Depositional controls, Carboniferous, Northern England

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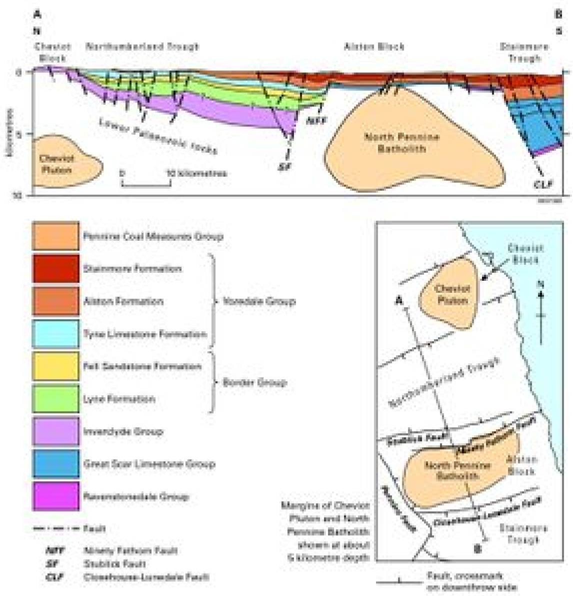
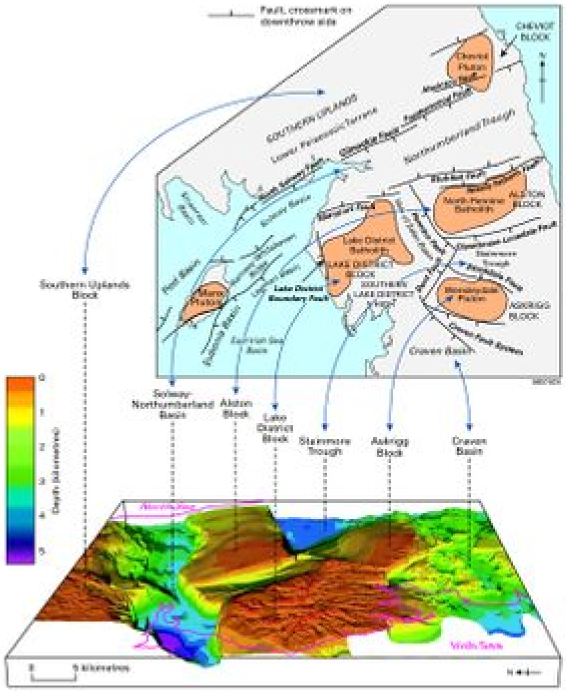
The structural framework

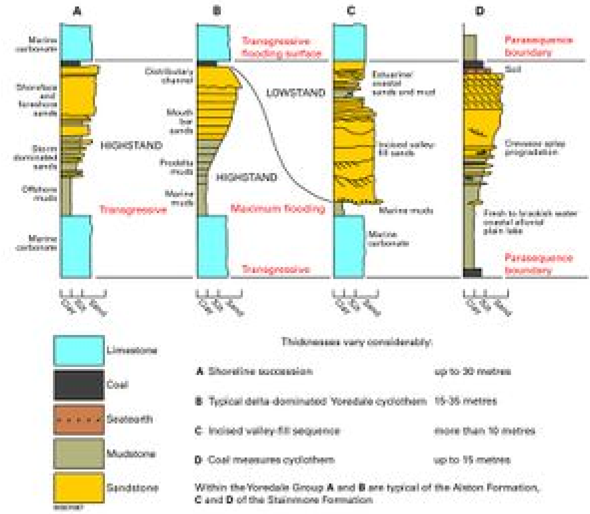


Sketch cross-section from the Cheviot Block to the Stainmore Trough, showing the half-graben structure of the Northumberland Trough (after Chadwick et al., 1995. The Northumberland–Solway Basin and adjacent areas. BGS Subsurface Memoir). P916069.



3D model showing depth to the Lower Palaeozoic ‘basement’ across northern England, viewed from the west. The principal structural features that influence Upper Palaeozoic and later geology are identified and related to a ‘blocks and basins’ sketch map rotated into a top-to-north orientation. P916037.

Detail of the Concretionary Limestone Member of the Roker Formation from a coastal exposure near Sunderland [NZ 412 555]. (P693033).



Illustrative logs and interpretations for some types of high-frequency clastic sequences within the Yoredale and Pennine Coal Measures groups of northern England (after Tucker et al., 2003). P916071.

Over a hundred years ago, it was appreciated that the Carboniferous of northern England was deposited in a series of troughs or 'geosynclines', separated by higher areas. Towards the end of the 20th century, the recognition that these basins and blocks were formed as extensional or transtensional features during a period of lithospheric stretching was a major development in our understanding of the region. This period of crustal extension, in a stress-field with a dominantly horizontal component of north–south tension, began in the Late Devonian and continued until late Visean times; it gradually produced a rifted topography of fault-bounded blocks with intervening graben and half-graben basins. Rifts opened along preexisting lines of structural weakness embedded in the underlying crust, with the Iapetus Suture Zone providing a primary control. For example, the fault system forming the southern margin of the Northumberland–Solway trough is rooted into the Iapetus Suture so that the trough effectively formed by extension in the suture's hanging wall. The extensional regime allowed the local occurrence of basaltic magmatism.

Rifting was pulsed, with particularly active episodes in Courceyan, Chadian to early Arundian and in mid to late Asbian times, although the magnitude and perhaps the timing of each pulse, appears to have varied significantly from basin to basin. The buoyant and rigid behaviour of the blocks is usually ascribed to the presence beneath them of low-density granitoid plutons, emplaced during Late Ordovician or Early Devonian magmatic events. Within this framework, the Carboniferous record of uplift, tilting and submergence of individual blocks points to a complex history of fault-block rotation and lateral as well as vertical movements along the boundary faults. Further, block boundaries are not always fault-controlled, but may be transitional across the hinge zone into a half-graben. In these cases, large areas between the main blocks and flanking the troughs are now covered by a shelf carbonate succession deposited in a regime that was neither wholly 'block' nor wholly 'basin'. The principal structural units (P916037) are described below.

The Southern Uplands Block and its offshore continuation into the Mid North Sea High, broadly separated the Peel–Solway–Northumberland Basin from the Midland Valley of Scotland. Evidence suggests that, at times, the barrier was breached by a series of narrow north-north-west-trending basins.

Traversing the north of England is the composite Peel–Solway–Northumberland Basin. Interpretation of geophysical profiles across the basin indicates that it developed over the inferred line of the

Iapetus Suture, with extension and growth faulting further facilitated by pre-existing intracrustal detachment surfaces such as the Causey Pike Fault. The southern margin of the basin is defined by the Maryport–Stublick–Ninety Fathom fault system. Throughout much of its length the northern margin is also formed by a system of en échelon synsedimentary dislocations including the North Solway, Gilnockie and Alwinton faults. In the early Carboniferous, the Cheviot Block separated the Tweed Basin from the main Northumberland Trough, although the extent of its continuation offshore is still uncertain. The eastern side of the Cheviot Block, onshore, was submerged in the Asbian and its boundary with the Northumberland Trough is poorly defined. The latter basin is a half-graben, with the rock succession thickest close to the major bounding fault in the south (P916069). Seismic data reveal a number of fault-controlled, linear intrabasinal highs that may have been exposed and subjected to contemporary erosion during the early, pre-Chadian period of basin evolution. To the west, the Peel and Solway basins formed as complex and roughly symmetrical grabens.

On its south side, the Northumberland Trough is bordered by the Alston and Lake District blocks. Underlain by the North Pennine Batholith and bounded by faults on three sides, the Alston Block formed a prominent high until the Asbian. The Lake District Block is underpinned by the Lake District granitic batholith and probably remained emergent during early Carboniferous times. Thereafter, southward tilting of its upper surface gradually allowed northward onlap of Arundian and younger strata and it is likely that latest Visean, Namurian and Westphalian strata were deposited over most if not all of the block. The Southern Lake District High is essentially the south-dipping flank of the Lake District Block, which from seismic evidence was dissected during Visean times by a series of small north-trending half-grabens. The Lake District block extends westwards as the Ramsey–Whitehaven Ridge, an elevated tilt-block, bounded to the north-west by the Maryport Fault and to the south-east by the Lagman and Eubonia faults. At its western end, the ridge merges with the Manx Block, a structural high underpinned by the granitic Manx Pluton.

To the west of the Alston Block, the Vale of Eden Basin developed from the Visean onwards as a half-graben structure adjacent to the Pennine Fault system. To the south of the block, the Stainmore Trough is an embayment open to the east. The northern margin of the trough is bounded by the Closehouse–Lunedale–Butterknowle fault system, which links northwards via the Pennine Fault to the Stublick Fault at the northern margin of the Alston Block. In contrast to the floor of the Northumberland Trough, seismic evidence indicates that the floor of the Stainmore Trough is relatively flat, with little evidence of significant intrabasinal faulting. The southern margin of the Stainmore Trough is formed by the Askrigg Block, a northward dipping massif underpinned by the Wensleydale Granite. Thence the basin network extends through the Craven and Lancaster Fells basins and continues westward into the East Irish Sea Basin. The northern margins of the Askrigg, Craven and Lancaster Fells structural units define the southern limit of the Northern England region described here; these units are described in the companion volume for the Pennines and adjacent areas.

The timing of early Carboniferous extension remains a matter for debate. Geophysical interpretation indicates that the earliest, synrift Carboniferous strata in northern England were deposited in the axes of the main troughs. Very thick, early Carboniferous deposits appear to form the lower part of the synrift succession in the Northumberland–Solway Basin and the Stainmore Trough, but their character is unknown since they are located at depths beyond the reach of existing exploratory boreholes. From likely correlations with surface outcrops in northern Cumbria, these early deposits (at least in the Northumberland Trough) may well include fault-related breccio-conglomerate and basaltic lavas erupted at the onset of rifting. Siliciclastic rocks interbedded with limestones of Arundian and Holkerian age were proved in the Seal Sands Borehole (NZ 5379 2380) and may be typical of much of the basin fill in the Stainmore Trough. The synextensional rocks of the region are largely confined to the basinal areas, and are thickest close to the major bounding faults. Up to around 5000 m of synrift strata lie adjacent to both the Maryport–Stublick–Ninety Fathom fault system along the southern margin of the Solway–Northumberland Trough, and to the Closehouse–Lunedale– Butterknowle fault system at the northern margin of the Stainmore Trough. Equivalent strata are largely absent from the structural highs though relatively complete but thin, synextensional sequences do occur on the eastern part of the Cheviot Block and on some of the main intrabasin highs. Only relatively small thicknesses, up to 200 m of beds from the later part of the extensional phase, occur around the margins of the Alston and Lake District blocks.

Both the Peel–Solway–Northumberland Trough and the Craven Basin were inundated from a seaway to the west, while the Stainmore Trough was probably flooded from the east. Borehole evidence shows that deep marine conditions were maintained throughout Dinantian times in the Craven Basin and concealed eastern part of the Stainmore Trough. However, the exposed Dinantian successions of both the Solway–Northumberland and west Stainmore troughs were deposited in relatively shallow marine conditions and there were frequent fluviodeltaic incursions. During later phases of extension, deposition gradually spread more widely until, Asbian to Brigantian times, rapid subsidence gave way to slow downwarping of the major troughs and their adjacent bounding block areas. Minor extensional faulting continued into the 'postextensional' phase.

Tectonic influences on local sea level

The position of relative sea level was a primary control on the nature of the Carboniferous sedimentary successions. Active growth of the major structures beneath the region caused the sea to be persistently deeper in some areas, thus influencing both the type and thickness of sediment deposited. In general, the block areas subsided more slowly than the intervening basins, resulting in the accumulation of thinner sequences of Carboniferous rocks over the blocks than in the basins. Despite these marked variations in subsidence rates, it seems that during much of the Carboniferous, sedimentation across northern England everywhere kept pace with subsidence so that the depositional surface across both blocks and basins was at any time almost horizontal.

During the Dinantian and most of the Namurian, limestone and marine mudstone were deposited in maximum water depths of a few tens of metres; coals, seatearths and many of the sandstones represent emergence of a few metres. Lateral changes in lithofacies and stratal thickness point to recurrent syndepositional activity along basin margins and inherited fault lines such as the Closehouse–Lunedale fault system. From the late Namurian, significant marine influence was progressively lost over the entire region and subsidence and river-borne sedimentation were balanced, maintaining a stable delta-top environment through to the late Westphalian. Deposition was increasingly dominated by sand, silt and mud, carried into the region by large prograding river deltas draining a land area far to the north. With time, marine intervals became less frequent and of shorter duration. The likely changes in palaeogeography inherent in this situation are summarised in (P916070).

The initial, rapid fault-controlled subsidence along the early Carboniferous rift axes, was locally accompanied by the eruption of basaltic lavas, now preserved in northern Cumbria and Northumberland, and along the southern margin of the Southern Uplands. Earliest Carboniferous (Tournaisian) sedimentary successions include variable thicknesses of unfossiliferous conglomerate and sandstone derived from erosion of the Late Devonian landscape. The lithofacies closely resemble that of the upper Old Red Sandstone in southern Scotland (Stratheden Group) where, in the Tweed Basin, there is locally a conformable passage from uppermost Devonian into lowermost Carboniferous strata.

Limestone deposition predominated during Visean times in much of south and west Cumbria, in

Ravenstonedale and on the Alston and Askrigg blocks. Sedimentary environments ranged from shallow shelf seas to ramp and slope areas, though the central parts of the Alston and Lake District blocks were only partially and briefly submerged. Differential subsidence between the Alston, Cheviot and Southern Uplands blocks and the Tweed and Northumberland basins had been most active during the early part of the Tournaisian and reduced progressively from the Visean onwards.

In late Visean times, uplift of source areas to the north led to southwards progradation of a giant clastic delta complex that rapidly filled the basinal areas of northern England. The Cheviot Block was the first to lose structural independence in the Asbian, with deposition between the Northumberland and Tweed basins becoming uniform and continuous. At the same time, the Alston Block became more closely linked with the Northumberland Trough as the degree of differential subsidence across the Stublick–Ninety Fathom line gradually decreased. Thereafter, from the Brigantian onwards, a similar pattern of cyclic sedimentation developed throughout the region, although relatively thin Brigantian and Namurian successions over the Alston Block indicate that it was still subsiding more slowly than the adjacent Northumberland Trough. This situation persisted until the beginning of the Westphalian, but then uniform subsidence affected both block and basin until at least the Bolsovian (Westphalian C). The Westphalian D red beds of the Canonbie area are the youngest Carboniferous strata now preserved in northern England and their lithofacies shows establishment of a fluvial–terrestrial environment.

Climate

Palaeomagnetic and lithofacies evidence (the latter including worldwide facies distributions) independently suggest that Britain was situated in near-equatorial latitudes for much of the Carboniferous Period (P916033) c–d). In northern England, Tournaisian terrestrial strata laid down in small isolated basins include pedogenic horizons (cornstones) indicative of a semi-arid climate; the coeval offshore deposits preserved in the Northumberland Trough are assemblages of interbedded mudstone (some with halite and gypsum pseudomorphs), sandstone and argillaceous dolostone ('cementstone') deposited in a marginal marine environment subject to periodic desiccation. The discovery of thick, early Visean anhydrite beds in the Easton Borehole (NY 4412 7170) confirmed largely arid climatic conditions and shallow marine deposition. By the late Visean, Britain lay at the southern margin of the equatorial belt, but experienced fluctuations of climate with the possibility of monsoonal-type rains. Thereafter, during the later part of the Carboniferous, Britain moved into humid, equatorial latitudes, as confirmed by the extent of coal within the sedimentary sequence that accumulated. The end of the Westphalian saw a return to more arid conditions.

From late Visean times onward, the southern hemisphere experienced repeated phases of glaciation as its continental mass (Gondwana, by then the southern part of Pangaea — (P916033) drifted across the South Pole. The coldest intervals may have brought about short-term, seasonally drier climate farther north, whereas melting ice may have resulted in a wetter equatorial climate, and would certainly have caused a eustatic rise in sea level. It has been proposed, but not established, that glacial fluctuations in southern Gondwana, controlled sedimentary cyclicity elsewhere. Across northern Britain, at least, this glacial/eustatic influence would have interacted with other, more local tectonic effects. A factor in the southern Gondwana glaciation may have been the rapid Carboniferous rise in the atmospheric O_2/CO_2 ratio that was coincident with the proliferation of land plants. At around this time there was a marked evolutionary expansion of several groups of spore-bearing plants such as sphenopsids (horsetails), lycopsids (clubmosses) and filicopsids (ferns). Two groups of seed producing plant — cordaites and pteridosperms — also expanded, whilst the first conifers, cycads and bennettitales appeared in late Carboniferous times. Other side-effects of the increase in atmospheric oxygen were seen in the coal swamps: the evolutionary rise of large insects, and the high frequency of wild fires.

Sedimentary cyclicity

Sedimentary cyclicity is a feature of the Carboniferous successions. The phenomenon is particularly developed in parts of the upper Visean and lower Namurian successions of the Northumberland and Stainmore troughs and the Alston and Askrigg blocks, which are characterised by the 'Yoredale facies'; an assemblage wherein each cyclothem is thicker, more extensive, and can be more widely correlated, than is the case for cyclothems elsewhere in the Carboniferous succession. Each Yoredale cyclothem has a limestone at the base, which is overlain sequentially by mudstone, sandstone, seatearth and coal (P916071). The cycles have an average thickness of around 20 m, range up to a maximum of several hundred metres, and are generally thicker in the basins and thinner on the blocks. Their immediate cause was a marine transgression followed by a progressive shallowing and change to fluvial conditions with subsequent emergence and the growth of delta-top swamp vegetation; a series of events repeated many times. In terms of sequence stratigraphy, the limestone was deposited during the high-stand phase with the base representing the sequence boundary, coincident with the transgressive surface. Lowstand facies are represented by palaeosols and coal at the top of some of the cycles.

The origin of typical Yoredale cycles has been much discussed, with tectonic, eustatic and sedimentary mechanisms all proposed. Since broadly similar patterns of relative cycle thickness are found for the Yoredale successions in both block and basin localities, a control on deposition that affected the whole region seems likely and from this perspective glacioeustatic sea-level oscillations are attractive. However, the advance and migration of delta lobes, or local tectonism such as that associated with syndepositional fault movement, both of which mechanisms are independent of sea-level change, can also result in cyclical deposits of mudstone and sandstone. It is most likely that a complex interaction of all of these mechanisms resulted in the deposition of the distinctive Yoredale lithofacies and the many other examples of Carboniferous cyclothems.

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