Sedimentary structures associated with extensional fault movement from the Westphalian of NE England

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SUMMARY: Although differential subsidence and extension has been well established as a control on sedimentation for the Dinantian of N England, the continuation of this tectonic regime into Silesian times is less well demonstrated.

The Westphalian (Upper Carboniferous) Coal Measures of the Durham coalfield in NE England, which were deposited on an essentially flat, deltaic plain, display abundant evidence of a subtle structural control on sedimentation. Medium-scale (hundreds of square kilometres) patterns of sedimentation, notably the disposition of major fluvial channel belts, were at times strongly controlled by active, ENE–WSW- and E–W-trending fault lines. The faults represent a response to a broadly N–S directed tension and many resulted from the reactivation of earlier, Caledonide crustal weaknesses.

The effects of such tectonic activity may be seen spectacularly at field-outcrop scale. At an opencast coal mine in southern Co. Durham close to the major Butterknowle fault, an exposed Upper Westphalian A sequence displays a plethora of tectonically associated structures. These include gravity slides, various dewatering structures, claystone dykes, convoluted and internally chaotic sandstone beds, desiccation cracks and signs of vertical drainage in an originally water-logged palaeosol profile, and abrupt bed thickness changes. The existence and orientation of two minor channels on the ESE side of the fault line, and other palaeoflow data, support the hypothesis that the Butterknowle fault displaced downward the area to its ESE at this time.

Fractures across the area of the opencast site were found to contain high concentrations of galena, sphalerite, pyrite/marcasite and other minerals which were apparently introduced at the time of formation of the N Pennine orefield (Carboniferous–Permian).

Across the area that is now northern Britain, the Carboniferous period was characterized by the extension of continental crust and basin subsidence. Recent tectonic models have emphasized the role of crustal attenuation and consequent 'rift and sag' (the model of McKenzie 1978; see Leeder 1982a) and subsidence produced by lithospheric stretching caused by the slab pull force resulting from subduction to the S (Johnson 1982; Bott *et al.* 1984).

The main phase of rifting and subsidence in northern Britain took place during Dinantian times, and its control on contemporary sedimentation is abundantly demonstrated by sequence thickness changes across the various structural hinge lines (Johnson 1967, 1982), (Figs 1 & 2). Rapid subsidence of the northern Pennine basins in Dinantian times appears to have slowed down through the succeeding Namurian period, coincident with a change from shallow marine to more deltaic environments of sediment deposition. By the beginning of the Westphalian, the original block and trough topography had been essentially eliminated and a wide deltaic plain established across the northern Pennines (Fig. 2). Distributary channels crossed this coastal plain, and were separated by shallow lakes and bays (Fielding 1982, 1984a). Further S in the central Pennines area, the Namurian basin depocentre was maintained through the Westphalian, though again subsidence rates were reduced, and the coastal-plain environment became established across the entire Pennine province by mid-Westphalian A times (Calver 1969).

In the Durham area, despite the almost uniform sequence of Westphalian strata, evidence of continued extensional faulting has recently been recorded (Fielding 1982, 1984b). The most striking manifestations of such activity are elongate, fault-bounded tracts characterized by expanded vertical sedimentary sequences, impoverishment or wedging out of coal seams, and vertical stacking of fluvial channel-belt deposits (fig. 4, Fielding 1984b). The faults that define such belts, notably the major Ninety Fathom and Butterknowle–Wigglesworth lines, are dominantly orientated ENE–WSW or E–W and, therefore, probably represent the reactivation of older, Caledonide structural weaknesses.

More direct evidence of Westphalian faulting may be seen on the field-outcrop scale. At Buckhead opencast (strip) coal mine in southern Co. Durham (Figs 1 & 2), which straddles part of the Butterknowle–Wigglesworth fault system, recent excavations have exposed a sequence within the Tilley Group of coals (Upper Westphalian A). The exposure displays many syndepositional deformation structures and other features strongly suggestive of a structural control on their formation. It is

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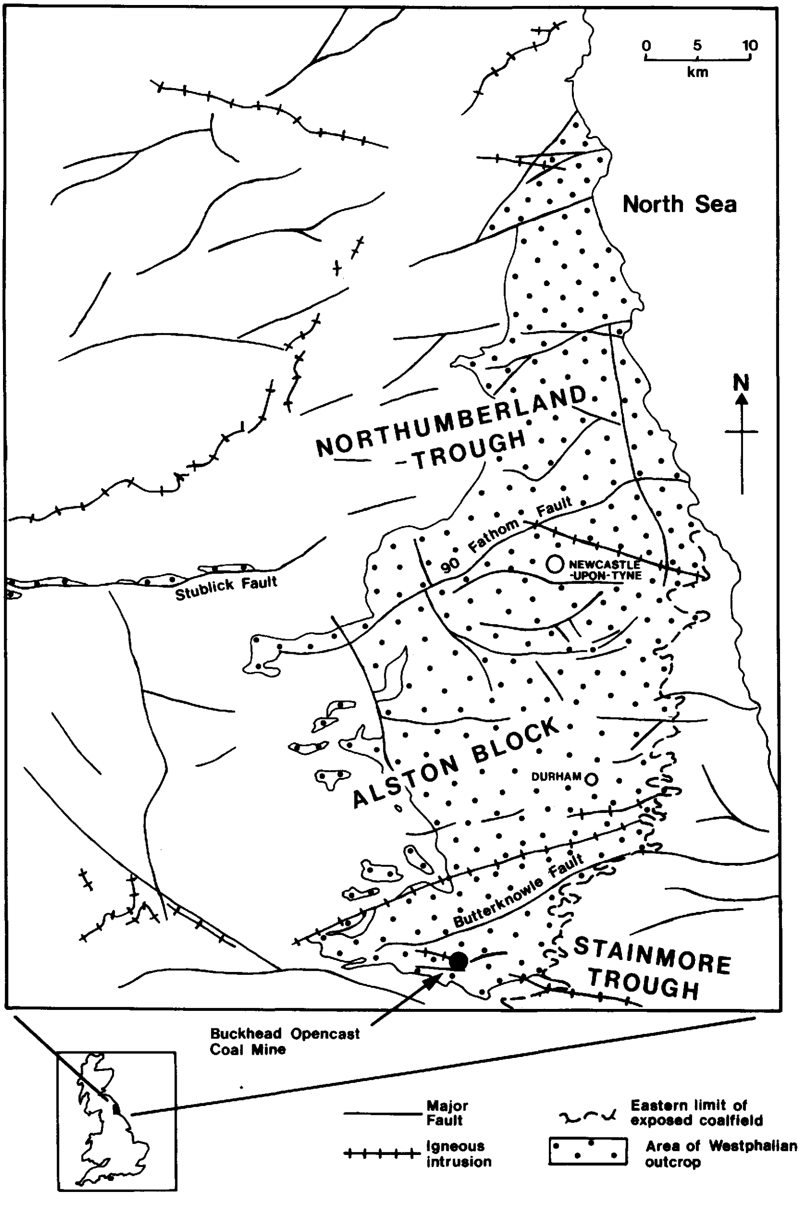

FIG. 1. Map showing the location of the Durham coalfield and Buckhead opencast site, and the regional distribution of major faults.

the purpose of this paper to describe and interpret these structures.

Succession

During the excavation of Buckhead opencast coal mine, (G.R. NZ 133243), the Bottom Tilley coal was uncovered along with an 8.5-m sedimentary sequence overlying the seam (Figs 3 & 4). The sequence, exposed in two adjoining faces, is largely composed of interbedded fine sandstone-to-granulestones and silty claystones (Fig. 4).

Between the two thin leaves of the Bottom Tilley seam, a 2.6-m thick sequence, comprising two coarsening-upward cycles of sub-equal thickness, is developed (Fig. 4). The lower of these reaches fine-sand grade, whereas the higher cycle has coarsened

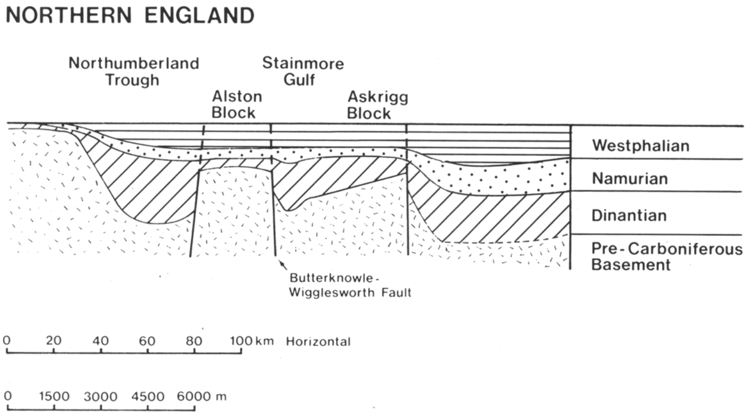

FIG. 2. N–S cross-section showing hinge lines and the development of the Carboniferous geological succession across northern England (after Johnson 1982).

only to siltstone with sandy laminae. Stigmarian rootlets penetrate almost the entire sequence and many are traceable from the lower sequence into the upper one.

The higher coarsening-upward sequence is notable for its containing an assemblage of sandstone-filled cracks, vertical dewatering pipes, and siderite nodules, with vertically orientated long axes, immediately below the upper coal (Fig. 4). The fine-grained sandstone-filled cracks are about 5–20 mm wide, slightly folded, up to 0.3 m long in vertical section, and polygonal in plan view.

Immediately above the upper seam is a series of medium-grained sandstone-to-granulestones interbedded with laminated claystones (Fig. 4). The sandstones contain abundant 'coaly scares', have loaded bases and occasionally show convolute lamination and even complete internal disorganization. Claystone dykes up to 0.15 m in width pass through the basal sandstone into the underlying coal. Interbedded claystones exhibit rare sandy laminae and abundant siderite nodules and lenses.

Higher in the sequence, sandstones are finer grained, and interbedded sediments consist mainly of silty claystones. Burrows referable to *Pelecypodichnus*, *Arenicolites* and *Monocraterion* are common in the sandstones, particularly where thin intercalations of silty claystones are present.

Towards the top of the exposed section, a sequence of interbedded fine-grained sandstones and claystones with a channelized base, display prominent low-angle accretion surfaces (Fig. 4). The Top Tilley coal seam is thought to lie a few metres stratigraphically above the top of the exposed sequence.

Indications of synsedimentary instability are widespread throughout the interval in the form of large-scale loading, various dewatering structures, abrupt lateral changes in sandstone thickness, character and overall abundance, and listric synsedimentary faults, in addition to previously mentioned dewatering pipes, disrupted bedding and claystone dykes (Fig. 4).

Palaeocurrent measurements from trough cross-bedding and ripple cross-lamination indicate palaeoflow towards the S and SSE. Low-angle accretion surfaces, exposed in two areas, dip towards the SSE and NW (Fig. 4).

Many of the sandstones, particularly the coarser beds, contain an association of euhedral dolomite and pyrite/marcasite cements, which post-date the ubiquitous quartz and kaolinite/illite diagenetic phases. Indeed, many of the sandstones contain veins of pyrite, marcasite, sphalerite, galena, and fluorite, a mineral suite reminiscent of the N Pennine orefield.

Interpretation

The alteration of sharply based sandstones and fine-grained claystones, and palaeocurrent data, imply fluctuating conditions of deposition, varying form high-energy unidirectional flows to quiet-water suspension fall-out. The apparent sheet geometry and flat-lying aspect of most of the sandstones implies deposition by unconfined flows. However, the two units with low-angle accretionary dips are considered as representing channels.

The exposed sequence is interpreted as the deposits of a shallow, subsiding lacustrine basin fed by coarse-grained sediment from a northerly source (Fig. 4). Water depths in the lower part of the sequence (between the two coal seams) were 0–2 m, and in the upper part are uncertain, though the lack of rootlet penetration and a comparison

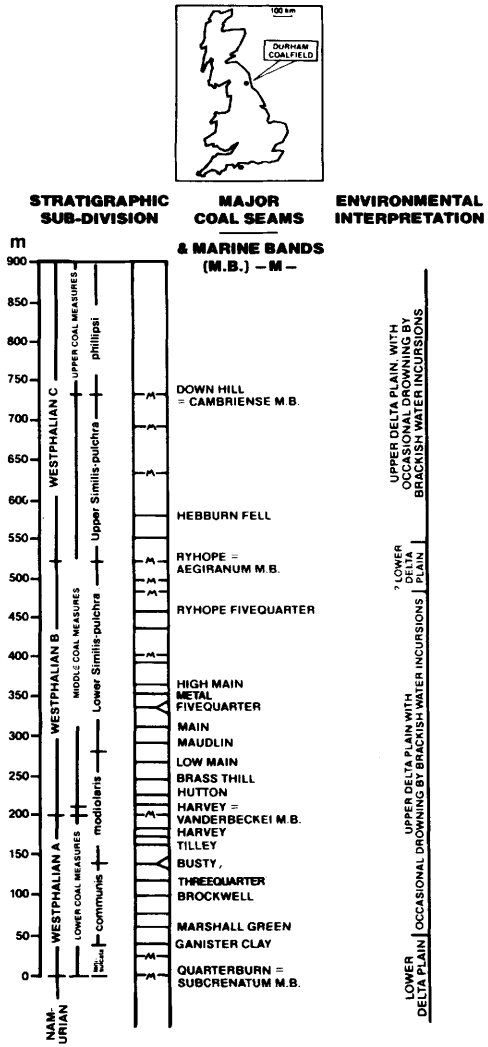

FIG. 3. Stratigraphical column for the Durham coalfield, showing the major coal seams and broad environmental interpretation.

with similar sequences exposed elsewhere suggest a likely depth of 3–5 m.

The two areas displaying low-angle accretion surfaces and channel morphology are interpreted as the remnants of laterally accreted, minor distributary channels which, from their geometry, flowed across the shallow basin towards the NE, though not simultaneously. Geometrical relationships indicate that the channels were about 10 m wide and 2 m deep.

From their three-dimensional geometry, the polygonal sandstone-filled cracks are interpreted as the products of desiccation, and are therefore indications of a fluctuating water table at the time of deposition of the sequence.

The various deformational structures, being confined to individual beds or a small number of beds, are interpreted as having a syndepositional origin. Such structures, formed by the failure of waterlogged sediment columns, could have been initiated by the repeated, rapid dumping of sand on to waterlogged (particularly, fine-grained) sediment surfaces or by tectonic stresses (Leeder 1982b). Elsewhere in the Durham Coal Measures, syndepositional deformation structures are largely restricted to load-casting, almost certainly reflecting the former of the two possible mechanisms. Synsedimentary gravity slides are rare within the British Coal Measures and particularly so in the Durham area. Of the two published reports of such occurrences, one is from the tectonically unstable South Wales coal field (Elliott & Ladipo 1981).

The abundance and variety of synsedimentary deformational structures in the Buckhead exposure are difficult to account for in terms of sedimentary processes, and a tectonic control on their formation is thought likely. The most plausible source of seismic disturbances in the area is the nearby Butterknowle–Wigglesworth fault system. The minor channels at Buckhead trend ENE–WSW, close to the orientation of the Wigglesworth faults, suggesting that the latter controlled the disposition of the former (Fig. 4; cf. Fig. 2). Further, palaeocurrent measurements and the orientation of gravity slides indicate southward-inclined palaeoslopes.

Movement on the Wigglesworth fault is proposed to explain the observed phenomena. A downthrow on the SSE side of an arm of the fault located to the immediate N of the exposure would best explain the observed palaeocurrent–palaeoslope data. Such a disturbance, occurring during the deposition of the sequence above the two thin coals, would have created an elongate lacustrine hollow which filled dominantly with silt and mud deposited out of suspension. Periodic turbidity currents (probably triggered by seismic disturbances and or distributary channel flooding) delivered coarser grained sediment southeastward over the fault scarp into the basin, which was repeatedly shaken by further shocks. Twice during this period, minor distributary channels were attracted into the elongate lacustrine basin, passing northeastward along the foot of the fault scarp (Fig. 4). From the observed bedding relationships, the vertical height of the fault scarp was probably never greater than a few metres.

The well-drained palaeosol situated between the two coals could possibly reflect flexural stress, resulting in a slight uplift (1–2 m), which preceded activation of the fault itself.

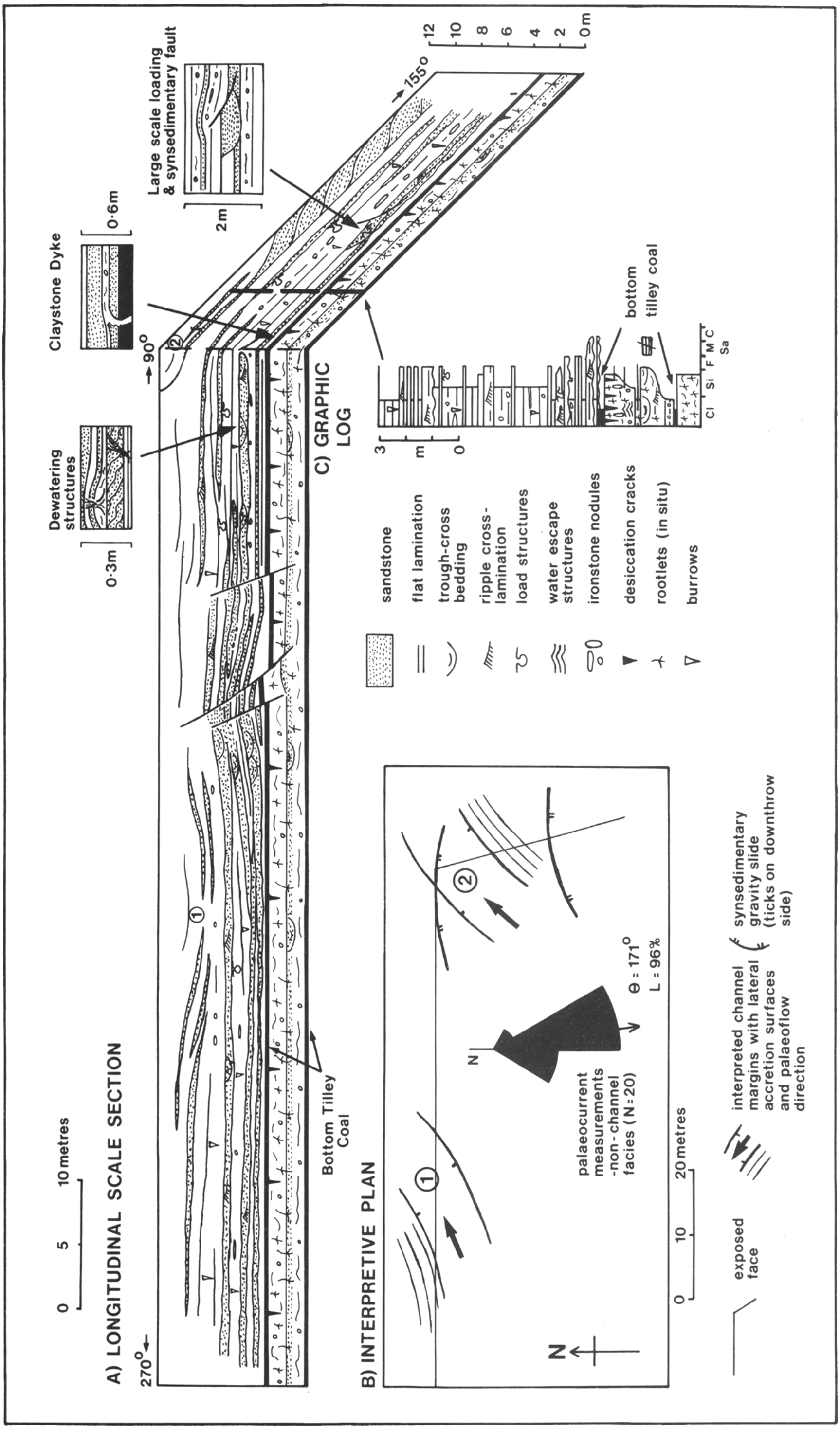

FIG. 4. Scale drawing, sedimentological log and interpretation of the Buckhead exposure.

The exotic cement phases recorded in sandstones are best explained by the passage of solute-charged brines along tension gashes associated with faults which had recently been active, during the late Carboniferous and post-Carboniferous period. It is noteworthy that mineralization was active in the N Pennine orefield for 100 My after the end of the Carboniferous (Dunham 1970) so there was time for the mineral cements to accumulate slowly in the sandstones.

Conclusions

1 Reactivation of Caledonide structural weaknesses in NE England has recently been suggested as a control on sedimentation of the Westphalian (Upper Carboniferous) Coal Measures of the Durham coal field (Fielding 1984a). Evidence for such a control lies in the correspondence between distributary channel belt and major fault trends.

2 More detailed evidence for such a control has been recorded from an opencast coal mine close to the surface trace of the Butterknowle-Wigglesworth fault system. There, within an Upper Westphalian A sequence, numerous syndepositional deformation structures in combination with palaeocurrent data suggest repeated tremors associated with minor fault movements. Such movements evidently created elongate palaeotopographic hollows into which at least two minor distributary channels were attracted. The structural disturbances were preceded by local uplift of 1–2 m, demonstrated by the temporary drainage of a previously and subsequently waterlogged palaeosol.

3 The detailed case study described in this paper demonstrates the application and interpretation of tectonic activity within coastal-plain sequences. Within this context the role played by palaeopedological analysis is of particular importance, having hitherto been somewhat underestimated.

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