Read at the Annual Conference of the Ussher Society, January 1990

Changes in deltaic sedimentation in the Upper Carboniferous Westward Ho! Formation and Bideford Group of SW England

XU LI

Xu Li 1990. Changes in the deltaic sedimentation in the Upper Carboniferous Westward Ho! Formation and Bideford Group of SW England. *Proceedings of the Ussher Society, 7, 232-236.*

The 1200m thick Upper Carboniferous Westward Ho! Formation and Bideford Group on the N Devon coast. SW England, i show a progressive upward decrease in subsidence rate. Palaeontological evidence in the upper 500m succession (upper part of Cycle 3 to Cycle 9 of the Bideford Group) suggests that it spans a long period, equivalent to four Upper Namurian and Westphalian goniatite marine horizons. In contrast, the lower 700m succession (Westward Ho! Formation, and Cycle 1, Cycle 2 and lower part of Cycle 3 of the Bideford Group) lacks body fossils and has no marine horizon. Sedimentological evidence indicates a very rapid rate of sedimentation and subsidence. Each of Cycles 2 to 9 of the Bideford Group lacks syndepositional deformation structures and shows generally coarsening upward regressive sequences with the lower part of each sequence characterised by relatively deep-water black shales and turbidites and the upper part by strongwave influenced laterally extensive siltstones and sandstones, suggesting a steep concave offshore slope. In contrast, the Westward Ho! Formation is dominated by subaqueous syndepositional deformation interbedded with evidence of wave activity. Thus these 400m thick sediments were deposited near the wave base on a rather flat offshore slope that was rapidly subsiding. Cycle 1 of the Bideford Group acts as a transitional unit.

Xu Li, Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR.

Introduction

The Upper Carboniferous succession along the N Devon coast SW of Westward Ho! (SS 42102912) consists of the Westward Ho! Formation and nine deltaic cycles of the Bideford Group. It has been studied by many workers (Prentice 1960, 1962, 1965; Walker 1966, 1969. 1970; Reading 1965; de Raaf *et al.* 1965; Money 1966 and Elliott 1976) but the context of this succession has been uncertain due to the lack of fossils for dating and difficulties of correlation with adjacent areas.

The British Geological Survey (Edmonds *et al.* 1979) included the Westward Ho! Formation in the Crackington Formation which, in its type area to the south of the Culm Synclinorium, and at Clovelly 10km to the south of Westward Ho!, is turbiditic and ranges in age from uppermost Namurian to the *G. amaliae* Marine Band of the Westphalian A. However recent collection of goniatites and nonmarine bivalves suggest that on both stratigraphical, as well as sedimentological grounds the Westward Ho! Formation is distinct and clearly underlies the Bideford Group. Reading (1965) and Cornford (1987) have suggested these deltaic successions accumulated in a tectonically separate area. Within this area detailed study of the succession can assist an understanding of the evolution of the basin.

The differences between the Westward Ho! Formation cycle, Cycle 1 of the Bideford Group and the remaining cycles of the Bideford Group are described in detail in terms of stratigraphy, palaeontology and many aspects of sedimentology, for example, sedimentary facies, syndepositional deformation structures, rate of sedimentation, wave features and water depth.

Stratigraphy and palaeontology

The present stratigraphic column shown in Fig. I is built up from previous work (Prentice 1960, 1962, 1965; Reading 1965; de Raaf *et al.* 1965 and Edmonds *et al.* 1979) and fossils recently collected by the author. The strata occur along the coast SW of Westward Ho! as a conformable sequence, but are folded into upright open anticlines and synclines with WNW oriented axial traces. However, there is no fold repetition of the lower three cycles (Westward Ho! Formation cycle, Cycle 1 and 2 of the Bideford Group) unlike the higher cycles of the Bideford Group.

Earlier workers recorded one Westphalian marine band represented by *Gastrioceras amaliae* near the bottom of Cycle 6 (Fig. 1) and nonmarine bivalves in Cycle 3, 5, 8 (Edmonds *et al.* 1979). Non-marine bivalves have also been noted in the lower part, 1.5m thick, of Cycle 8 at Cornborough Cliff by the author. The shells, including material collected earlier by BGS, have been identified by Dr. R.M.C. Eagar. This Cornborough band includes the large *Carbonicola cf.* C. *extenuata* group, with smaller C. *proxima* and allied varieties. The association has a considerable stratigraphical significance, lying near the top of the *Lenisulcata* Chronozone (Eagar 1956, 1962, 1975). Both the *Gastrioceras amaliae* marine band and the Cornborough Cliff nonmarine bivalve band confine Cycle 6, 7, 8 to a Westphalian A age.

A non-marine bivalve band including *Carbonicola* cf. *pseudacuta, C. cf. lenicurvata* and C. *cf. scotica* has been found in Cycle 3 by BGS (Edmonds *et al.* 1979). Shells of *Naiadites* cf. *productus, N. hibernicus* and more material of *Carbonicola* have been collected immediately below the Raleigh Sandstone by the author. Dr. Eagar suggests that the combination of evidence from both *Carbonicola* and *Naiadites* indicates a late Namurian horizon, probably immediately below the *Gastrioceras cumbriense* marine band.

Therefore, the boundary between Namurian and Westphalian should lie somewhere between Cycle 3 and Cycle 6. This boundary is much higher than indicated by Edmonds *et al.* (1979) who placed it somewhere in the Crackington Formation below the section observed at Westward Ho!

Two marine bands have been found in the Crackington Formation in the adjacent Hartland area (Edmonds *et al.* 1979): *Gastrioceras subcrenatum,* indicating the base of Westphalian, and *Gastrioceras listri* which is earlier than *G. amaliae*. In the Bideford Group well preserved *Teichichnus* and *Ophthalmidium ophthalmoides* trace fossils are abundant in the topmost part of the Raleigh Sandstone (Fig. 1); the two forms indicate deposition in marine conditions (Chisholm 1970; Calver 1968). This marine episode could be equivalent to either the *G. suhcrenatum* horizon or the *G. listeri* horizon or even *G. cumbriense* horizon. The time span, therefore for deposition of the 500m succession from the middle part of Cycle 3 to Cycle 9 of the Bideford Group is much greater than previously thought and the lower 220m must include at least three major marine horizons. However, no body fossil has ever been recorded from the lower three cycles (Westward Ho! Formation cycle, Cycle 1 and 2 of the Bideford Group) and there is not even a suspected marine horizon from both detailed studies of the black shales and trace fossils.

Sedimentology

All these Westward Ho! Formation and Bideford Group cycles have been interpreted as deltaic cycles by de Raaf *et al.* (1965), Walker (1969, 1970) and Elliott (1976). Elliott (1976) also suggested that the nine cycles of the Bideford Group were deposited in a similar fluvial-

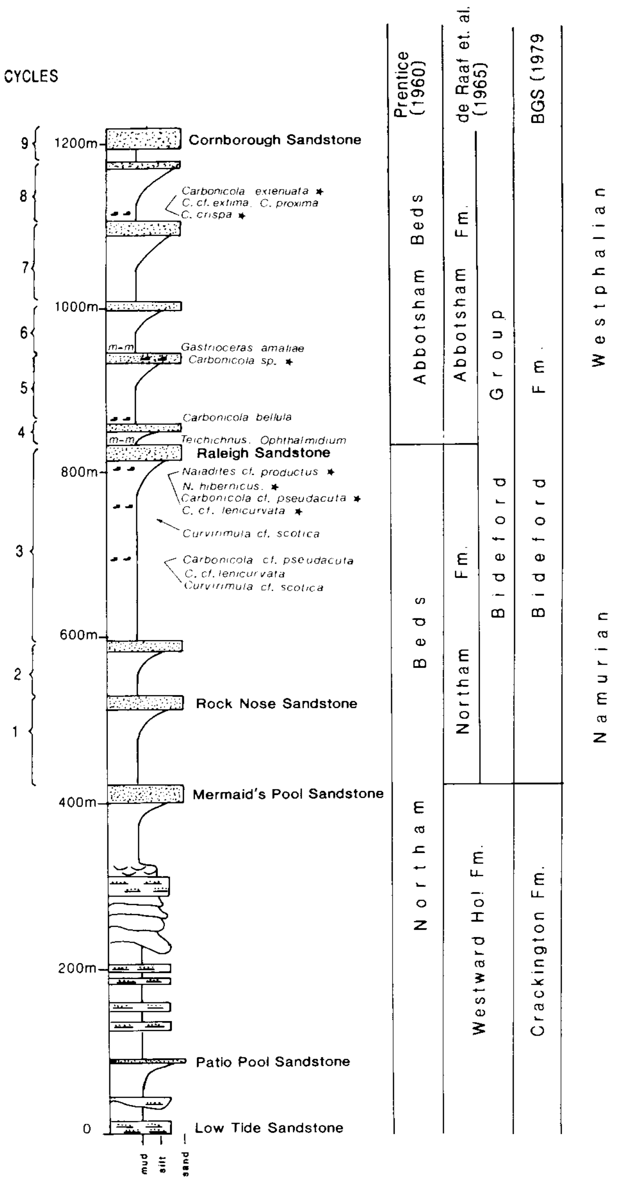

Figure 1. Stratigraphy of the Westward Ho! area, North Devon. Thicknesses given in metres. Numbers 1 to 9 indicate cyclothems of the Bideford Group. The faunas with stars are recently collected by the author and identified by Dr. R.M.C. Eagar, the faunas without stars were collected by the Geological Survey (Edmonds *et al.* 1979). The major sandstones are stippled and turbidites shown by the dots-above-line graded bedding symbol.

dominated deltaic environment by assuming they represented lateral changes in a single, switching deltaic system.

In each of the topmost 6 cycles (de Raaf *et al.* 1965) there is a gradual coarsening and shallowing upward. Wave activity is confined to the upper parts of the cycles, and turbidites, if they occur, are found only in the lower part of each cycle within quiet water mudstone. In contrast, as Walker (1969, 1970) has noticed, in the Westward Ho! Formation and Cycle 1 of the Bideford Group "agitated water" (shallow water) facies indicated by cross-laminated siltstones and "deep water" facies indicated by turbidites, turbidity current channels are closely interbedded and in many cases there is no transitional facies representing a shallowing process. Based on Walker's work (1966, 1969, 1970) on the Westward Ho! Formation and Cycle 1 of the Bideford Group, the author has mainly concentrated on detailed description and interpretation of subaqueous syndepositional deformation features. The following description of the Westward Ho! Formation cycle, and Cycles 1 and 2 of the Bideford Group, is a summary of the author's work. The description for the remaining cycles of the Bideford Group is mainly based on de Raaf *et al.* (1965).

The Westward Ho! Formation cycle

The Westward Ho! Formation consists of black mudstone, turbidites, siltstone slumps, large collapse depressions, and subaqueous sandstone channels, with fluvial channel-fill deposits (the Mermaid's Pool Sandstone) forming the topmost part. Predominantly the turbidites in the Westward Ho! Formation (Fig. 2) are 10-40mm thick, graded or rippled siltstone beds in a silty mudstone background and they occur in 2-3m thick groups. At 90m and 220m from the base (Fig. 2) and beneath the Mermaid's Pool Sandstone in a Torridge Estuary section (SS 45892867), wave generated features (e.g. internal wave laminations) occur in siltstones with widespread palaeocurrent directions (Fig. 2), indicating shallow water sedimentation. As Walker (1970) has noticed, in the Westward Ho! Formation transitions from turbidites or turbidity current channels to "agitated-water" facies indicated by cross-laminated siltstones are extremely rapid without any development of facies representing a shallowing process.

At 50m, 300m and 315m from the base (Fig. 2) there are five syndepositionally deformed units and subaqueous channel complexes set within a banded black mudstone facies background, interpreted as a prodelta or an interdistributary bay environment. Three of the units have a common character: a large depression with an irregular base, 6-10m in depth and more than 60m in width, filled with chaotic silty mudstone matrix with sandstone blocks and covered with parallel-bedded sandstone beds which pinch out laterally away from the depression. Two of the units have another common character: a large depression with a very irregular base, 6-12m in depth and more than 100m in width, entirely filled with parallelbedded sandstone beds.

This 420m thick Westward Ho! Formation Cycle is dominated by fine grained subaqueous deposits showing various syndepositional deformation features, indicating rapid sedimentation of a large amount of fine grained sediments in a shallow water as suggested by the wave features. Comparing the irregular based subaqueous depressions with those of the modern Mississippi delta, they are interpreted as collapse depressions triggered by degassing, dewatering and wave-induced bottom pressure (Coleman 1981). These depressions occur primarily in the shallow-water areas of interdistributary bays (Coleman 1981) where "agitated-water" facies could develop. After the collapse, turbidity currents sometimes developed in these areas without deepening. If a turbidity current carried sediment directly over a collapse depression, the first kind of complex described above could be formed. If a turbidity current eroded the collapsed chaotic sediments and then filled the depression with sediments carried by the turbidity current, the second kind of complex could result.

Mudflows and slumps dominate the upper-middle part of the Westward Ho! Formation cycle. The topmost 50m of the Westward Ho! Formation beneath the Mermaid's Pool Sandstone is interpreted as a prodelta silty mudstone deposit with a few single sandstone turbidite beds. However in the Torridge Estuary (4km away) (SS45892867) (Walker 1970) the Mermaid's Pool Sandstone is underlain by a coarsening upwards sequence with the frequency of irregularly cross-laminated sandstones increasing upwards.

The Mermaid's Pool Sandstone consists of three fining upward sequences and a coarsening upwards sequence with *Arenicolites* burrows on the tops of the upper two sequences. Each of the three lower sequences exhibits a channel-fill deposition from a waning flow regime probably indicating a distributary channel in a fluvialdominated deltaic environment.

Cycle 1 of Bideford Group

Cycle 1 of the Bideford Group (Fig. 2) consists of 36m of black mudstone, 12m sharp based, graded siltstone turbidites and 82m interbedded cross-laminated siltstones, graded siltstones and silty

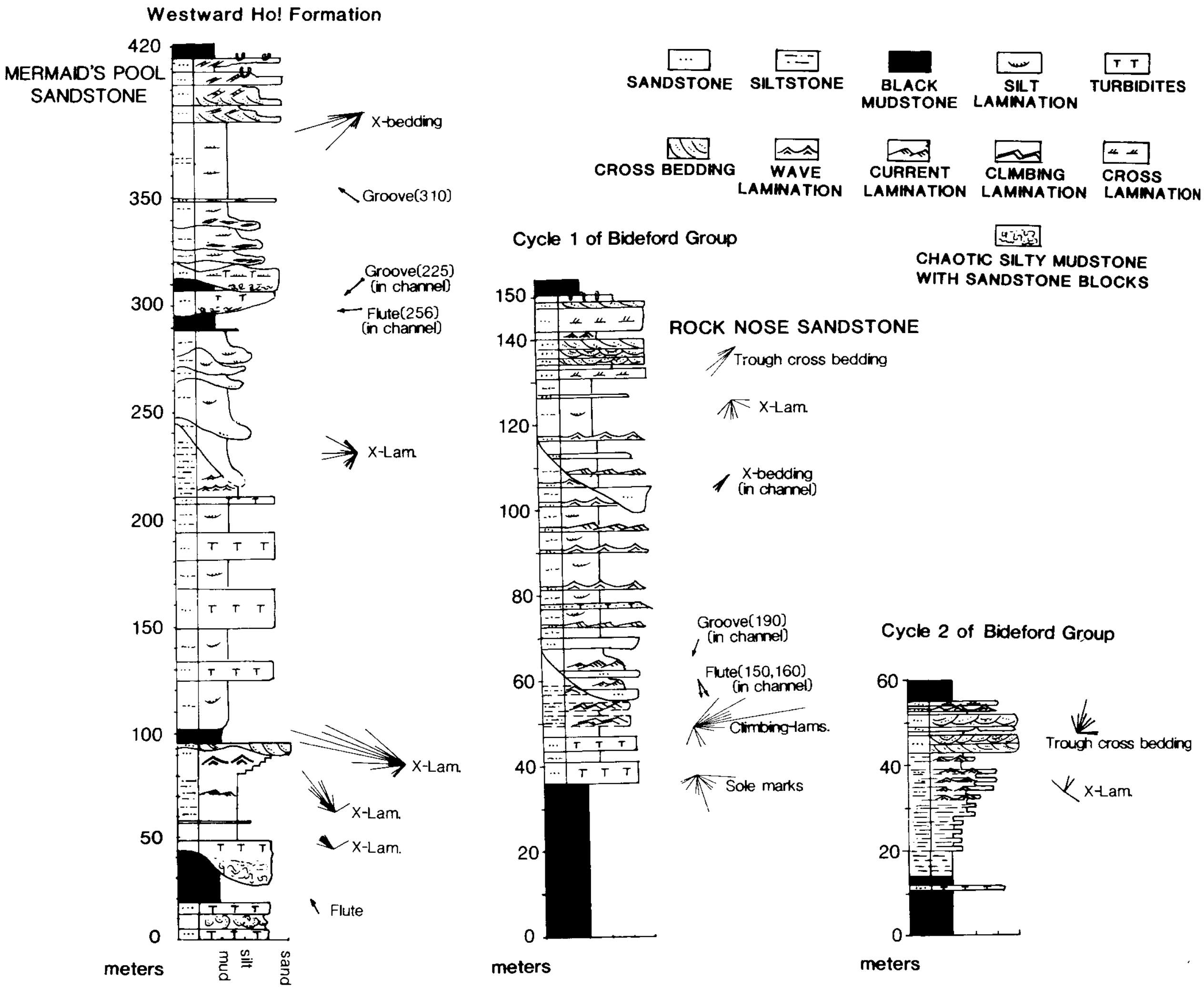

Figure 2. Sedimentological sections of the Westward Ho! Formation cycle, Cycle 1 and Cycle 2 of the Bideford Group. Thicknesses given in metres and the rose diagrams and arrows are palaeocurrent vectors. The Westward Ho! Formation and Cycle 1 of the Bideford Group are modified from Walker (1969, 1970) and Cycle 2 of the Bideford Group was measured by the author.

mudstones, interpreted as delta front. These are followed by a fluvial channel sandstone, with thin coal seams and bioturbated siltstone on top. Many of the sandstone beds, interpreted as delta front deposits, show internal wave laminations in cross-section view and wave ripples on the top surface exposures of the sandstone beds.

On the polished wave-cut platform near the base of the cliff, two channels can be seen to cut through the delta front deposits (Fig. 2). They are interpreted as turbidity current feeder channels as they are concave-shaped, slump-margined, 25m in width and 4-6m in depth and filled with interbedded sandstone and mudstone. Sole marks in the channels indicate a southward flow. A slump occurs in the upper part of the delta front deposit.

The 20m thick topmost sandstone (Rock Nose Sandstone) shows a fining-upward trend from large planar cross-bedded sandstone to trough cross-laminated sandstones with a consistent SW flow direction; it is covered by bioturbated siltstone. As with the Mermaid's Pool Sandstone, this sandstone could also be a distributary channelfill deposit.

Cycle 2 and the remaining cycles of the Bideford Group

Cycle 2 of the Bideford Group (Fig. 2) is an "ideal" gradually thickening and coarsening upwards sequence showing, in upwards succession: black mudstone (5mm scale); banded mudstone (20mm scale); banded mudstone; interbedded siltstone and mudstone; interbedded wave-rippled sandstone and mudstone; major sandstone body with trough cross-bedding, showing a NE flow direction.

The wave features only appear above 32m from the base of the cycle and increase upwards, represented by laterally extensive, well-bedded sandstone and siltstone sheets with well-developed wave ripples, indicating strong sediment reworking and redistribution by wave action. Clearly, a wave base can be placed 32m from the base of the cycle. Therefore, the deep water deposits below the wave base are 32m in thickness and the wave affected shallow water deposits above the wave base are only 10m in thickness and are covered by a fluvial channel sandstone.

Similarly, the remaining 7 cycles of the Bideford Group are roughly all "normal" gradually coarsening upwards regressive sequences with wave base somewhere in the middle part of the cycle, representing the progradation of a shoreline into a relative deep water basin. Turbidites sometimes occur but below the wave base in the basinal black mudstones.

Two major sandstones, the Raleigh Sandstone and Cornborough Sandstone (Fig. 1), are characterized by an almost constant thickness over a great lateral extent, as indicated by inland mapping (Edmonds *et al.* 1979) and they probably represent widespread fluvial deposits controlled by sea-level changes. This interpretation is supported by both palaeontological and stratigraphical evidence.

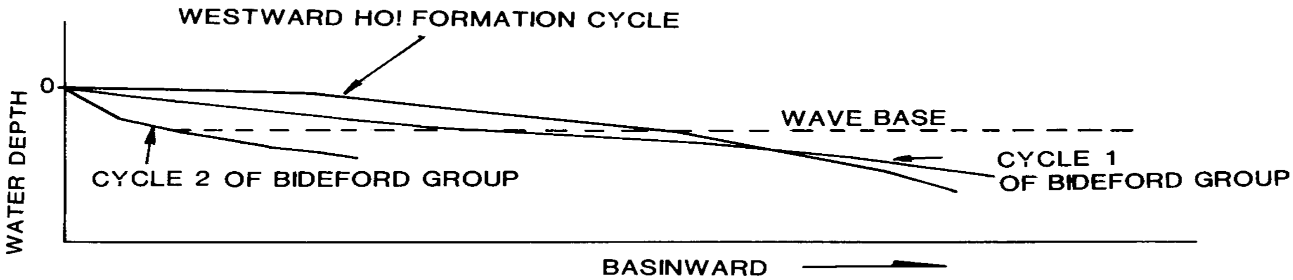

Figure 3. Schematic offshore profiles of the Westward Ho! Formation cycle, Cycle 1 and Cycle 2 of the Bideford Group.

Comparison of Westward Ho! Formation cycle, Cycle 1 of Bideford Group and the remaining cycles of the Bideford Group

The new palaeontological evidence suggests that the upper part of the succession was deposited relatively slowly, embracing a long period of time. There is no positive evidence for the lower part. However a faster rate of sedimentation is likely because the absence of any body fossil except for a few well preserved surface trails, *Kouphichnium* and *Cochlichnus,* that occur in the lower part of Cycle 1 of the Bideford Group, indicating no particular salinity (Pollard 1988), shows an absence of marine condition. This contrasts with elsewhere in the Namurian where marine bands are generally abundant and suggests that deposition may have occurred during a limited period oftime.

The main distinction between the two parts of the succession is in the rate of subsidence, the lower part was fast, the upper part slow. The abundance of syndepositional deformation in the lower part and its virtual absence in the upper part may be due to deposition in a relatively deeper water basin in the lower part and relatively shallower lower water basin in the upper part. However, a significant difference between the two parts of the succession is that the deformed sediment and turbidities in the lower two cycles are interbedded with wave--affected shallow water deposits without a transitional facies representing shallowing. Therefore, most of the sediments in the lower two cycles are the result of shallow water sedimentation near or above wave base and yet there is no sediment strongly affected by wave power at the top of the cycles. In contrast, the remaining cycles of the Bideford Group are all the result of progradational sedimentation from relatively deep water below wave base into shallow water above wave base and normally the upper half or one third of the section is strongly affected by wave power.

In modern deltas, high nearshore wave power is commonly associated with steep concave offshore slopes and low nearshore wave power associated with flat offshore slopes (Coleman 1981), as nearshore wave power is in large part controlled by frictional attenuation which is a function of the subaqueous slope. The subaqueous slope in turn depends on grain size, the nature of the continental shelf, rate of subsidence of the basin and on the rate at which the river can supply sediments to the nearshore zone.

Thus in the study area, a flat offshore slope is suggested for the Westward Ho! Formation cycle. This is supported by the large amount of sediment supply and the rapid rate of sedimentation. In contrast, in Cycle 2 of the Bideford Group the upper 10m nearshore deposits show very strong wave power effect, suggesting a steep concave offshore slope. The features in Cycle 1 of the Bideford Group support it as an intermediate case. Therefore, a schematic diagram of the relative offshore profiles for the lower three cycles is suggested in Fig. 3. The relative relationships of these three profiles may also depend on the changes of wave action generated in the basin through the three cycles, for example, the changes of wave strength and wind direction.

Thus the Westward Ho! Formation cycle, which is at least 400m thick, was deposited in water that was relatively shallow throughout and the great thickness was a consequence of subsidence during sedimentation. In contrast the upper cycles appear to have been deposited in basins that were initially deeper.

References

Calver, M.A. 1968. Coal Measures invertebrate faunas. *In:* Murchsion, D.G. and Westoll, T.S. (eds) *Coal and Cool-Bearing Strata.* Oliver and Boyd, London, 147-177.

Chisholm, J.I. 1970. *Teichichnus* and related trace fossils in the Lower Carboniferous of St Mounance, Scotland. *Bulletin of the Geological Survey of Great Britain, 32,* 21-51.

Coleman, J.M. 1981. Deltas: Processes of Deposition and Models *for Exploration.* Burgess.

Cornford, C., Yarnell, L. and Murchison, D.G. 1987. Initial vitrinite reflectance results from the Carboniferous of north Devon and north Cornwall. *Proceedings of the Ussher Society, 6,* 461-467.

de Raaf, J.F.M., Reading, H.G. and Walker, R.G. 1965. Cyclic sedimentation in the lower Westphalian of north Devon, England. *Sedimentology, 4,* 1-52.

Eagar, R.M.C. 1956. Additions to the non-marine fauna of the Lower Coal Measures of the north Midlands coalfields. Liverpool *and Manchester Geological Journal. 1,* 326-389.

Eagar, R.M.C. 1962. New Upper Carboniferous non-marine Lamellibranchs. *Palaeontology, 5,* 307-309.

Eagar, R.M.C. 1975. New non-marine bands and *Carbonicola* burrows in lower Westphalian A measures of the British Pennines. *Bulletin de la société Belge de Geologie, 83,* 205-213.

Edmonds, E.A., Williams, B.J. and Taylor, R.T. 1979. Geology of Bideford and Lunday Island. *Memoir of Geological Survey of Great Britain.*

Elliott, T. 1976. Upper Carboniferous sedimentary cycles produced by river dominated, elongate deltas. *Journal of the Geological Society of London, 132,* 199-208.

Money, N.J. 1966. Carboniferous rocks of North Devon: the Appledore Formation. *Proceedings of the Ussher Society.1,* 235-238.

Pollard, J.E. 1988. Trace fossils in coal-bearing sequences. *Journal of the Geological Society, London, 145,* 339-350.

Prentice, J.E. 1960. The stratigraphy of the Upper Carboniferous rocks of the Bideford Region, North Devon. *Quarterly Journal of the Geological Society, London, 116,* 397-408.

Prentice, J.E. 1962. The sedimentation history of the Carboniferous in Devon. *In:* Coe, K. (ed) *Some Aspects of the Variscan Fold Belt.* Manchester University Press, 93-108.

Prentice, J.E. 1965. Discussion of: Recent finds in the Upper Carboniferous of South-West England and their significance. *Nature, London, 208, 747*-748.

Reading, H.G. 1965. Recent finds in the Upper Carboniferous of South-West England and their significance. *Nature, London, 208,* 745-747.

Walker, R.G. 1966. Deep channels in turbidite-bearing Formations. *Bulletin of the American Association of Pet'oleum Geologists, 50,* 1899-1917.

Walker, R.G. 1969. The juxtaposition of turbidite and shallow water sediments: study of a regressive sequence in the Pennsylvanian of North Devon, England. Journal *of Geology, 77,* 125-143.

Walker, R.G. 1970. Deposition of turbidites and agitated-water siltstones: a study of the Upper Carboniferous Westward Ho! Formation, North Devon. *Proceedings of the Geologists' Association, 18,* 43-67.