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Carboniferous Sedimentary Basins of Northern Europe and the Nature of Emergence around the Margins of the Mesozoic Rifted Sedimentary Basin of the North Sea [and Discussion]

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Carboniferous sedimentary basins of northern Europe and the nature of emergence around the margins of the Mesozoic rifted sedimentary basin of the North Sea

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The evidence of the infilling, shape, longevity and setting of the Carboniferous basins of northern Europe, long available in the public domain and now, with additions from the petroleum and coal-mining industries, is assembled. It suggests that their nature and origin are products of a sequentially and spatially nesting hierarchical mechanism of crustal change, within a framework that remains stationary within the bounds of the subcontinent. The observed dynamic morphology of subsidence in the coal-mining basins suggests an alternating sequence of downwardly narrowing linearly elongated, generally rectilineal zones, across which vertical movement takes place in the crust. The narrowing sequence of vertical movement is elliptically basinal or domal in the near surface, with subordinately horizontal tensional and compressional zones within it; rotational and counter-rotational respectively, below the wider, overlying, tensional and compressional zones; and finally, a vertical plane lying beneath the transition point between the two rotational zones. It is concluded that, to produce the observed pattern, the earliest cycles in the mechanism have cumulatively underprinted their successively more primary lines of disturbance, to produce the upward diminishing hierarchy of sizes of rectilineal block motions, responsible for the Carboniferous, preceding and succeeding basins.

Introduction

Long before it attended the birth of geology in Europe, successful mining had always had to embrace internally generated cumulative views of the architecture conditioning the unfolding morphology in many of the very varied European mineral bodies mined. These views have always been expressed, not in scientific terms, but in the stepwise chronological record of the morphology of previous workings, together with each new plan for their advance. The scientific view of the relations between successive mountain chains and the rising swells or subsiding sedimentary basins in what is now NW Europe has also been cumulatively advanced in successive steps from those originally presented by the founding fathers such as Lyell and E. Suess. The rapidly branching chain of supporting references stretching back for more than a century can be entered from the exhaustive lists accompanying the two most recent major compilative works here cited, i.e. Ziegler (1980) and Bless *et al.* (1977). Much of the substance of the review by Bless *et al.* is devoted to an examination of the limits of error in the stratigraphical controls that determine true comparability of the geological sections selected in each basin.

Interest in first the gasfields and then the oilfields of the North Sea, and renewed interest in the potential of the surrounding land areas, generated very large quantities of new evidence in NW Europe on the areal scale required to study the evolution of sedimentary basins in general. These syntheses gave a fresh geological, as opposed to solely geophysical, view of the up to multi-megayear and near gigayear mechanism responsible for the palimpsests of a general process of change in the upper crust: a process that we may observe, often apparently 'frozen' – because it is so slow, at different steps in the process, in different places within the upper crust. Only by the release of such syntheses and supporting data is there any increase in the traditional geological 'depth of focus' brought to bear within the tens of kilometres thick field of the general crustal mechanism responsible for generating a succession of basins and swells, horst and graben, etc. Traditionally, it was necessary to make the best of the products of such deep-seated processes as were exposed within a slice of only 1 km or so thick.

Examination of the implications of a succession of uniquely complete large-scale stratigraphic palaeogeographic reconstruction has had to await petroleum geologists such as Kent (1975, 1977, 1980) and Ziegler (1975, 1978, 1980) over the mid to late 1970s. Ziegler (1980) states that 'the Permo-Carboniferous fault system of NW Europe was time and time again reactivated, particularly during the Mesozoic, and played a pre-eminent role in the development of post-Variscan sedimentary basins'.

Field geologists' constructions of 'deep' cross sections of the crust below rift valleys, etc., may often 'look right' for two reasons: firstly, because, for lack of evidence to the contrary, they imply that the upper crust may act mechanically as a single entity; secondly, within that entity, the mechanics of the system conditioning its movement and stasis has been made mechanically analogous to one of the systems so familiar on all kinds of scales, in the open situations observed everywhere at the surface. Such systems underlie the stability of Roman (and natural) arches, mantelpieces cantilevered over fireplaces, shelves between their supporting brackets and 'concertina-like' horizontal stacks of books when being passed from one pair of hands to another. As will be argued below, however, even when in precisely analogous boundary conditions, the 'structural blocks' in an upper crustal cross section do not necessarily operate in the familiar form in which they can be intuitively 'seen to work' when observed at the surface. Some of the 'space problems' and the difficulties arising from implied tensional or compressional conditions are only brought about by the assumption that the mechanical systems so familiar at the surface must also condition the deeper movement and rest position of structural blocks.

COMPARATIVE ASPECTS OF THE MECHANICS OF BASIN AND GRABEN FORMATION OBTAINABLE FROM PARALLEL OBSERVATIONS OF THEIR MINING ORIGIN IN THE COAL BASINS OF NORTHERN EUROPE

The state of geomechanics in upper crustal studies and soft-rock mechanics in coal-mining

For the upper crust it is possible to make suggestive-looking overall abstractions from the general patterns within the lineaments – cumulatively modified by successive episodes of translational, rotational and differential strain movement, both of and within 'blocks'. Although certain limiting overall proportionalities in the statics and dynamics from the physics of the system must contribute, there is as yet no quantitative, all-embracing 'mechanics of upper crustal movements' to explain the observed patterns on all scales of occurrence.

Thus a possibly fourfold, upwardly propagated succession of changes in the upper crust may be observed. The four primary constituents of such a succession may be as follows. (1) The (perhaps bottom-most) zones of either old–cold–thick or young–hot–thin now crystalline crust whose essential attribute is that they are much longer than they are wide, and hence form a lineament. (2) The corresponding, perhaps middle depth, orogenic 'zones of disturbance' of the once simply stratified, and then more extended, layers of the upper crust. (3) The adjacent, perhaps shallower systems of macro-fault lines. These may be in the form of either (horizontally) 'translational fault-and-end-splay' or major (vertically) rotational fault or paired vertical fault systems (the major horst and graben). They may possibly overlie the one locally plan parallel member of the set of earlier deeper (once bottom-most but subsequently eroded) lineaments imposed in each earlier cycle of change. If this is so, then movement on the parallel much earlier basal lineament might well be expected, when contemporaneous examples of (1) and (2) are being originated nearby. (4) The corresponding very slightly more elongate and wider overlying basins and swells. These are of a flexural nature and across them, more or less at the contemporary surface, sedimentation or erosion takes place. These basins and swells in many recent 'greatest depth of focus' studies appear to be the final members of such a vertical sequence of upwardly propagating original and reactivated movements in the upper crust (that is, wherever the longer axes of the wider zones of flexural movement both vertically succeed, and lie parallel to identifiable, narrower, underlying forms of lineament).

The analogous vertical and lateral sequence of patterns within, seen in the products of both upper crustal and soft rock mechanics, may be due to a rheologically similar mechanism. In both domains, the mechanism produces the two observed linked phenomena. Firstly, subsidence basins and 'upsidence' swells over a flexural plane parallel to the Earth's surface. Secondly, highly localized sub-vertical planar discontinuities, across which movement of the strata takes place. Both phenomena have been quantitatively observed, and the ratios between their forms, in different cross section setting and dynamic relations, quantitatively characterized, as a result of innumerable observations of them in the mining domain.

A similar overall set of ratios in the domains of upper crustal and soft-rock mechanics may condition the internal patterns geologically observed, although on a completely different scale.

It is necessary for the earth scientist, interested in the data on the relations between trans- and intralineament and corresponding flexural movement within the mining domain, to appreciate the origin and nature of certain essential configurations that obtain in deep coal mining. These data are primarily obtained by empirical observation of the movements themselves (Peng 1978). Although perpetually in use within the mining industry for precise prediction of surface subsidence and form of strata movement, the mass of empirical data involved is almost entirely unpublished.

A general terminology for descriptions within a hierarchy of scales, of disturbance, horst and graben, basins and swells in upper crust

Many special terminologies are employed to identify morphological features of the general tectonic and depositional framework seen from a different standpoint. The special terminologies originate when the features are seen in the detail obtainable in field stratigraphic, petrographic, etc., studies. These special terminologies may imply that the morphological features occur on a particular scale, or they may carry some connotations of origin, particularly when considered in isolation from its predecessors and successors. Examples of this may be found in palaeogeographical terms such as 'shoal', 'shore line', 'St George's Land' and 'Northern Continent', in palaeoecological descriptions such as those implying a broaching of old 'land barriers', to explain the palaeogeographical disposition of a marine fauna containing new elements, and in sedimentological terms particularly those contrasting certain kinds of facies. Such sedimentary facies are those that imply a change in the rate of tilt of the depositional surface lying between two foci or loci of contrasting maxima in rate of vertical movement of the Earth's surface, e.g. slow or rapid, transgressional or regressional, shallow water or deepwater facies.

A more generalized and strictly non-scalar morphological terminology for the analysis of patterns within a general system of lineaments and flexures appears desirable. It would enable any repetitions to be observed, within a nesting hierarchical set of scales – parts of which are observed in different places throughout the upper crust – and which may also operate within the rheological framework of coal-mining strata control and subsidence. It is also desirable if the evidence obtainable from (*a*) analysis of essentially descriptive field geological observations of local patterns in the internal structure of lineament and flexure *on all scales* is to be added to (*b*) the strictly geophysical measurements of the modifications to the Earth's energy and stress fields, and the deeper-seated changes in the physical properties to the crust across basins and grabens, etc.

The deep coal-mining engineer tends to place all geological phenomena locally disrupting or impeding the (revenue earning) advance of his highly capitalized longwall panels in the one category of 'geological disturbances' to the continuity of mining. It seems appropriate to borrow from this terminology and categorize any linear feature occurring on any scale that the rheological continuity of the zone in the enclosing crustal layer, when viewed on the same scale as 'a disturbance'. It may be of linear or areal flexural form.

In order to 'disturb' the enclosing zone, firstly, the zone must be of a width and thickness that is determined by the minimum overall scale on which 'the disturbance' is observed and, secondly, the disturbance must (usually) post-date what is the (otherwise) *undisturbed* enclosing zone. Thus, the frame of reference within which a zone, thus defined, may be referred to as 'undisturbed' must always be within a particular range of areal scales, and hence occur at a particular level in the hierarchy of 'lines of disturbance'.

At one end of the scale, the areal framework of the enclosing layer may be of 'continental' size and of 'whole crustal plate thickness'. This is appropriate when viewing, say, the belt formed by the Caledonian orogeny as a 'line of disturbance' within its surrounding and, at this level in the hierarchy, 'undisturbed' zone. At the other end of the scale, it may be as small as is appropriate to the vertically and laterally dying line of disturbance caused by a small fault that dies out both upwards and downwards within the boundaries of the crustal layer containing only a few neighbouring and, at this level in the hierarchy and otherwise undisturbed, Westphalian C. On the smallest scale in the nesting processes to be considered, the line of disturbance may be a strata control engineer's induced 'fault' disturbing the overlying strata for only a few tens of metres over the gateroad of his longwall mining panel, before the extension he desires passes into a block rotational form, and finally into the tensional zone within a surface subsidence curve.

From a bird's-eye view, at some considerable distance from the thus shrunken frame of reference of the 'undisturbed' zone containing it, a major 'rift valley' can thus become a single lineament of 'disturbance'. This is only true at one of the higher levels in the hierarchy of such lines of disturbance to the continuity of the hierarchy of 'crustal layers' of diminishing thickness or extent, or both, within any major zone on the continental surface. It can be seen intuitively that there may be a nesting hierarchy in the range of areal sizes and thicknesses of the 'undisturbed' zones, implied at each level containing a member of the hierarchy of correspondingly longer and thicker 'lines of disturbance'.

The term 'subsidence basin' can have a purely morphological connotation. The term appears to be applicable on all scales of occurrence of any possible general nesting hierarchical mechanism which, *inter alia*, produces it within the surface of 'undisturbed zones'. Although the term 'upsidence' has been used in the mining domain as a corresponding term for flexurally continuous surface but of opposite polarity, a 'swell' may be more appropriate: that is, always provided that the scale of the frame of reference within which the term 'swell' is employed is precisely the same as that on which neighbouring basins are being identified. A 'swell within a swell' (or within a basin) is of a lower scalar order in frame of reference, and it distinguishes a form of local interruption to the continuity of a much larger scale basin containing it. In this case, the term 'hump' for such a swell within a basin, e.g. above deep-seated 'horst' block, might be appropriate.

Finally, when distinguishing an intervening zone at any level in the hierarchy which neither appears to be involved in any movement, nor to contain any flexural or linear 'disturbances' within it, it might be appropriate to use the term neutral 'block' or, when viewed only superficially, neutral 'zone'.

FOUNDATION MORPHOLOGY OF THE CARBONIFEROUS BASIN FLOOR IN NORTHERN EUROPE

Palimpsests of pre-Caledonian tectonic elements within the Erian–Hibernian floor of the Upper Palaeozoic

Many European authors since Cogné (1976) describing the structural architecture of Laurasia (NW Europe before the opening of the Atlantic) have drawn attention to the underlying influence of a foundational 'core shape', in the form of an inverted T or inverted, flattened Y. In most Palaeozoic 'plate' reconstructions the 'triple point' of the inferred suture lines at the T junction between the belts is usually placed somewhere in what is now the Atlantic just off SW Ireland.

However, it is possible to describe them solely in the morphological terminology expounded above. The belts then shrink to 'lines disturbance' crossing what then become 'undisturbed' areas. As expected, part of the southeastern 'thick-pencil' edge of the indisputable Caledonian 'line of disturbance' curves across Britain between Pembroke and the top of East Anglia, and part of the northern edge of the probably pre-Caledonian line sweeps across Britain between the Bristol Channel and Dungeness.

With one 'triangle of exception', both of these trends are nicely reflected in the bimodal fault patterns now impressed within each of the coalfields of England and South Wales. The belt of exceptional coalfields lie within a tall right-angled triangle with its apex in Morecambe Bay, its perpendicular dropping down to the top of the Severn Estuary and its hypotenuse dropping down to North Foreland (NW Kent). The line of the hypotenuse parallels the east-northeastern edge of the London–Brabant Massif in Ziegler's (1978, fig. 2, p. 592) reconstruction of the late Caledonian framework of NW Europe.

When taken in conjunction with inferences, discussed below, from the location and morphology of the North Sea Cainozoic basin, it is tempting to infer the existence of two other and similarly fundamental 'lines of disturbance'. By using this terminology, there is no need to seek evidence of whether they are or are not 'suture lines' of some earlier plate accretions. Their supposed existence is implied purely from the profundity and enduring nature of their effects on all the later observed features.

The earlier and deeper of these two 'other' successively imposed inferred 'foundation lines' of disturbance would run north–south, through the centre of the northern North Sea. The position of the shallower of the two inferred 'foundation lines' would run northnorthwesterly; it could be located in a number of alternative places, so its position is unknown. Part of it *might* be off the northnorthwestern edge of the London–Brabant Massif. Certainly the continuation southwards of this inferred north–south 'foundation line' of disturbance to a point in the North Sea halfway between Lincolnshire and Schleswig-Holstein would appear to terminate at a 'junction' and to swing southsoutheast, parallel to this edge of the Massif. Such an inferred southsoutheastern foundation line would then continue under present day Amsterdam, to form another 'triple-point' with the well known Variscan line where the latter changes direction, in the vicinity of the junction between the Ruhr Graben and the Rhine–Leme Graben.

The late Caledonian framework of northwestern Europe has been reconstructed by Ziegler (1978, fig. 2, p. 592). The succession of primary mobile belts, underlying all stratigraphically later crustal eras, can be thus shrunk into 'foundation lines': lines disturbing the otherwise undisturbed European crust. The existence of two earlier lines of disturbance originating in lower (earlier) crustal eras is inferred. The slightly more definitive of the two inferred lines of disturbance, running northnorthwest–southsoutheast, taken together with the east–west probably pre-Caledonian line and the northeast–southwest Caledonian lines, are responsible for the existence of the triangular London–Brabant Massif in this pre-Variscan continental framework. The largely triangular London–Brabant Massif is shown by Ziegler with its three apices located in Pembroke, in the North Sea just north of East Anglia, and in Belgium not far to the northwest of Brussels.

The central hypothesis underlying this commentary on evidence available from mining and geoscientific consideration of Carboniferous basins in northwestern Europe

It is suggested that, apart from the 'foundation lines', the crust contains sets of intersecting macro-lines of disturbance, together forming an irregular grid of intersecting lines. Each successively imposed set would be parallel to each of these successive actual or inferred primary 'foundation lines of disturbance' located as an orogenic belt. Some of these primary lines were associated with plate collisions. The subordinate, largely parallel, members of the grid of associated macro-lines would be successively superimposed on the 'undisturbed' palaeocontinental zones. These zones would contain both (*a*) the successive earlier foundations lines (where not completely eroded, either at the surface or by absorption into the underlying mantle), and (*b*) all their associated parallel 'macro-lines' of disturbance.

Thus, on these hypotheses, on each successive occasion, both a new set of macro-lines of disturbance was imprinted and movement on the earlier sets would be reactivated in a manner analogous to the soft-rock strata control engineer's fracture-faulted and, much wider, induced cleavage zones. In the 'upper crustal case', however, reactivation takes place within the 'undisturbed' or 'less viscoplastic' phases below the upper crust.

In each cycle of change, it would then be the successive layers of foundation blocks that controlled the position of all overlying subsequent graben, asymmetrical graben and trap door 'hinge-line and fault systems' and the shape and dynamics of sedimentation in all overlying surface subsidence basins of sedimentation. In each cycle, these features all lie within those wide flat-bottomed basins of deposition recognized as 'the' Palaeozoic and Mesozoic and Tertiary 'sediments and metamorphosed sediments' of NW Europe as a whole.

The other constituent of the floor of the coalfield basins of northwestern Europe: Devonian and Lower Carboniferous subsidence and depositional basins and eroded swells

Kent (1980), in his earlier work on the structural framework conditioning the subsidence of the North Sea basin as a whole, emphasizes that the subsidence began early in the Upper Palaeozoic and has been virtually continuous ever since. He states that '... initial subsidence of the basins of the NW European Shelf ... began shortly after the end of the Caledonian Orogeny ...' (Kent 1980, p. 282). He draws attention to the migration, outwards from the centre, of certain segments of the hinge lines between the vertically negative areas that were subsiding and the vertically positive uplifting areas, on the other side of these segments. He describes '... overlap in England of Lower Devonian across Cambrian and Silurian in the southern Midlands, by the overlap in turn of the Upper Devonian onto the older rocks of the Welsh Highland and East Anglian Massif. ... Thus except for Cornubia (which is essentially Hercynian†) each of the Palaeozoic blocks was a positive structure during the Upper Palaeozoic, as indeed through the Mesozoic'. He states (p. 282) that this observation on the positive nature of earlier Palaeozoic blocks also applies to the 'Fyn–Rinkøbing High in Denmark and the other Massifs which bound the basin of NW Germany and of the Central Massif in France'.

Ziegler makes the same point in his wider palaeogeographic reconstruction of the late Devonian framework of the combination of NW Europe (Ziegler 1978, fig. 2, p. 594). He also gives details of the shape, maximum thickness and nature of the Devonian sedimentation in the basins of Ireland, Scotland, W Norway and Svalbard, the Midland Valley Graben, the Orcadian and the Northumberland basins. He describes the accompanying post-orogenic emplacements of granites in the (inferred) simultaneous uplifting of the Scottish Highland and S Upland Massifs.

Contemporaneously in the south, in the predominantly marine part of the Devonian basin of sedimentation, Ziegler (1978, fig. 4, p. 596) illustrates the further emergence of two dissected broadly east–west lines of 'highs', flanking their associated Cornwall–Rhenish and Central American–Saxonian 'troughs'. He points to the large reef-fringed carbonate platforms established in the mid-Devonian (during Givetian times) 'in the shelf areas and on local highs' (p. 597), and to the general vertically continuous and in this sense 'stationary' tectonic setting of sedimentation.

Ziegler (1978, p. 598) draws attention to the 'extension tectonics' to the north of the lines formed, firstly, by the Normanian geanticline and the mid-German High and, secondly, by the Averno–Lugian geanticline and the Bohemian Massif, which 'persisted throughout late Devonian times into early Carboniferous times'. (Within coal-mining subsidence basins, such 'extension and compression tectonics', recognized by upward movement of such features as kerb-stones to relieve horizontally compressive stress, are a corollary of outward propagation of a subsidence basin. They are also preceded by a zone of tensional strain, such as would allow graben and basin formation in the upper crust. However, in this case the northwardly propagating 'subsidence waves' would have to originate deep within in the mantle.) He describes the onset of the Variscan orogeny in the Upper Visean and the start of underthrusting along the margins of the Normanian mid-German high: '... With the general advance of the deformation front during Namurian and Westphalian, the basin axis of the Variscan foredeep migrated

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† It is here suggested that because its lineaments are parallel to east–west margins of earlier foundation blocks, Cornubia also has a pre-Caledonian (? Cadomian), or earlier, foundation.

northwards and the newly folded-up sediments were subject to erosion.' He shows, on his palaeogeographic reconstruction of the Lower Carboniferous (Dinantian) of NW Europe and surrounds (Ziegler 1978, fig. 5, p. 597), both the areas of Flysch sedimentation, abutting the deep basin 'black shale' areas, and the classical Carboniferous Limestone deposited around the (then relatively neutral) Caledonian 'highs' in the remainder of the basin, to the north.

In Britain, local areas of lateral change, overlying certain earlier foundation blocks, are clearly seen – within the subsiding basin of deposition of more widespread Lower Carboniferous facies. They are reflected in modern stratigraphic recorrelation of the original (largely lithostratigraphic) division of the Carboniferous, into 'Carboniferous Limestone', 'Millstone Grit' and 'Coal Measures'. In one immediately illuminating stratigraphic–lithostratigraphic cross section of Britain in the Carboniferous, Ramsbottom *et al.* (1978, fig. 1, p. 6) show clearly (*a*) the early onset of 'Millstone Grit' facies, in the uppermost Dinantian of the southwest around Bristol, and (*b*) the persistence of 'Carboniferous Limestone' facies, into the Namurian of the 'Derbyshire dome' (then one of the basins within the Pennine basin), followed northwards by (*c*) the greater and greater persistence of 'Carboniferous Limestone' facies higher and higher into the Namurian until the Midland Valley of Scotland is reached, and the northward record terminates. Without oil industry data, it is the whereabouts of present-day exposure that selects two-dimensional vertical ribbons of exposure, illustrating a northward advance of the fluviatile 'Millstone Grit' element over the Namurian chronological interval.

Reading (1969) reviews certain Carboniferous sedimentation sequences in selected (largely Namurian and Westphalian) depositional basins of western Europe, north of the Variscan front. He draws attention to the sedimentary facies succession, infilling the basins, initially black shale; then greywacké turbidite (down the front of the fluviatile platform, which is usually spreading out, and thus filling and covering the basin); and finally the fluviatile facies (retained on the top of the platform only to the extent that the bottom of the basin continues to subside). He then states (p. 1410) that 'basins of considerable depth were filled with great rapidity'. He concludes that, by late Namurian times – when fluviatile conditions predominate – that, with one exception, successions over NW Europe do not substantially differ. The exception is in the Cornubian trough, where turbidites persist into the Westphalian A; this is also seen in Ramsbottom *et al.* (1978, fig. 1).

Depositional conditions on the floor of the coal-bearing sedimentary basins of northern Europe

By the time the lithostratigraphic interval formerly known by such terms as the Productive (coal) Measures had been reached, the depositional floor of most of the overall basin of northwestern Europe (north of the Variscan front), the sedimentation *surface* of the local basins of deposition, was generally at or above 'sea level'. The local basins were 'full up' and sediments were 'washed across the top of them' by the widespread and repeatedly avulsing system of fluviatile sedimentation long known as the 'Coal Measures'. Subsidence across the shelf no longer exceeded sedimentation anywhere.

In general, a vast sheet, over which fluviatile sedimentation persisted, occupied the immensely long east–west shelf between them covering most of northern Europe. It was bounded to the north by the eroded, but presumably rejuvenated, grassless, 'bad lands' of 'the uplands of the Laurasian shield'. To the south, it was bounded by the Variscan trough. Sedimentation exceeded subsidence. The preserved column was thinner over the tops of certain relatively much more slowly subsiding intervening blocks across which the fluviatile sediments travelled to reach the various 'sinks', in which a greater rate of downward movement of the base persisted over the Westphalian time interval.

Thus, by the beginning of the Coal Measures, the pattern of basins, swells and neutral blocks were well established to the north of the Variscan belt. The period of both (*a*) 'still-stand' (giving carbonate sedimentation) on the swells above the more neutral blocks, and (*b*) 'rapid subsidence' (giving 'flysch' in the foredeep and 'greywacké turbidite' sedimentation) in many of the minor basins had largely ceased. Because an avulsing fluviatile system now covered the vast majority of northern Europe, depositional conditions at the floor of the coal-bearing sedimentary basins of Europe did not differ substantially.

Below this floor, the rate of preservation of the fluviatile components of the sediments was still controlled by the hierarchical movement of the blocks making up the tectonic framework underlying them. Thus, where they exist – because the edges of the basin have not been sliced off and eroded by the next (Mesozoic and Tertiary) cycles – the subaerial components of the sediments (the coal seams) are generally all seen to converge on one another towards the edges of the basins, as the intervening fluviatile components thin towards swells.

THE MACRO-'BASIN' OF UPPER CARBONIFEROUS DEPOSITION IN NORTHWESTERN EUROPE

The palaeogeography of the macro-'basin'

Ziegler (1978, fig. 9) shows the extent of the main 'basin' of deposition in the Upper Carboniferous, being greater than 2000 km long and about 500 km wide but only, on average, about 1–2 km deep. It is shown stretching from the westnorthwest to eastsoutheast across northern Europe, from beyond the west of Ireland to eastern Russia and to be cut off to the north and south respectively by two very different types of land area. To the north, the 'basin' is margined by the ancient Upper Palaeozoic land area over the Scottish–Norwegian Caledonides and the Fenno-Scandian shield. To the south the main 'basin' is shown terminating against the Variscan line of disturbance, with its newly emerging mountain chains, within which are the very subordinate Plessis, Saar, Salle, Upper Silesian and Carpathian basins of deposition. On this map, the sediment fill is shown to be shale, sandstone and coal (flysch sedimentation having largely ceased at the end of the Lower Carboniferous) (Ziegler 1978, fig. 8).

A number of small land areas, low humps, largely over (here inferred) Caledonoid blocks, within the main 'basin' are shown (figure 1). It will be seen that the larger triangular area of the Welsh Massif just touches S Ireland. The inherited near 'neutral block', here exposed as the London–Brabant Massif, is also shown in its Carboniferous setting.

The location and aspects of the geometry of the subsiding 'basins proper' and less subsiding 'swells' within the Upper Carboniferous macro-'basin'

Ziegler (1978, fig. 9) shows 'spot' thicknesses of 'intra-Westphalian' sediment at the centre of the larger of the smaller depositional 'basins proper' within the main 'basin'. The subsiding 'basins proper' are the ones with a distinct centre-point or line and their margins (shown by isogonals over the largest interval between a lowermost and an uppermost stratigraphic horizon present right across the basin) everywhere dipping into it in all directions. The deepest are the NW German (3.5 km) and the Central North Sea (3.2 km) basins. The other deep

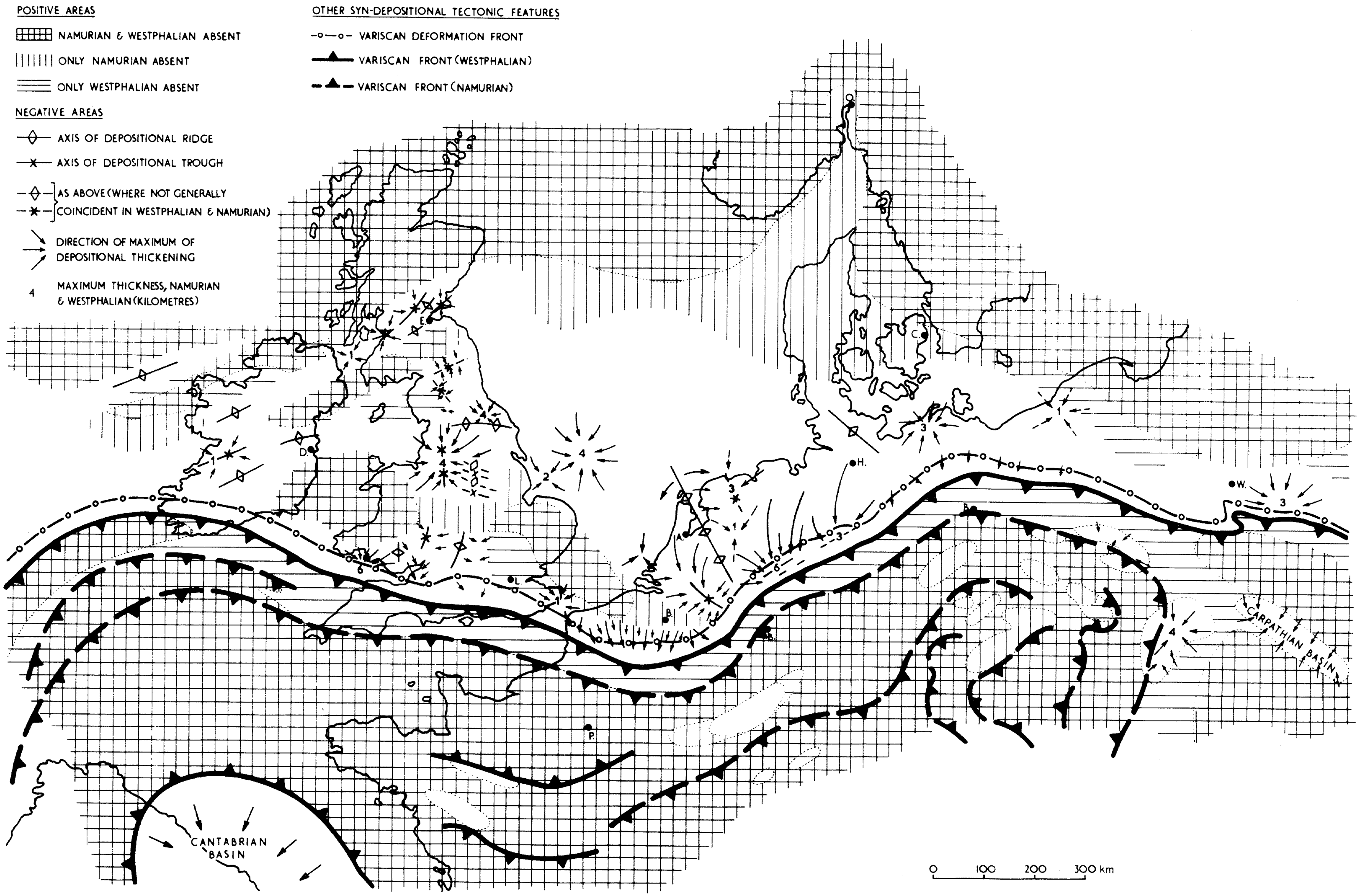

FIGURE 1. The Carboniferous basins of Europe, based on Ziegler's (1978) figs 5 and 6. D = Dublin, E = Edinburgh, L = London, P = Paris, B = Brussels, etc. Sets of isogonal dip lines have been added around the major basins, and the positions of the more minor depositional basins: those between four short Caledonoid trending 'humps' in Central Ireland, added from Ramsbottom *et al.* (1978); the five minor, but comparatively steep-sided, elongate basins of the Midland Valley of Scotland, added from Francis, in Craig (1965); the Campine–Brabant and the remaining six, shallower, mid to eastern European basins identified, along with most of the others, added from Bless *et al.* (1977).

depositional basins are the Pennine basin (2.7 km), the Kent – northern France – southern Belgium 'ex-foredeep' basin (2.5 km), the Saar (2.1 km) (intra-montane) basin, the South Wales (1.8 km) and the Lublin (1.2 km) basins. Although Ziegler shows both those 'humps' that (probably) remained above seam level in the Upper Carboniferous, and also the dispositions and maximum depths of the main basins, he does not show the dispositions of the suite of humps between the basins that did not pierce the surface of sedimentation, but only attenuated it. These may be inferred from the pattern shown by the isogonals in the basins.

In the Namurian, the flattish-centred Pennine basin with a north–south-trending axis centred north of Manchester, almost rectilinear relatively steep sides, and with east–west and north–south-trending margins is flanked, beyond its east side 'subsiding monocline', by a series of three equally steep-sided westnorthwesterly pitching elongate minor 'semi-basins' possibly underlain by 'trap-door' graben. By the Westphalian A, B and C times, this 'depositional monocline' had ceased to move. It then becomes a low semi-conical shaped basin (as shown by Calver 1969, fig. 1*b*, p. 3). Its eastern quadrant covers the underlying minor pitching basins. Were the record complete, it must surely have terminated against a line overlying that of the major change of facies in the underlying Namurian and the present-day Craven fault belt. This, in turn, overlies a deep-seated east–west lineament in the Upper Caledonian foundation, running through S Denmark and the southern Irish Sea.

Bless *et al.* (1980) give selected cross sections of the total Carboniferous over the whole of northwestern Europe. They show both (*a*) the draping off and the thickening towards the centre of the isochronous sedimentation interval that takes place between the margins and the centre of underlying block-controlled basins, and (*b*) the corresponding thinning of the isochronously identical sedimentation sequences over the 'swells'. This style of illustration does not bring out periods of slight overlap or offlap, or both, over the transition points between neighbouring underlying blocks.

As observed when mining in the coal basins of northern Europe, the morphology of 'underlying-graben' (formed by coal extraction in successive panels) and overlying induced subsidence basins appears to be directly analogous with the morphology of the products of this process observed in nature, in the upper crust. In mining, the morphology of the mechanism (controlling 'more rigid layer' graben-induced subsidence flexure, in the overlying more rheid layer) is innately associated with a horizontal tensional zone over the convex upward part of the shoulders of the corresponding subsidence flexure. In nature, whether overlap or offlap predominates in the sedimentation at the shoulders of the basin, this may be critical in determining the relative rate of deceleration of the underlying centre and shoulder blocks, in the underlying more rigid layer. Because, in nature, the blocks in plan view appear to exhibit differences in their structure, investigation by means of a succession of coincident palaeogeographic reconstructions of basin formation, built up successively above a post-orogenic tectonic cycle foundation map, appears necessary for such critical features.

The sedimentary facies infilling the basins and draping the swells

During the deposition of the avulsing fluviatile Coal Measures facies, the centres of the bottoms of the basins were obviously subsiding at up to ten times the overall rate of subsidence of the centre of the tops of the intervening 'swells'. It was often more the rate of preservation of the parts of the sediment column, than the rate of sedimentation *per se*, that increased in the middle of the basins, and decreased over the swells and the more neutral zones.

A detailed lithostratigraphic cross section of the preserved parts of the thick succession in the 'Sulzerpacher Schichten' and 'Geisheck Schichten' of the Saar basin (Kneuper 1971, fig. 2, p. 155; fig. 3, p. 159) shows the typical pattern of 'Coal Measures' cross sections. Cross sections of wide sheet sandstone bodies, and occasionally successively stacked lenticular cross sections of ribbon-like sandstones of all sizes, are surrounded by envelopes of finer sediments, the whole being threaded by a complex, anastomosing, succession of relatively thin coal seams with their underlying seatearths. Collectively, the coal seams form not more than a small percentage of the total thickness of the section. (Where exceptionally thick and apparently vertically continuous, the sections of sandstone grade sediment are now easily broken down into the fluvial cycles within them (see, for example, Clarke 1963, fig. 11, p. 682).) Even though they portray only sediment grade and not sedimentary structure as well, it is salutary to compare such lithostratigraphic cross sections with those generated by Bridge & Leeder (1979) from their mathematical simulation model of alluvial sedimentation.

Bridge & Leeder (1979) use a range of flood plain geometries, of compactional relief and of aggradation rates and optional tectonic fault controlled marginal movement to show the small effect of change in these parameters on the character of sedimentation in the resulting detailed lithostratigraphic cross sections. The overall character of the sedimentation produced is identical to that in the Coal Measures, both over the flat depositional upper surface overlying large 'less negative' blocks, and in central parts of flattish-bottomed basins overlying the flat depositional upper surface of large underlying, more negative blocks.

The only discernible difference in sedimentation sequence over the surface of the less negative (more positive) zones or, in the northern part of the NW German basin (Hedeman & Teichmuller 1971, p. 137), apart from the expected diminution in the overall thickness, is the resulting winnowing away of the silty and muddy constituents of the many sandstones in the succession, leaving them white near orthoquartzite, instead of grey, nearer in greywackés mineral composition. This can only be due to the lower overall rate of aggradation of sediment for the same total amount of aqueous flow across the two kinds of submerged block.

The difference in lithostratigraphic cross section between Coal Measures sedimentation in (*a*) a 'flat-bottomed' or a 'flat-topped' (subsidence) situation, and that in (*b*) the smaller, narrower, steep-sided but comparably deep, elongate elliptical or circular, whole- or 'hinge line terminated semi'-basins has been demonstrated by both Duff & Walton (1964), in an example from the Pennine depositional basin, and Read & Dean (1976), in examples from the Midland Valley of Scotland depositional basin. They show that when sediment thickness between the subaerial deposits diminishes and the coal seams converge, the number of 'cycles' between them decreases. The number of 'cycles' decreases (in proportion to the diminishing overall thickness of the column) as the margining 'humps' and 'swells' of the basin are approached. Where this convergence ultimately gives rise to an extensive 'plateau' of very thick coal, it could be said that the successive subaerial deposits in each cycle overlap the successive fluviatile (or marine) deposits at the edge of the basin, e.g. against 'St George's Land' (a contemporary expression of the Wales–Brabant Massif) on the south side of the Pennine basin.

Duff & Walton (1962) have also made an extensive statistical analysis of cycles. In doing so, they found that the classical 'cyclothem' (Wanless & Weller 1932) is generally the exception rather than the rule in the (virtually Carbonate-free) Westphalian 'Coal Measures'.

The rare very thin, but very persistent, marine 'black shale' bands (with the 'Tonsteins') are the only laterally extensive deposit in the 'Coal Measures', other than the subaerial coal seams. With regard to the marine bands, Clarke (1963, p. 690) has suggested that 'the whole northward mountain chain may have suffered depression, causing the rivers to aggrade in their valleys (and thus sedimentation on the coastal plain to diminish). If the coastal plain macro-'basin' as a whole continued to subside during these rare intervals in which the land area (macro-'swell') to the north, then the rare very thin layers of marine deposits would spread sometimes across the whole of the macro-'basin' shelf, e.g., the Aegiranum Marine Band.' The only other explanation appears to be the more commonly invoked worldwide eustatic rise (and sudden subsequent fall) of sea level.

The termination of sedimentation across the shelf was heralded by the macro-'basin' wide advance of the east–west aligned 'front' of the subaerial 'red-bed' facies. It occurred in successively higher horizons in all basins southward, has often been analysed in European palaeogeographic reviews of the close of the Carboniferous (e.g. by Hedeman & Teichmuller (1971)). Very late (?)Stephanian, very small, coal-bearing, intra-montane limnic basins were formed at a number of scattered localities over a large land area to the south of the Variscan front. They have been preserved, for example in France, wherever the Alpine orogeny has not sliced them up (or otherwise removed them from contemporary means of geological detection).

Tectonic phenomena in the European Coal Measures basins

On evidence of the diachronous spread of 'red beds' (see above), apart from very minor localized heralding movements, the overall depositional phase of the Carboniferous in northern Europe terminated with the slow rise, along a (presumably) east–west, mega-axis lying in the land area to the north of the Upper Carboniferous macro-'basin'. This would have been the horizontal hinge (or perhaps rotation) line along which the macro-'basin', as a whole, tilted upwards – everywhere, at least, where the record is preserved, i.e. to the north of the Variscan 'line of disturbance'. The now reddened alluvial sedimentation with occasional thin carbonate layers (Spirobis Limestones) continued to flow across both the local (?graben underlain) basins, of relatively greater – and across the intervening swells and neutral zones of relatively greater and lesser – subsidence, respectively. No large 'upper-Stephanian' sequence of deposition is preserved in this now tectonically positive, and hence erosive, phase in northern Europe.

The smaller-scale constituent 'basement' blocks within those larger blocks underlying the basins, began to move positively, probably no more continuously in the time scale than is evidenced by the changes they had earlier brought about in subsidiary basin and hump topography both within, and between, the Namurian and Westphalian. Being smaller-scale constituent blocks, e.g. within the Pennine or within the Scottish basin as a whole in space scale, the effects they produced were smaller on the areal scale, as well as on the time scale. Ziegler (1980, fig. 1, p. 251) shows only a few tiny scattered Autunian sedimentary basins in NW Europe, with most of the area shown as land.

Ziegler (1980, fig. 1, p. 251) shows the pattern of mega-faults, including graben and 'hinge line and fault' systems (producing 'trap door' depositional semi-basins above, when reactivated) with the dyke swarms and major volcanics that together sliced up the newly deposited Carboniferous during this late-Stephanian–Autunian time of emergence and erosion.

Evidence of the amount of locally elliptical uplift and extension, from the mine plans within the worked coal-bearing basins, suggests that the pattern of uplift followed the same pattern as the subsidence. During subsidence, the relief of the broad elongate elliptical basins, swells and near neutral zones (both of them containing their subordinate basins and humps) flooring the depositional basin of the Upper Carboniferous (as a whole) has been suggested wherever cross sections can be made, but not fully mapped. A similar, but subaerial, pattern may have emerged, had the palaeogeographer been present to map the surface of the crust in this period of hierarchically scaled differential N European *uplift* – as opposed to the same overall pattern of N European *subsidence*.

Additional evidence on the nature of block control of uplift around the North Sea basin available within detailed coalfield mining records

The worked coalfields of northern Europe contain multiple overlapping detailed mine plans on which are to be seen both (*a*) very nearly all the 'lines of disturbance' and, because the samples are so complete, (*b*) the statistics of very nearly all of the undisturbed areas between these lines. Within these 'undisturbed' areas, many of these plans show, at least sample, and often detailed, levelling by the mine surveyors on each of these overlapping plans of the worked areas of the coal seams.

Thus there is a unique, nearly complete, sample of both the amount and the inferred shape of crustal extension produced on the major 'swells'. The two directions in which the aggregate fault 'want' per unit horizontal length of coalfield are at a maximum and a minimum, together with the total amount of this horizontal tensional strain in these two directions, are both obtainable from the statistical distributions of fault orientation, strike length, hade, throw and intensity. These are obtainable from analysis of the normal faulting shown on the mine plans in each coalfield.

In the NE Coalfield of Britain, the increase in surface area, shown by the normal faulting, is about $\frac{1}{2}\%$, and 'This is near the order that might be expected of an elliptical regional uplift or doming of the crust in N. England to remove (or not deposit) 4/5,000 ft. [*ca.* 1.2–1.5 km] of Mesozoic and 5,000 ft. of Paleozoic rocks' (Clarke 1962, p. 212).

From the statistical distributions of strike lengths and throws given in the relevant part of the NE Coalfield, the elliptical uplift would have been locally more nearly circular on the constituent Alston block, with its longer axis east–west. Over the uplifted area occupying the southeastern part of the Northumberland Trough, it would have been less 'nearly circular', but still with a direction of principal horizontal tensional strain east–west. In other words, the same 'blocks' as gave slight differences in vector amount of subsidence also acted to give slight differences in vector amount of uplift.

Over the now emergent sub-block on the northeast quadrant of what was earlier the Pennine basin, from the normal fault pattern shown in the Yorkshire Coalfield uplift would have been more strongly elliptical, with its long axis northeast–southwest. As the (exceptional) Upper Palaeozoic 'foundation triangle' is approached, semi-conical uplift gives an internally radially fractured 'arrowhead' shape, with its north–south centre line on the mega-line of disturbance now seen as the Pennine fault – Namurian depositional monocline/Malvern Hills lineament (see Wills 1956, fig. 3, p. 96).

A triangular 'trap door' uplift is inferred to have operated in the Bristol coalfield to produce the areas of only just subvertical coal seams, once 'stope' mined, in this area. The hypoteneuse of this particular triangle is part of the fan of lineaments between the inferred mega-line of disturbance, at the southeastern edge of the Welsh Massif, curving down and southwestwards, to join the westward margins of the ((?)shallower) Variscan 'mega-line', the two continuing together as the well known Variscan–(?)Cadomian line across southern Ireland.

With regard to differential movement of the smallest constituent foundation blocks (at the highest in level in the crust, but lowest in the hierarchy of size) beneath coalfields, casual studies have been made of the fault statistics recorded in the mine plans in the areas (*a*) over, and (*b*) surrounding a few of these 'micro'-blocks. The elongate, but only a few kilometres long, Harton (tectonic) Dome in the Durham Coalfield and the Ashby anticline in the S Derbyshire and Leicestershire Coalfield, both clearly show smaller crustal extension over these small 'humps' than in the annular ring-like area around them. This is interpreted as implying regional uplift followed by a slight additional tensional strain due to subsequent, very local, slight drawing down of (1) a ring-like area around the dome, and (2) along the two synclinal lines flanking the anticline. In other words, no 'plie-de-couverture' or 'compressional folding', either after or before (or both) a period of 'tensional faulting', is involved. All that need be involved is slight differential vertical movement in a hierarchy of small upper crustal blocks.

'Mine plan' studies of the east–west trending *en échelon* systems of the faulted monoclines that partition the Alston and Askrigg blocks in the northern Pennine hills have shown that the here abnormal want due to the here abnormal (45°) hade of the fault member of this type of disturbance is exactly compensated for by the crustal shortening produced by the associated folding (Clarke 1962, p. 213). Morphologically, but here at a gigantic increase in scale, these mirror the 'rotational slips' observed, and quantitatively analysed, by the civil engineering soil-mechanist.

Similar but more detailed studies have been made of the tectonics of the Ruhr coalfields. Mine plan studies of the southern Belgian – northern French coalfield, being so greatly 'thrust and napped', are likely to defy all but the most persistent analyst.

The northern European coalfield mine plans show the integrated effects of both the Variscan, Laramide and the Alpine periods of emergence or less widespread subsidence. However, the intensity of drilling and shaft sinking within the coalfields is usually sufficient to identify the differential or incremental amount of crustal extension that is attributable to the major reactivation of swells and their associated tensional fault patterns during succeeding late-Mesozoic–Tertiary tectonic hiatus. Thus to enable this later movement to be subtracted from the integrated post-Variscan position sampled in all NW European mine plans, e.g. as shown in the NE Coalfield of Britain by Clarke (1963, pl. 2, p. 308). The correlations between pre- and post-Permian, etc., movements established in the coalfields may be carried between coalfields when the areas sampled by deep reflexion seismic surveys by the oil industry become similarly available.

It is by these means that the amount of uplift around the margins of the Mesozoic depositional and tectonic basin in the North Sea may now be given some additional quantification.

CONCLUSIONS

1. With the recent input of data into the public domain from the oil and coal industries and on the basis of a study of the origin, nature and setting of the Carboniferous basins of the northern European subcontinent, it is hypothesized that they may be the products of a nesting hierarchical subcontinentally fixed mechanism of crustal change. The evidence that has been assembled is primarily that of an observed succession of morphologies, and does not rest on the morphologies giving rise to measured or measurable properties generated through processes that lie essentially within the physics or applied mathematics of change in the upper crust.

2. The *geological* evidence available on the middle-sized depositional basins within the Carboniferous 'basin' of northern Europe is most easily observed north of the Variscides. The data available on the basins and their intervening less rapidly subsiding swells and neutral zones show that (*a*) they were generally of elliptical or semi-elliptical shape and lie in a nesting hierarchy of sizes whose location is conditioned by the underlying tectonic framework; (*b*) the bottom of the middle sizes of basin subsided at a diminishing rate and the bottom of most of the intervening swells and planar zones subsided at a more steady rate; (*c*) except in the neutral blocks, this pattern of movement of the same nesting hierarchy of elliptical, etc., basins and swells was inverted.

3. The *mining* evidence in the coal-bearing basins of northern Europe shows that (*a*) on propagation, the graben formations induced at depth by mining, each give rise to a *wider* overlying zone of block tilting (involving initial rotation and counter-rotation on a horizontal axis, within a wavelike set of translational movements in the vertical plane, as the axial length of the propagating graben grows. (*b*) Concurrently, this overlying zone, in turn, gave rise to a still *wider* overlying subsiding basin in the less self-confined strata at the surface level. Each side of the generally symmetrical basin has, at the near surface, a concentric pair of zones. The outer zone is one of intrinsically horizontally extensional and the inner zone of intrinsically horizontally compressional movement.

The dynamically changing *morphology* of the both horizontally and vertically propagating system retains almost fixed width: depth ratios. These width: depth ratios, except where the subsiding layer is very thin compared with depth, are almost independent of depth. The mining industry quantifications of the evidence are entirely from observation and quantification of the morphology of graben and predicted subsidence basin formation and *not* from the physics of the system.

4. On the evidence of relative rates of initial infilling during the Upper Carboniferous and provenance of the sediments (more than basin morphology) it is necessary to distinguish between the Carboniferous basins lying along the line of the Variscan Front (Flysch) in the supposed area of active plate collision, and those elsewhere. It would appear, from the pattern within the morphology of the 'elsewhere' type of Carboniferous basins, that a mechanism for propagation of vertical movement existed in the crust of continental Europe that is comparable to that seen in coal-mining in the basins. On the hypothesis given in this paper, an original line of active plate collision left both a suture line and a set of parallel lines of lesser disturbance in the crust. Later collisions left both suture lines at different angles to the original line, and parallel lines of lesser disturbance higher in the crust. On such a mechanism, with further collisions, the more primary lines would either be preserved (but stiffened beyond movement in the 'old shield' areas) or be absorbed in the mantle during 'plate tilting'. Thus in the Carboniferous, the northern European crust, collision and orogenesis at the Variscan front reactivated movements on one of the sets of parallel-oriented, more deeply imposed, earlier lines of disturbance. This initiated rectilineal and triangular block movements propagating upwards towards the surface (but downwards in hierarchical size sense). Propagation was upward through a successively more dense array of earlier imposed, successively more criss-crossing hierarchy of blocks, whose relations to one another are fixed within the subcontinental crust. These control the fixed configuration of the overlying contemporary basin and swell movements. The results of these movements are seen on the reconstructed surface of the Carboniferous in areas away from the Variscan orogeny. The final movement was a 'whole

plate tilt'. Subsequent block movements were often in the opposite sense to basin or swell forming movement.

5. Because of the stationary scalar nesting hierarchical nature of the single mechanism that, in this hypothesis, is involved, for analytical purposes it has been necessary to devise a terminology independent of horizontal and vertical scale, i.e. to employ the term 'line of disturbance' within (at a comparable level of disturbance, and hence (because of convergence) comparable level in the crust) 'undisturbed' surrounding surfaces. In this terminology, to make the frame of the undisturbed surface the same at each level in the crust, the area covered by the frame containing any given number of lines of disturbance becomes smaller and smaller at higher and higher levels within the lithosphere.

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Discussion

A. W. BALLY. What is the resolution of the seismic lines that Mr Clarke has shot across the coalfields? Do they show details of the sedimentary structures within the coal measures?

A. M. CLARKE. We use interface waves trapped on the boundaries of the coal seams themselves if we need a vertical resolution of 1 m or less. When we are working on the surface we are only interested in the structure in the first $\frac{1}{2}$ s of recording time and use a geophone spacing of a few tens of metres. This spacing, combined with accurate static corrections, gives us a vertical resolution of between 5 and 10 m. The smallest fault displacements we map as diffractions.

We have done some work on modelling facies variations statistically. The seismic reflexions from these variations show good lateral continuity and we can follow features like shoestring sands, and distinguish them from sheet sands. Various papers describing such records have been published (Buchanan *et al.* 1981; Gebala & Nowak 1980; Jackson 1981; Ziolkowski 1981).

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