep gradients. The earliest channel (1) exposed at the northern end of The Roaches outcrop (**Figure 9**) has a 40 m thick fill and is deeply incised through much of the slope sequence of the earlier delta. This is the only channel fill which is also exposed on the other side of the syncline at Ramshaw Rocks, 2.5 km further away from the delta front. There is significantly less incision into the slope at this location. The channel fills exposed at the Roaches and Ramshaw Rocks areas lie approximately 4 - 6 km. behind the delta front which lay close to the Dane Valley at this time (**Figure 2**). Erosion over this distance probably required a number of flood cycles. The knick-point at the up current limit of erosion formed a step in the channel with very turbulent deeper water down current from the knick point and shallower water

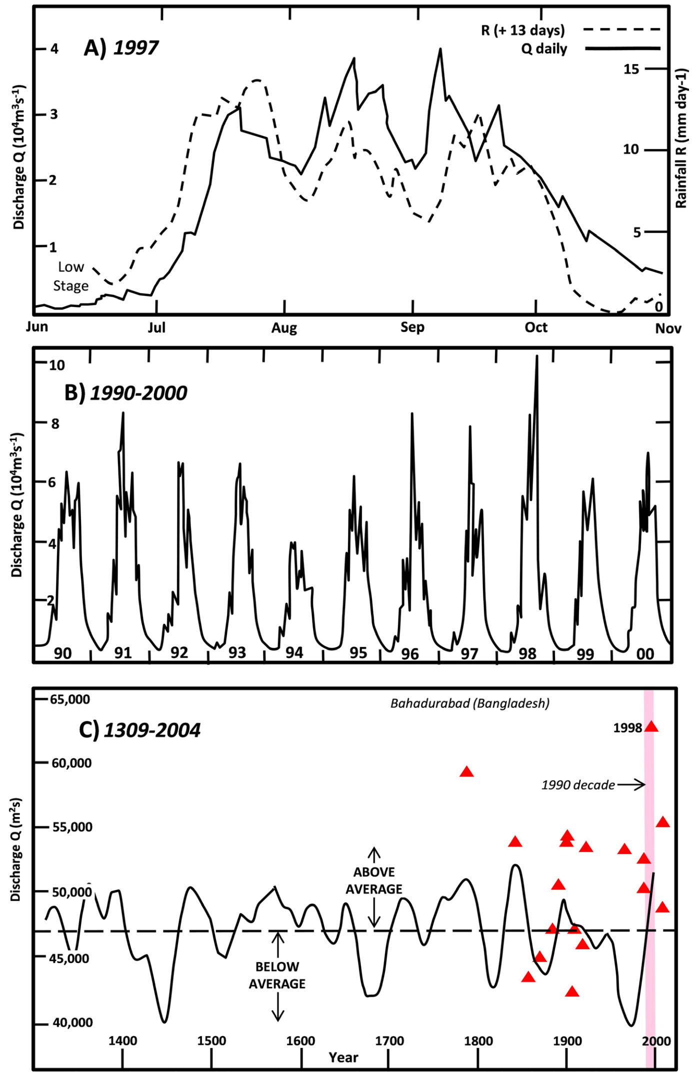

Figure 11. Measured discharge variation in the Brahmaputra River over different time-scales. (A) Variations during 1997 flood peak in relation to monsoon rainfall fluctuations in the catchment area; (B) Annual variability in river discharge for years 1990-2000 (After Jian *et al.* 2009 [63]); (C) Reconstructed average annual discharge for period between 1309 and 2004 C. E. using tree ring data in East Asia to estimate monsoon rain variability; plotted using a 50-year low-pass filtered reconstruction (solid black) to highlight multi-decadal variability. Red triangles show measured Brahmaputra peak discharges for selected years (After Rao *et al.* 2020 [64]). The pink bar shows that the 1990 decade shown in B is an above average period.

up current (**Figure 12(B)**). As the river discharge started to decrease, net erosion gave way to net deposition forming the FLCS channel-fill facies immediately down-current from the knick-point.

In subsequent periods there were two possible outcomes for these incised channels. In many cases the channels were abandoned, probably because of the high likelihood of avulsions with the very high discharges (**Figure 12(C)**). Prior to abandonment the deeper part of the channel was filled with the FLCS facies. After abandonment the partly empty channel was filled with fine-grained deposits.

These are never exposed in natural outcrops in the UK Pennines being always covered with vegetation. They are only seen in rare stream sections and cannot be distinguished from delta plain deposits which are of similar facies (siltstones and ripple laminated sandstones). This explains why observed widths of the coarse sand fill never exceed 500 m, although the active channels were probably wider in many cases. A similar range of channel widths was described from the Upper Grindslow Shales (the lower part of the Kinderscout Grit delta sequence), which are filled with a similar coarse sandstone facies [31].

If the channel was not abandoned, and flood discharges in later years were not as great, bars similar to those occupying the Type 3a sheet channels are developed, depositing identical cosets of MSXB. As the bars moved down the channel they encountered the knick-point cut during a previous years flood. Large foresets then built out down channel from the knick-point as the migrating bars filled in the deeply eroded channel (Figure 12(D)). This explains why the LSXB occupies the greater width of the channel. This is impossible if they were alternate bars as previously suggested. These hybrid channels contain all three of the main lithofacies types.

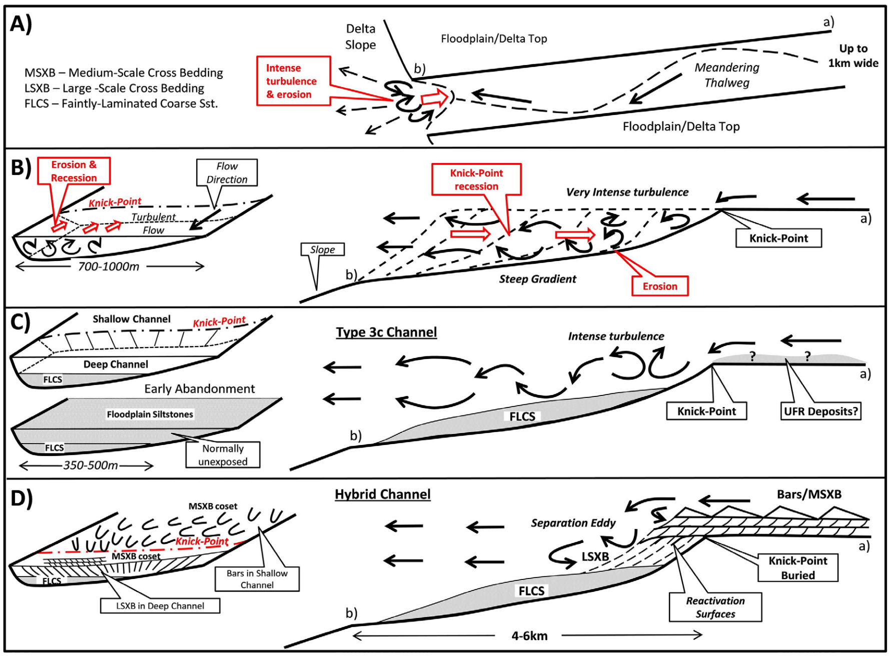

Figure 12. Stages in the evolution of Type 3c incised channels. (A) Intense turbulence leads to erosion into the top of the slope; (B) This migrated up-channel eroding a knick-point; (C) FLCS facies deposited in incised channel following small reduction in flow strength. Early abandonment leaves a partly filled channel with FLCS; (D) Where the channel is not abandoned, a subsequent flood with lower discharge develops bars in the shallower channel. These build large foresets (LSXB) as they migrate across the knick point.

The different types of LSXB previously described (Figure 5) are now interpreted as the sedimentary response to rainfall-related discharge fluctuations. At lower discharges migrating bars constructed large slip faces as they crossed the knick-point; with a separation eddy developing as discharge increases (**Figure 5(A)** & **Figure 5(B)**). With more powerful floods (**Figure 5(C)**) and increased turbulence a similar facies (FLCS) is deposited in the lee of the LSXB, as observed at Ramshaw Rocks (**Figure 6**). With further discharge increases, erosion cuts into the foresets cutting convex erosion surfaces (**Figure 5(D)**), rather like reduced scale knick-point recession. This is one of two mechanisms previously suggested for the origin of these erosion surfaces [7].

6. Alluvial Stratigraphy

Excellent exposures in the Roaches/Ramshaw Rocks/Hen Cloud area at the southern end of the Goyt Syncline (**Figure 2**) allow the recognition of twenty three separate depositional events during the evolution of the upper Roaches Grit delta; between its reactivation following the eustatic minimum and final abandonment, prior to flooding and deposition of the *B. superbilinguis* marine band, which delineates the termination of the cyclothem (**Table 3**).

Table 3. Sequence of depositional events in the Upper Roaches Grit, identified in The Roaches, Ramshaw Rocks and Upper Dane Valley areas.

Event	Lithofacies	Phase
23	Wave reworked fine sandstone	2
22	Type 3a channel MSXB	2
21	Ripple laminted sandstones & siltstones	2
20	Type 3a channel MSXB, & LBS on slope	2
19	Type 3c channel mostly FLCS	2
18	Mainly siltstones	2
17	Type 3c channel FLCS	2
16	Type 3c channel hybrid	2
15	Type 3c channel hybrid	2
14	Type 3c channel FLCS	2
13	Type 3c channel hybrid	2
12	Type 3c channel FLCS	2
11	Fine grained sediments unexposed	2
10	Type 3c channel FLCS	2
9	Type 3c channel hybrid	2
8	Type 3a channel MSXB	1
7	Type 3a channel MSXB	1
6	Type 3c channel FLCS	1
5	Type 3c channel hybrid	1

Continued

4	Type 3c channel hybrid	1
3	Type 3c channel hybrid	1
2	Type 3c channel FLCS	1
1	Type 3c channel FLCS	1

Twenty of these events correspond to different styles of fluvial channel sedimentation as described above, most separated by avulsions during which there were rises in base-level of varying amounts. Three correspond to longer periods of floodplain sedimentation during longer-lasting avulsions and the last event (23) corresponds to wave reworking following abandonment of the channel system [1]. Reconstructed plan views for eight periods through Phases 1 and 2 are shown in **Figure 13**.

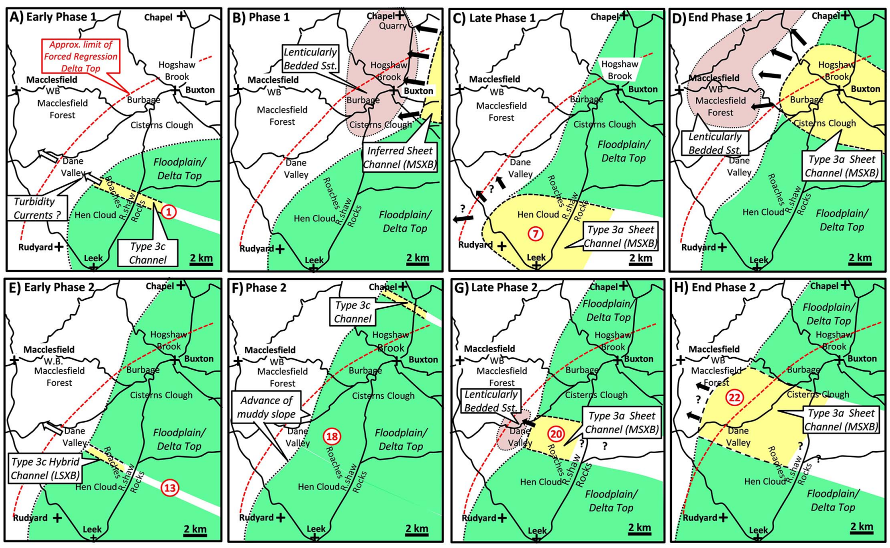

Figure 13. Eight snapshots showing the evolution of the upper Roaches Grit (Type 3) delta. (WB = Walker Barn Quarry) Numbers in red circles are events recognised in The Roaches area. Green = estimated position of alluvial plain. Yellow = mapped position of fluvial channel deposits. Purple = mapped position of lenticularly bedded sandstones. Timing of major delta sedimentation in the Buxton area (B & D) is estimated as no direct correlation with The Roaches area is possible.

The earliest event (1) (**Table 3**) is a deeply-incised, asymmetrical fluvial channel sand body (Type 3c) over 40 m thick which is filled entirely with structureless coarse sandstone, locally with faint irregular lamination (FLCS facies). At The Roaches (**Figure 9**) the channel cuts deeply into the slope sequence of the previously abandoned forced regression delta and must have formed before there had been a significant base-level rise. Later events (3) (4) & (5) are hybrid channels exposed in cross-section at Ramshaw Rocks (**Figure 6**) and partly along channel at Hen Cloud (**Figure 4(B)**) and southern Roaches area. There follows another

Type 3 channel with FLCS (6) incised into (5) ([7] Figure 3) and overlain by two Type 3a channels with MSXB. The first of these (7) is a 22m thick coset (Figure 4(B)) and probably came into the area following an avulsion before which there was a significant rise in base level (Figure 13(C)). Another sand sheet with MSXB (8) completes the first phase of sedimentation.

Phase 2 begins with a hybrid channel (9) and another thick channel with FLCS (10) (Figure 7), followed by a further avulsion (11) after another significant base level rise. Events (12) & (13) are possible flood events within the same channel (Figure 7 & Figure 13(E)). Channel (13) exposes the knick point with MSXB up current from the knick point, passing down channel and merging with LSXB deposited in the deeper channel down current to the north-west. In older interpretations this was regarded as a channel edge sequence through an alternate bar [7]. A very similar situation is seen in the Kinderscout Grit where the LSXB was originally interpreted as a Gilbert Type delta [21]. Further to the north-west along The Roaches escarpment younger Type 3 channels are exposed, with evidence of further avulsions following minor base level rises. This is terminated by a major avulsion and the deposition of flood plain sediments (18) (Figure 7 & Figure 13(F)).

In the Dane Valley, channels within Phase 2 cannot be directly correlated with the Roaches area because of a gap in exposure. A series of stacked channel fills are present on the eastern side of the Dane Valley (Figure 14 & Figure 15). These are all Type 3c channels and all three facies, FLCS, MSXB & LSXB are present in different channels, which have limited exposure. None of these channel fills are developed on the west bank of the Dane Valley proving that the delta front lay along the present course of the Dane River (Figure 14 & Figure 15), having retreated from its earlier limit after abandonment during the eustatic minimum. The delta was unable to prograde further westwards during this period because of the rapidly rising base level. A major avulsion inferred at the northern end of The Roaches escarpment (Figure 7 & Figure 13(F)) followed by the deposition of thick finer grained floodplain sediments (Event 18), (unexposed, but forming a 'slack' feature which always corresponds to finer grained sediments the Pennines) is correlated with thick siltstones exposed on the western river bank which form part of an extensive muddy slope which developed beyond the older channels during the prolonged avulsion (Figure 13(F) & Figure 15).

A return to active channel sedimentation is marked by event (20), a MSXB sheet sand (Type 3a) which can be mapped from the eastern Dane Valley back towards the northern Roaches (Figure 7 & Figure 15). This channel fed density current deposits over the muddy slope (see Section 7 below), exposed in the valley further north [1] (Plate 1) (Figure 13(G) & Figure 15). Further abandonment and avulsion led to more flood plain sedimentation (21) (Figure 7). This is correlated with ripple laminated sandstones containing *Pelecypodichnus* trace fossils (resting traces of marginal marine bivalves [65]) deposited at the top the delta slope in the Dane Valley area (Figure 14). A final phase of fluvial sedimentation (22) is presented by another sheet-sand with MSXB. This extensively exposed sand

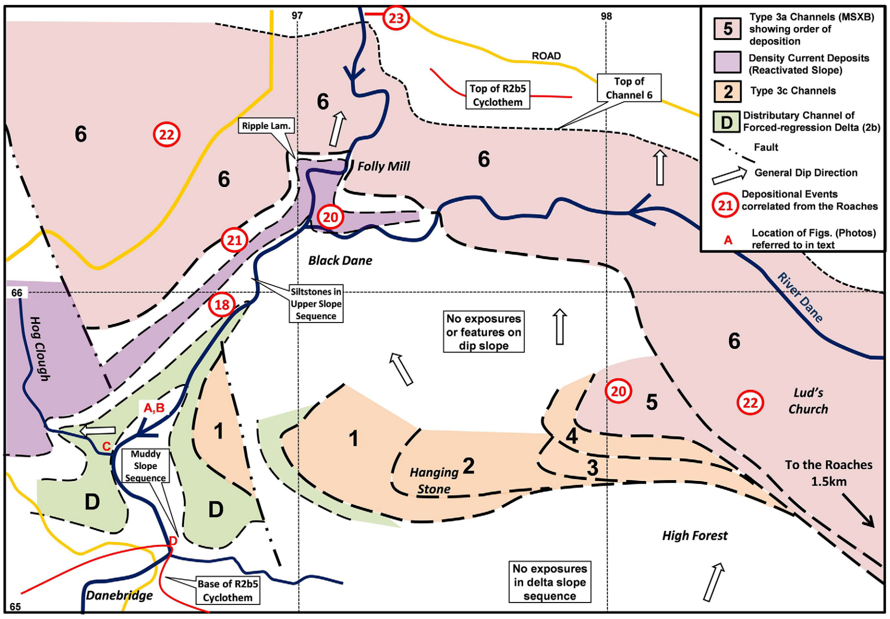

Figure 14. Geological map of the Dane Valley showing delta, channel & slope sequences. A, B, C & D show locations of photographs in **Figure 3**. Grid lines are 1 km spacing. Numbers in red circles are Events discussed in Section 6. Black numbers refer to order of deposition of the Six Type 3 Delta channels fills in the Dane Valley.

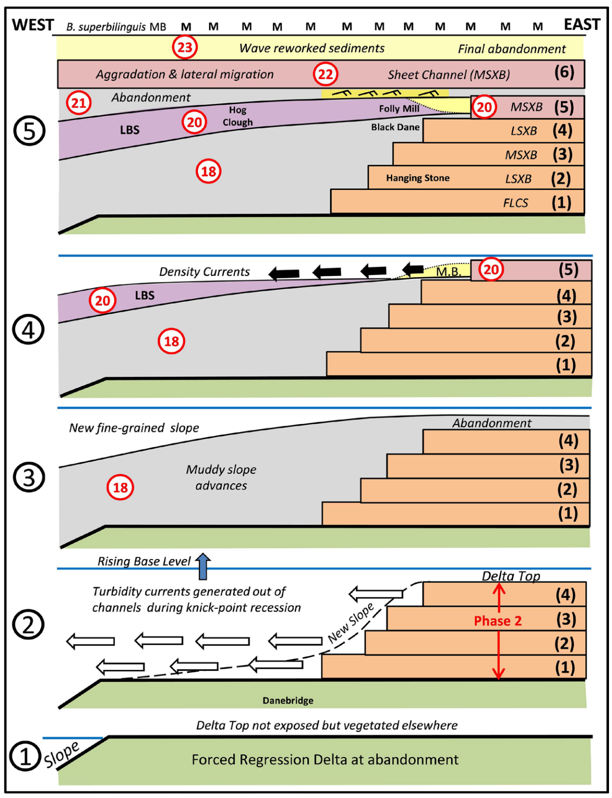

Figure 15. Sequence of events visible in the River Dane section. The red circles correspond to events correlated from The Roaches area to the SE. LBS = Lenticularly bedded sandstone. M.B. = mouth bar.

body can be mapped from the northern Roaches below the trig point (**Figure 9**) along the Dane Valley (**Figure 13(H)**, **Figure 14** & **Figure 15**) which it crosses, and then extends further west to the limit of the outcrop.

During avulsions, deltaic sedimentation switched to the northern area of outcrop around Buxton and Chapel-en-le-Frith (**Figure 13(B)** & **Figure 13(D)**). Four events are recognized in that area, although none can be correlated directly with the Roaches area stratigraphy. Density current deposits exposed at Burbage and Hogshaw Brook overlie a reactivated slope sequence and are fed by an inferred MSXB sheet channel active to the east of Buxton where the R2b5 cycle does not outcrop (**Figure 13(B)**). This was probably during Phase 1. Another overlying MSXB sheet channel is believed to be the source for the extensive density current deposits outcropping further west in the Macclesfield Forest area (**Figure 13(D)**). These sediments were deposited in deeper water over the lower slope and adjacent basin floor of the abandoned forced regression delta (**Figure 16**). They are overlain to the east of the Forest by a 75 m thick slope sequence, mainly mudstones and siltstones with ripple laminated sandstones with *Pelecypodichnus* in the top few meters. This slope was generated in front of the slowly advancing floodplain to the north of active channel sedimentation in the Roaches/Dane Valley area during the later stages of Phase 2, eventually building out over the slope of the older abandoned delta (**Figure 16**). The final fluvial event (22), the MSXB sheet channel exposed in the Dane Valley and the Roaches eventually migrated north-westwards and overlay the top of this thick slope (**Figure 13(H)** & **Figure 16**). A wave-reworked abandonment sequence of very fine grained sandstones and siltstones containing marine trace fossils (23) overlies the sheet channel [1] (Plate 2).

7. Delta Slope Sedimentation and Processes

Two delta slope successions are present. The earlier slope interval, up to 80 m thick (post-compaction) was deposited by the forced regression delta and constitutes the main basin fill phase [3] [6]. It is mainly composed of mudstones and siltstones (**Figure 3(D)**); with ripple laminated sandstones with *Pelecypodichnus* trace fossils [1] (Plate 2) deposited when currents flowed down the slope during floods. Thin mouth bar deposits with wave ripple lamination and small scale cross-beds are seen towards the top (**Figure 3(A)** & **Figure 3(B)**). (See references [1] [6] for more details). The overall 'muddy' nature of the slope reflects the waning power of the delta prior to its final abandonment during the eustatic minimum [3]. The slope was reactivated during the final phase of deltaic sedimentation [3]. A rapidly rising base level, caused mainly by high subsidence, in combination with the post-glacial sea-level rise and compaction of the earlier fine-grained slope sequence created enough accommodation space for a second thick slope sequence to accumulate; although this was not recognized during earlier studies [1]. The Roaches Grit delta plain was approximately 30 km wide, and at any one time active fluvial sedimentation was probably confined to just one channel (**Figure 13**). Most of the slope lay adjacent to the delta top flood plain area and received

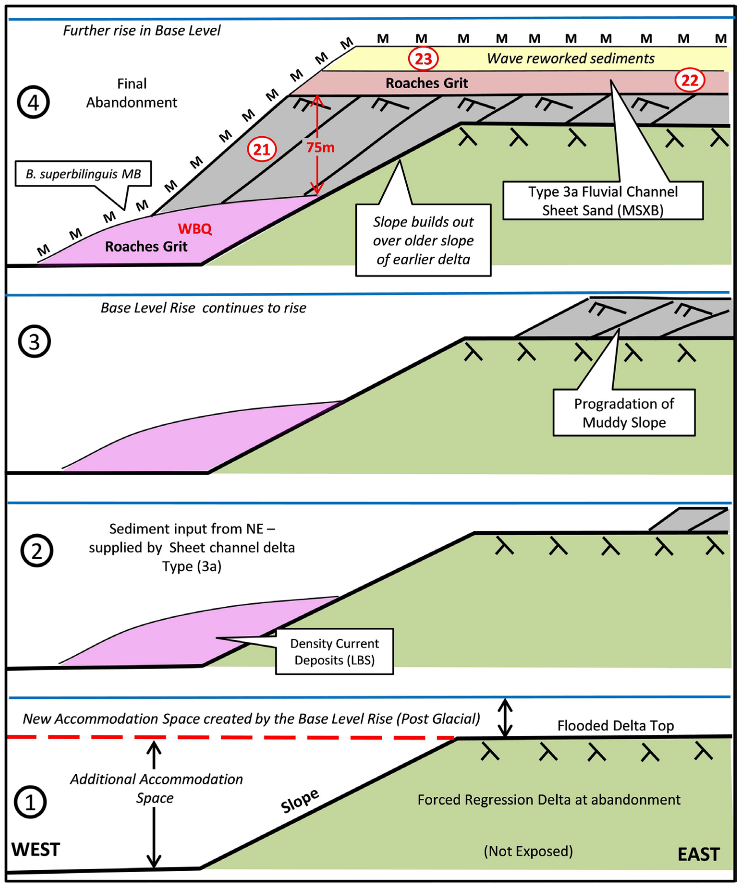

Figure 16. Sequence of events during deposition of the Roaches Grit delta in the eastern Macclesfield Forest (Figure 2(B)). This area was marginal to active channels during most of upper Roaches Grit sedimentation. WBQ = position of Walker Barn Quarry.

fine grained sediments washed out of the delta plain during annual flooding. There was only very limited progradation because of the rapidly rising base level (Figure 15 & Figure 16).

In front of active fluvial channels, two contrasting processes occurred depending on which kind of channel was active. With the deeply eroded channels cut by knick point recession (Type 3c) sediment by passed the slope and was swept further out into the basin (Figure 17). This was direct turbidite generation from fluvial channels as originally suggested for the late Kinderscoutian in Derbyshire [31]. The Roaches Grit delta slope lacks channels filled with coarser sediments. The one channel formally tentatively identified [1] is now reclassified as the earliest fluvial channel (1) eroded deep into the slope sequence of the earlier abandoned delta (Figure 9). The possibility of feeder channels filled with fine sediments after abandonment cannot be excluded, although these would be very difficult to differentiate from the fine-grained slope sequence in highly vegetated northern England Pennine outcrops. The turbidites generated during this process are not seen at outcrop as they are envisaged to have been deposited well to the west of the delta in an area where the Carboniferous is now buried by younger sediments. Examples of this type of basin floor turbidites are seen in the Corbar Grit and Five Clouds Sandstone in the immediately underlying R2b4 cyclothem (Table 1 & Figure 18). They must have been generated somewhere in the East Midlands area at least 50km further east; the fluvial Lower Ashover Grit [6] [10] (Figure 2) being the probable point of origin.

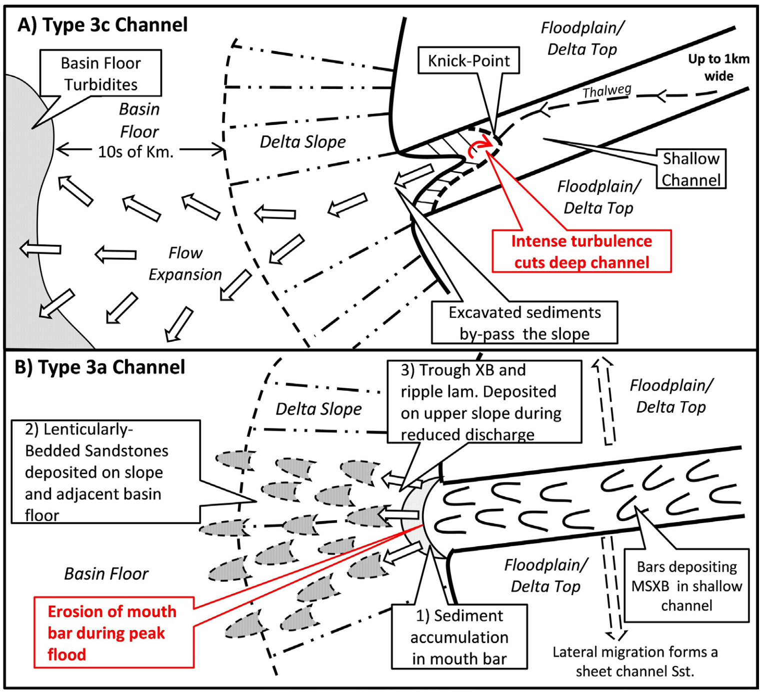

Figure 17. Types of slope processes operating in the upper Roaches Grit Delta. (A) Incised channel (Type3c), with direct turbidite generation out of the channel during knick point recession at peak discharge; (B) Laterally migrating channel with MSXB (Type 3a), sediment builds up in mouth bar and is then re-deposited mainly on the delta slope as density current deposits (LBS). Dunes and ripples active on upper slope.

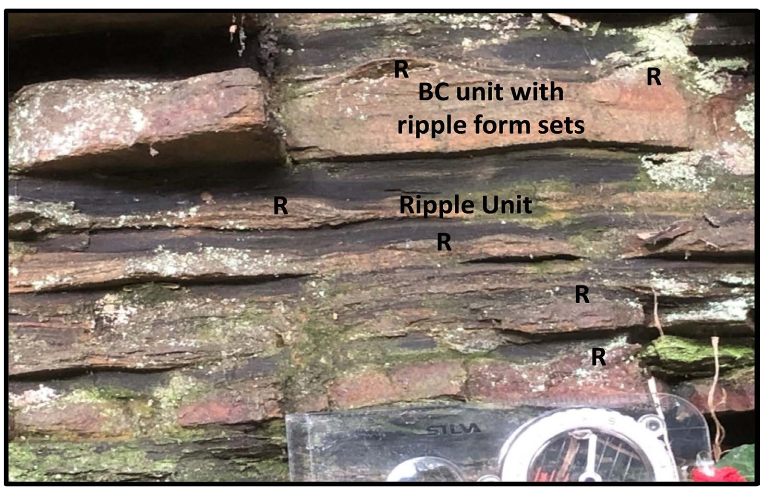

Figure 18. River Dean, Corbar Grit (R2b4 Cyclothem) showing an example of basin floor turbidites in a relatively distal facies.

During periods when the channels with MSXB (Type 3a) were active, very different processes operated. These channels carried sediment to the top of the slope and built mouth bars. These are rarely observed because of a combination of low preservation potential below the active prograding channels and poor exposure of this part of the sequence. An example preserved in a small quarry west of Chapel-en-le-Frith (**Figure 2(B)**) comprises several meters (base not exposed) of slightly undulatory bedded medium to coarse sandstones cut into by isolated trough cross-bedded units. These are directly erosively overlain by the MSXB sheet-channel fill (**Figure 13(D)**). During peak floods (and also possibly during storms) sediment was swept further down the slope to form lenticularly bedded sandstones (see [1] for a more detailed description). These have many similarities to turbidites, but also some significant differences, as summarized in **Table 4**. They are here referred to as density current deposits in order to distinguish them from the classical turbidites; although both are interpreted to have been deposited from powerful underflows. They show many similarities to the Scar House Beds in Yorkshire (Namurian, Arnsbergian, E2b3) (**Figure 1**), and a depositional model for these is discussed by [66].

Three separate accumulations occur. Two of these; in the Dane Valley and around Buxton were deposited on the reactivated delta slope (**Figure 13**). In the Dane Valley mapping (**Figure 14** & **Figure 15**) shows they were fed by a Type 3a channel (MSXB) in Event (20) (**Figure 13(G)**), which can be mapped back to the outcrop below the Trigonometry Point at the northern Roaches area (**Figure 9**). The Dane Valley and Buxton area deposits are inter-bedded with cross-bedded and ripple-laminated sandstones, and must have been deposited fairly high on the slope (**Figure 18**). Small distance of travel accounts for their lenticular nature, as there was insufficient time for the flow to spread out. Rapid deceleration accounts for the absence of ripple tops as seen in classical turbidites (**Figure 19**). The most extensive deposits outcrop in the Macclesfield Forest area (**Figure 13(D)** & **Figure 16**), although the best exposure in Walker Barn Quarry (**Figure 20**) is now filled in. These were deposited further out into the basin on top of the abandoned slope of the earlier forced regression delta and immediately adjacent basin floor (**Figure 16**). The sediments are believed to have been originally sourced from the extensive Type 3a channel (MSXB) exposed in the Buxton area (**Figure 13(D)**) and then transported down the slope across the Goyt Syncline where the R2b5 cyclothem is now concealed by younger sediments.

Table 4. Comparison between basin floor turbidites and density current deposits: Pennine Basin

Feature	Density Current Deposits	Turbidites
Fluted Bases	YES	YES
Amalgamation of massive sandstones.	YES	YES
Parallel Lamination	YES	YES

Continued

Ripple lamination at top (C unit)	NO	YES
Channeling	YES	YES
Bed Continuity	Lenticular	Usually laterally extensive
Associated Sediments	Cross-bedding, current ripple lamination & siltstones	Mudstones only
Pelecypodichnus trace fossils	YES in associated sediments	NO
Place of Deposition	Slope & immediately adjacent basin floor	Basin floor distant from the slope
Feeder Channel	Type 3a MSXB sheet channel	Type 3c incised channel with knick-point

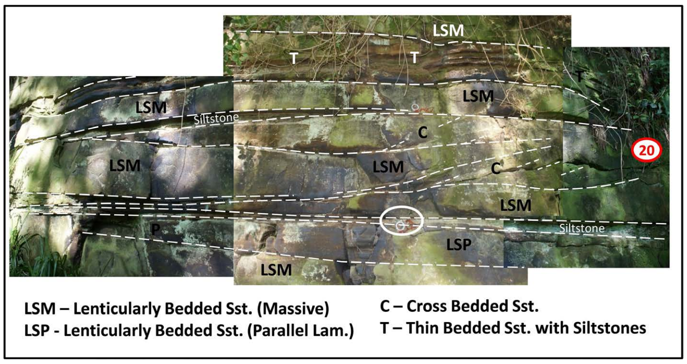

Figure 19. Folly Mill in the Dane Valley; exposes the upper part of the Lenticularly-Bedded-Sandstone sequence deposited on the reactivated delta slope. This was sourced by a channel dominated by MSXB (20) which outcrops on the dip slope 1 km further east. Silva compass, circled, gives scale. See Figure 14 for locations.

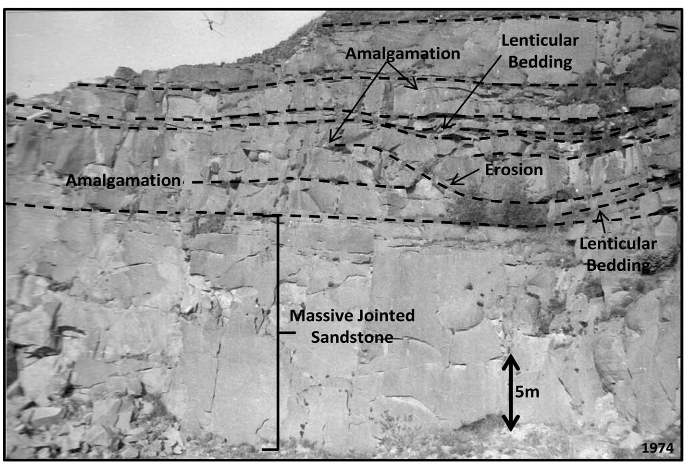

Figure 20. Walker Barn Quarry (now filled) photographed in 1974, showing density current sediments (LBS) deposited over the abandoned slope of the earlier (forced-regression) delta.

8. Discharge Variation and Climate

Sedimentary structures and facies variations in upper Roaches Grit channels discussed in Sections 3 and 4, and longer term changes in channel type discussed in Section 5, indicate variations in discharge over a number of different timescales (**Table 5**). Over shorter periods these were caused by annual or sub-annual discharge fluctuations related to variable monsoon rainfall or annual shifts in the ITCZ relative to the catchment area. Evolution in Type 3c channels from knick point recession and deposition of FLCS only, to deposition of LSXB fed by smaller bars (**Figure 12**) must have taken place over slightly longer time periods. A reconstruction of Brahmaputra discharge from 1309AD using tree ring data as a rainfall proxy [64] (**Figure 11(C)**) suggests variability during time intervals of 20-50 years. During each of these intervals successive annual flood discharge peaks were mainly above or below the mean [64]. Causes of these remain unknown, but modeling of the Indian monsoon suggests several factors can influence rainfall variability over periods of years, especially sea-surface temperatures [67] [68].

The two phases of sedimentation (**Table 3** & **Table 5**) each beginning with a number of shorter lived Type 3c incised channels and ending with longer lived Type 3a MSXB sheet-sand migrating channels suggest discharge reductions over significantly longer time periods. These may relate to larger scale changes in the monsoon system. A different explanation was proposed for similar migrating channels in the Lower Kinderscout Grit [21]. Those channels died out before they reached the top of the slope, and appear to relate to a period of shallower water sedimentation on the delta plain [21]. However, the channels in the Roaches Grit extended as far as the delta slope (**Figure 15** & **Figure 17(B)**).

Table 5. Sedimentology evidence for discharge variation in the upper Roaches Grit, over different timescales.

Feature	Timescale
Superimposed bed forms and bar front erosion in MSXB	Months (intra-flood) or annual (end-flood)
Erosion surfaces and changes in foreset type in LSXB	Months (intra-flood), annual (end-flood) or over a few years
Evolution of Type 3c channels from FLCS fill to hybrid channels with LSXB fed by smaller bars	Several years to decades
Phases of sedimentation from non-migrating Type 3c incised channels to migrating Type 3a sheet sands with MSXB	From hundreds to a few thousand years

No climate modeling has yet been carried out for the late Namurian. Annual shifts in the ITCZ near the end of the Carboniferous (300 ma) have been suggested [16] and also feature in the Early Permian climate model of [69]. The latitudinal range of ITCZ variation in the Upper Carboniferous remains unknown and probably varied over time. In present day Africa the northern (summer) limit averages 20˚N [51] (**Figure 10(B)**) and a similar northernmost latitude was suggested in the Early Permian model of [69]. The Caledonian catchment area was extensive and spread over a latitudinal range of more than 10˚ (**Figure 10(C)**). Today the width of the ITCZ averages 10˚ in latitude [70], although in parts of Africa it does not currently align with the rainfall belt [71]. In the Roaches Grit and other Pennine deltas an optimum position at 10˚N in Northern Hemisphere summer would have maximized discharge, as run-off from all three catchment areas would have coalesced into a single river channel (**Figure 10(C)**). Even if the ITCZ and associated rainfall belt did eventually reach 20˚N it would have needed to pass through the 10˚N position twice during its annual migration. However, the presence of a continental red bed sequence of early Bashkirian age in Bjørnøya Island off the NE coast of Greenland [72] (**Figure 21**) casts doubts on the operation of a vigorous monsoon system that far north.

If the ITCZ did not migrate as far north as the optimum latitude of 10˚N (**Figure 10(C)**), parts of the catchment areas would have received less rain and the Pennine delta discharge would have been correspondingly less during these periods. During Northern Hemisphere winter the ITCZ would have passed through or lain across the Hercynian Mountains (**Figure 21**), the main catchment area for rivers draining into the Namurian basins of northwest Europe [2] [73]-[77].

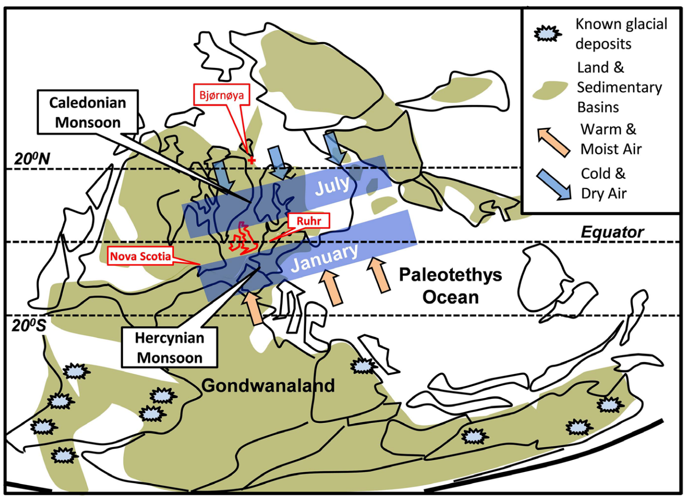

Figure 21. Paleogeography of Pangea at 323.2 ma: after Scotese 2014 [49]. Shows inferred air movements and speculative positions of the ITCZ related monsoon rainfall axes over Europe in January and July.

Over multi-cyclothem (100 ka) time periods major changes in the pattern of deltaic sedimentation in the UK Pennines have been documented [2]. From the Upper Kinderscoutian through to the early Langsettian (**Figure 1**), corresponding to part of the C2 Glaciation in Australia [2], 37% of 32 cyclothems in the Pennine Basin contain coarse grained, commonly incised channel sequences interpreted to have been deposited by rivers (Type 3) active late in the cycle shortly after the eustatic minimum [2]. In several of these cyclothems; R2b5 described in this paper, and a number in the Late Kinderscoutian (R1c) (**Figure 1**) the late cycle deltas build out into deep water in under-filled parts of the Pennine Basin [2]. Coarse grained channel sequences of late Namurian and early Westphalian age occur in many of the same cyclothems in the Ruhr (**Figure 21**) and other NW European basins, where the river channels are fed by rainfall originating in the Hercynian Mountains [2] [73]-[77]. It has previously been suggested that this pattern of sedimentation is climate, probably rainfall related [2]. This could happen because annual migration of the ITCZ as discussed above (**Figure 21**) would have resulted in intense rainfall in both catchment areas at different times of year. In the remaining cyclothems of later Namurian and early Westphalian age, there do not appear to have been active river systems in the Pennine Basin after the eustatic minimum [2]. Coarser grained fluvial deposits are also rare in the Ruhr and other NW European successions, all suggesting a weaker monsoon system during these cyclothems.

Why are the unusual facies of the Type 3c channels confined to only a handful of Namurian cyclothems? Firstly these are deep water deltas with a large slope. Clearly this is a prerequisite for deep incision. Secondly, the channels are inferred to have had greater than normal discharges related to exceptionally powerful bursts of monsoon rainfall occurring late in the cyclothem [2]. Strong precessional insolation maxima will increase rainfall and hence fluvial discharge [78] [79]. Modulation by eccentricity may further enhance this process [80] [81]. Strong precessional insolation minima will increase ice accumulation [82] and hence sea-level fall. The Roaches Grit and other deep water Namurian deltas in the Kinderscoutian and Pendleian are inferred to be a response to unusually large sea-level falls, the associated forced regressions pulling the deltas into the deep under-filled basins [2] [3] At the end of the last Pleistocene cycle very high rainfall during and following the post-glacial sea level rise occurred in both the Asian and African monsoon systems [52] [82] [83]. Therefore, unusually strong precessional forcing events, or climatic responses, in some Pennsylvanian cyclothems, causing larger sea-level falls during precessional cooling and higher rainfall during precessional warming provides a possible explanation for the association between deeply incised channels with LSXB and deep water deltas.

9. Conclusions

This revised interpretation of an Upper Carboniferous deltaic sequence attempts to explain how World-wide climatic changes caused by orbital forcing (especially precession), during the late Carboniferous ice ages, were the main factors influencing sedimentation.

1) Precessional forcing events were probably the dominant control on both rainfall variability [69] [79], and on Southern Hemisphere ice volume fluctuations which caused glacio-eustatic sea-level changes [2].

2) A major sea-level fall associated with ice accumulation late in the cycle facilitated the forced regression delta (lower Roaches Grit), followed by rainfall failure during the glacial maximum which led to delta abandonment and retreat [2] [3].

3) Intense, precession driven monsoon rainfall late in the cycle reactivated the delta (upper Roaches Grit); rapidly rising base level created more accommodation space allowing the construction of a new slope which only slowly prograded over the abandoned slope of the older delta.

4) The ITCZ, on reaching 10˚N during Northern Hemisphere summer would maximize discharge from the known catchment areas.

5) Short-term fluctuations in river discharge inferred from structures in MSXB and LSXB were mainly caused by bursts of summer monsoon rains in the catchment area during or between successive floods, as occur at present in rivers fed by the Asian monsoon [63] [64].

6) Medium term discharge variations over longer multi-year time scales influenced channel sedimentation, with very high discharges causing knick-point recession in non-migrating channels, which then sometimes filled with LSXB during less intense floods.

7) Development of more stable, laterally migrating sheet sandstone channels (MSXB) in lower discharge rivers over even longer time-scales could relate to longer term shifts in the position of the ITCZ over the catchment area, or weakening of the monsoon as observed in African and Asian monsoons during the Holocene [51] [64].

8) Channel avulsions were frequent during deposition of the upper Roaches Grit and most of the delta area was a flood plain, with the flood probably concentrated in just one major channel.

9) The two different channel types (3a and 3c) seen are each associated with different processes on the delta slope which caused slightly different types of turbidity current sedimentation further out into the basin.

10) Over multi-cycle (100 ky) timescales, systematic variations in monsoon rainfall between different cyclothems are inferred from channel sedimentology, especially grain-size and incision [2]. The Pennine delta system was not continuously active, and the upper Roaches Grit delta along with similar deltas in the late Pendleian and late Kinderscoutian represented the extreme high end of discharge variation.

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Conflicts of Interest

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

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