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Late Devonian and Dinantian basin evolution in northern England and North Wales

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SUMMARY: This paper reviews the evidence for, and the effects of, syn-sedimentary tectonic activity in the exposed late Devonian and Dinantian sedimentary basins of northern England and North Wales. Because of later periods of fault reactivation and inversion, analysis of structural data yields only limited information regarding Dinantian tectonic activity. Stratigraphical data must also be utilised to constrain Dinantian basin evolution. The main criteria used are: thickness variations, local or regional unconformities, facies type and geometry, and the recognition of event deposits triggered by allocyclic mechanisms. Compilation of these data from a number of basins and highs provides evidence for episodes of extensional or transtensional tectonism. This evidence is supported by the occurrence of synchronous igneous activity and syn-sedimentary to eogenetic base metal mineralisation. Basin initiation in the late Devonian to Tournaisian was followed by further widespread extensional reactivation in the late Chadian/early Arundian and in the Asbian. A further episode of reactivation involving local inversion occurred during the Brigantian. Sedimentation during these tectonic phases was generally characterised by structurally funnelled input of siliciclastic sediment and the reduction or cessation of carbonate sedimentation. In contrast, during intervening periods of relative quiescence, when isostatic, thermal or compaction-driven subsidence was dominant, progradation of carbonate shelves and ramps occurred. Basin style is characterised by asymmetric grabens and half-grabens which contain intra-basin synthetic and antithetic faults linked by transfer zones. Three structural domains have been recognised: (i) the west of England and Wales, characterised by NE-SW-trending faults, (ii) the east of England characterised by NW-SE-trending faults, and (iii) the north of England characterised by E-W to ENE-WSW-trending faults with granitic intrusions located in major footwall highs. This regional structural style is related to the arcuate trend of Caledonian basement structures around the Midlands Massif that were reactivated during late Devonian and Dinantian times by approximately N-S orientated extension.

The recognition that Dinantian tilt-blocks (Miller & Grayson 1982; Grayson & Oldham 1987) and half-grabens (Leeder 1974; Gawthorpe 1987) of northern Britain were formed as extensional or transtensional features during a phase of lithospheric stretching (Bott 1976, 1987; Dewey 1982; Leeder 1982, 1987a) has been a major development in our structural understanding of the region. This has allowed the application of theoretical models of fault behaviour, geometry and relative subsidence (e.g. Gibbs 1984, 1987; Barr 1987; Jackson & McKenzie 1983) to the relationships between active faulting and sedimentation (Gawthorpe 1986, 1987; Leeder 1987b; Gutteridge 1987, this volume). Additional impetus has been derived from parallel studies of extensional tectono-sedimentary interactions in neotectonic areas (Leeder & Gawthorpe 1987).

The idea that tectonic processes influenced late Devonian and Dinantian sedimentation is not new, as several episodes of intra-Dinantian folding and associated 'event' deposits were identified by Hudson (1930, 1936), Hudson & Mitchell (1937) and Hudson & Turner (1933) from the Craven and Derbyshire areas. In the 1960s the integration of geophysical and stratigraphical studies (e.g. Bott 1967; Bott & Johnson 1967; Johnson 1967) added strong support to the idea of structural control on late Devonian and Dinantian sedimentation in northern England. The importance of eustatic influences on sedimentation continues to be debated (e.g. Ramsbottom 1973, 1981; George 1978; Walkden 1987; Horbury, this volume) and have been significant, especially during tectonically quiescent periods.

It is now timely to assess the evidence for syn-sedimentary tectonic activity in late Devonian and Dinantian sedimentation on a regional scale, integrating the results presented by earlier workers for specific areas with recent biostratigraphical, sedimentological and structural data. This paper aims to:

1. evaluate the late Devonian and Dinantian evolution of northern England and North Wales in an attempt to recognise episodes of tectonic activity;
2. identify structures which were active during sedimentation, particularly those which controlled large-scale basin morphology;
3. indicate which factors were important in controlling the spatial and temporal development of these basins.

1. METHODOLOGY

The late Devonian and Dinantian basins of northern Britain (Fig. 1) cannot be studied solely as extensional or

transtentional features, since many basins have suffered the effects of late Carboniferous inversion (Gawthorpe 1987; Ord *et al.* 1988; Lee 1988). This deformation led to reactivation of some formerly active extensional structures as thrusts or strike-slip faults. Further complications arose during Permo-Triassic and Jurassic times when renewed extension caused further reactivation of basement structures. Thus, in order to reconstruct the late Devonian and Dinantian history of the basins it is necessary to search the record of the basin fills for the tell-tale signs of active fault control on sedimentation (e.g. Alexander & Leeder 1987; Gawthorpe 1987; Leeder 1987b; Leeder & Gawthorpe 1987).

Crucial to the application of this approach is the ability to correlate the various stratigraphical indicators of active tectonism on an intra- and inter-basin scale. The chronostratigraphical framework used in this analysis is based upon the various Dinantian stages outlined by George *et al.* (1976), as modified by more recent workers (e.g. Ramsbottom & Mitchell 1980). However, major problems exist with current biostratigraphical correlations owing to facies control of faunas. This has led to the development of a number of biozonation schemes, based on different fossil groups, which have varying degrees of precision and whose correlation is not always certain. Consequently there are very few reliable 'time-lines' for correlation purposes. This problem is most apparent when correlating between marine-dominated basins and those with predominantly fluvio-deltaic facies. The Dinantian radiometric time-scale is also very poorly defined at present (see Leeder & McMahon 1988) and thus estimates of rates of sedimentation and subsidence and the duration of tectonic events are not well constrained. Despite these problems sufficient data is available to allow broad correlations within individual basins and to establish the timing of inferred tectonic events on a regional scale.

In reconstructing the development of the Dinantian basins we have used four main lines of evidence, thickness variations, unconformities, facies variations and event deposits.

1.1. Thickness variations

The development of a half-graben is accompanied by the accumulation of a prism of sediment which thickens towards the active, fault-bounded margin of the basin. As the basin develops, sediment layers onlap the hanging wall slope of the half-graben. This is seen in seismic reflection profiles across Mesozoic and Cenozoic basins (e.g. Badley *et al.* 1984) and has been demonstrated for the Stainmore/Askrigg half-graben by Burgess & Mitchell (1976) and Wilson & Cornwell (1982). The occurrence of intra-basinal antithetic, synthetic and transfer faults complicates this simple pattern due to the generation of sub-basins on a variety of scales. Examples of sub-basins have been described from Northumberland (Day 1970; Frost & Holliday 1978; Leeder 1987b; Leeder *et al.* this volume) and Bowland (Gawthorpe 1987; Lee & Gawthorpe in prep.).

1.2. Unconformities

Local unconformities within half-grabens and asymmetric grabens may develop in both the footwall and hanging wall to major bounding faults and provide significant information regarding the timing of the tectonic activity and the geometry of structures. Uplift and tilting of the footwall may result from isostatic compensation during fault motion on relatively planar, crustal-scale faults. The uplift affects a zone several kilometres into the footwall and has been calculated to be a maximum of 10% of the throw on a fault dipping at 45° (Jackson & McKenzie 1983). Thus, in the stratigraphical record, condensed sequences and/or repeated unconformities may be expected. The intra-Pendleian (Namurian) unconformity beneath the Grassington Grit along the southern margin of the Askrigg Block is an example of this type of unconformity (see data of Dunham & Wilson 1985, fig. 13).

Within hanging wall sedimentary sequences several types of unconformity may be present. Tilting of the pre-rift sequence creates an unconformity across the basin, with progressive onlap of younger, syn-rift sediments away from the boundary fault. Dating of the oldest sediments onlapping this surface can constrain the timing of basin initiation, while its morphology can help constrain fault geometry. This base syn-rift unconformity is clearly displayed by a section across the Stainmore Basin (Wilson & Cornwell 1982; see our Fig. 3). Additional unconformities may be developed within the syn-rift sequence. Rotation associated with syn- and antithetic faults may create local unconformities in their footwalls which can provide evidence for the location and timing of movement on intra-basin structures. Examples of this type of hanging wall unconformity are present in the Bowland Basin (Arthurton 1984; Gawthorpe 1987). In contrast to these local unconformities, basin-wide unconformities within hanging wall sequences may also be present. These unconformities can provide constraints on the episodic

Fig. 1. Dinantian palaeogeography of northern England and North Wales showing inferred positions of structural highs, basins and land areas. Based on Leeder (1982), Gawthorpe (1987), Gutteridge (this volume), Strank (1987) and Somerville & Strank (unpublished). Lines show location of chronostratigraphic sections (Figs. 2 to 8). LFB = Lancaster Fells Basin, BH = Bowland High, HH = Holme High, EB = Edale Basin, DH = Derbyshire High, EMH = East Midlands High, WB = Widmerpool Basin, NSB = North Staffordshire Basin. Boreholes: H = Harton, SS = Seal Sands, R = Raydale, BS = Beckermonds Scar, Sw = Swinden, B = Boulsworth, HC = Holme Chapel, F = Fletcherbank, A = Alport, Ed = Edale, Ey = Eyam, W = Woodale, GH = Gun Hill, CL = Caldon Low, D = Duffield.

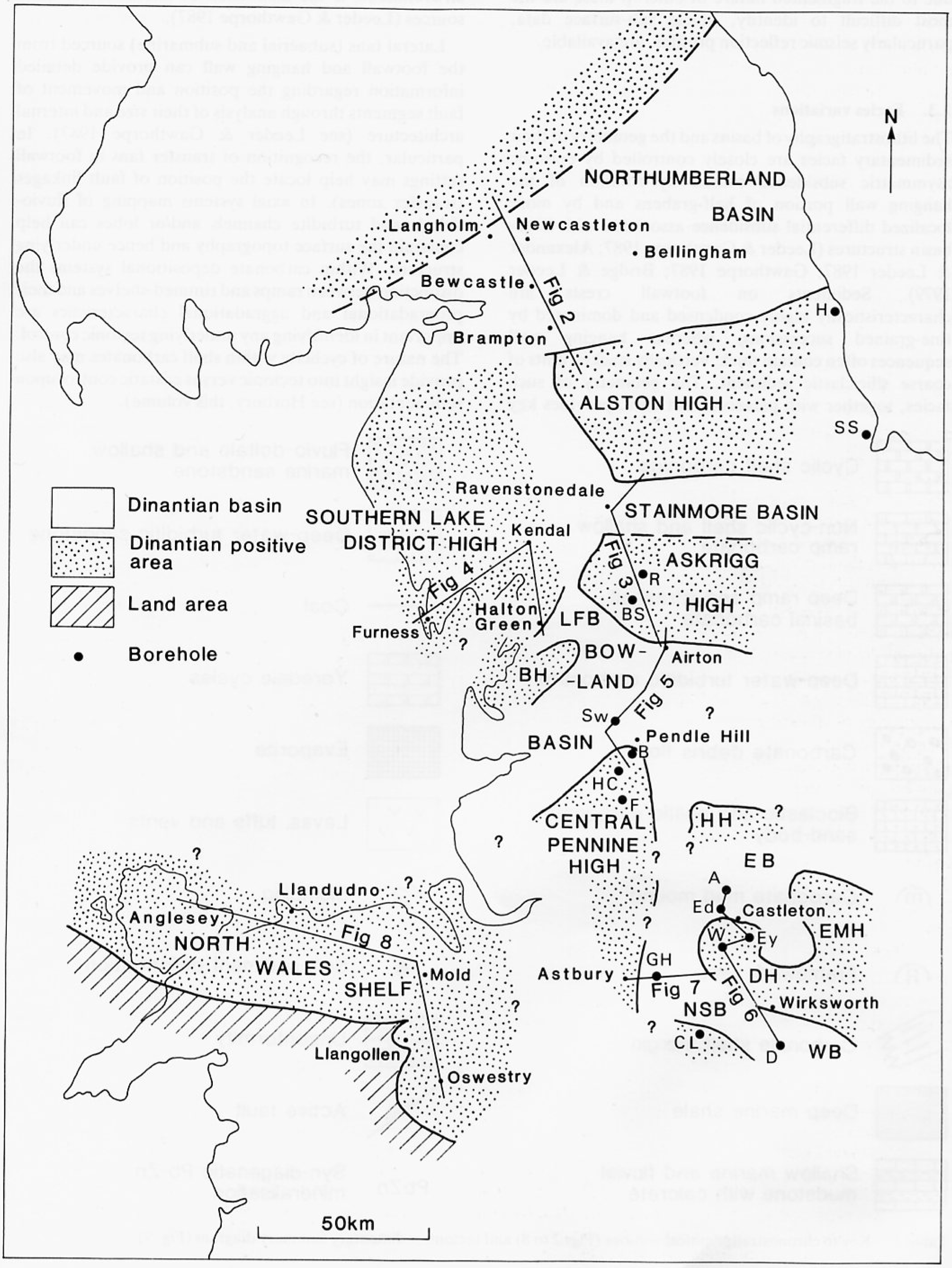
N
NORTHUMBERLAND
BASIN
Langholm
Newcastleton
Bellingham
Bewcastle
Fig 2
Brampton
H
ALSTON HIGH
SS
Ravenstonedale
STAINMORE BASIN
SOUTHERN LAKE
DISTRICT HIGH
Kendal
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Fig 3
ASKRIGG
HIGH
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BS
Halton
Green
LFB
Furness
BOW-
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Airton
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Astbury
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NSB
Wirksworth
CL
D
WB
Llangollen
Oswestry
Dinantian basin
Dinantian positive area
Land area
Borehole
50km

nature of rifting and help distinguish between active and relatively quiescent phases in basin evolution. However, due to the fragmented nature of outcrop these are the most difficult to identify, unless sub-surface data, particularly seismic reflection profiles, are available.

1.3. Facies variations

The lithostratigraphy of basins and the geometry of their sedimentary facies are closely controlled by episodic asymmetric subsidence caused by rotation of the hanging wall portion of half-grabens and by more localized differential subsidence associated with intra-basin structures (Leeder & Gawthorpe 1987; Alexander & Leeder 1987; Gawthorpe 1987; Bridge & Leeder 1979). Sediments on footwall crests are characteristically highly condensed and dominated by fine-grained successions, whereas hanging wall sequences often contain thick, vertically stacked units of coarse siliciclastic sediment. The geometry of such facies, together with palaeocurrent data, provides key evidence for tectono-sedimentary interactions and basin morphology. Of particular importance in siliciclastic environments is the distinction of lateral versus axial sources (Leeder & Gawthorpe 1987).

Lateral fans (subaerial and submarine) sourced from the footwall and hanging wall can provide detailed information regarding the position and movement of fault segments through analysis of their size and internal architecture (see Leeder & Gawthorpe 1987). In particular, the recognition of transfer fans in footwall settings may help locate the position of fault linkages (transfer zones). In axial systems mapping of fluvio-deltaic and turbidite channels and/or lobes can help constrain the surface topography and hence underlying structure. Within carbonate depositional systems the distinction between ramps and rimmed-shelves and their progradational and aggradational characteristics are important in identifying any underlying tectonic control. The nature of cyclicity within shelf carbonates may also provide insight into tectonic versus eustatic control upon sedimentation (see Horbury, this volume).

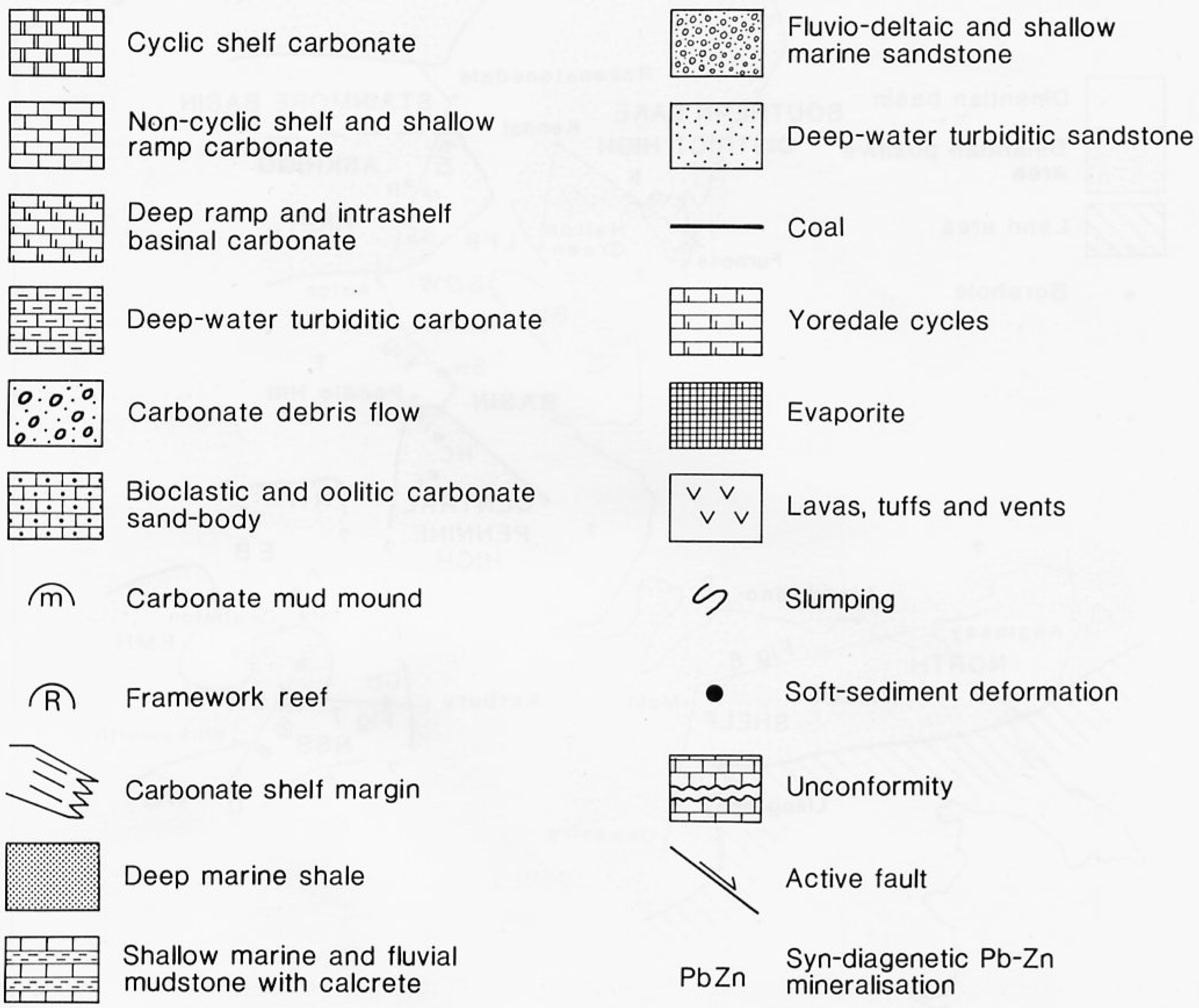


Table 1. Key to chronostratigraphical sections (Figs 2 to 8) and tectono-sedimentary summary diagram (Fig. 9).

1.4. Event deposits

Activity along normal faults induces the production of a variety of features in the sedimentary fill due to the release of seismic energy and associated instantaneous changes in slope. Such features include slump folds, debris flows, megaturbidites and liquefaction structures. Widespread occurrence of such features at particular stratigraphical intervals may be used to deduce the timing of fault activity (e.g. Gawthorpe & Clemmey 1985). The spatial distribution of seismic-related features may in turn be used to identify the active structures themselves (e.g. Leeder 1987b). The widespread occurrence of event deposits, or the identification of a distribution related to observed structures, is important in identifying allokinetic deposits.

1.5. Discussion

It should be emphasised that, taken in isolation, none of the above criteria are necessarily indicative of active tectonism. For example, thickness and facies variations may be a function of differential compaction over antecedent basement topography (Collier, this volume), and unconformities may result from eustatic regression rather than active fault-controlled differential subsidence. However, when the criteria are combined, they provide strong evidence for periods of active faulting.

2. EVOLUTION OF INDIVIDUAL AREAS

Using the criteria outlined above, this section summarises the sedimentary evolution of the exposed

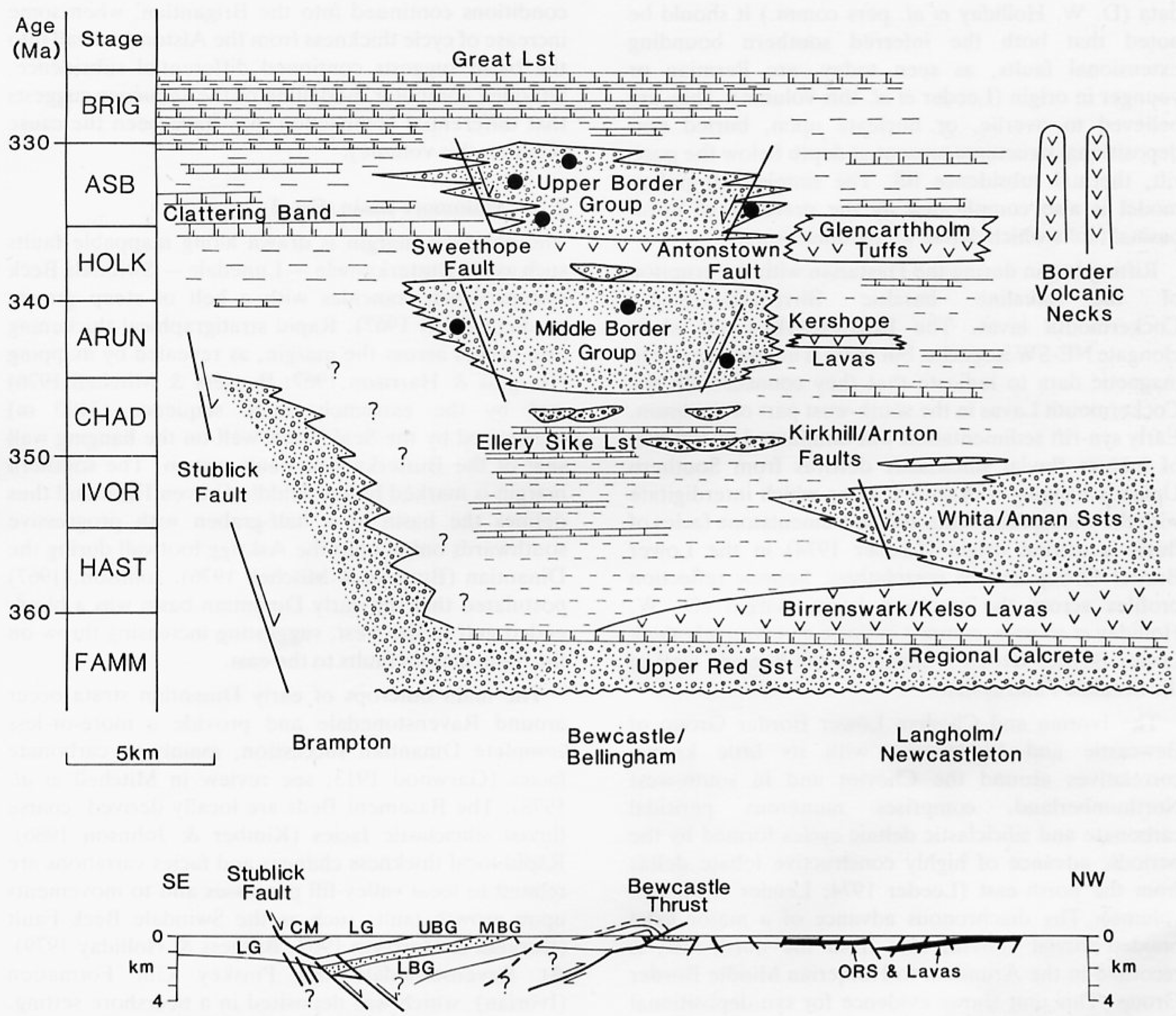


Fig. 2. Chronostratigraphical and structural section across the Northumberland Basin. Structural section from Leeder *et al.* (this volume). Location of section shown in Fig. 1. Details of geochronometric scale used in Figs 2 to 8 is given in Leeder & McMahon (1988). Key to chronostratigraphical sections is given in Table 1. ORS = Old Red Sandstone, LBG, MBG, UBG = Lower, Middle and Upper Border Groups respectively, LG = Limestone Group, CM = Coal Measures.

late Devonian and Dinantian basins and highs of northern England and North Wales (Fig. 1). The areas are described with the aid of summary chronostratigraphical diagrams, cross-sections and isopach maps (Figs 2 to 8).

2.1. Northumberland Basin (Fig. 2)

The basin has a half-graben form and lies between the Southern Uplands and Alston footwall 'highs', with the major boundary fault defined by the Stublick Fault (Trotter & Hollingworth 1932; Johnson 1960; D. W. Holliday *et al.* pers. comm. 1987). It is not known whether the Ninety Fathom structure was also active; the evidence from the Harton borehole (Ridd *et al.* 1970) to the south of the fault suggests that northwards thickening is gradational over several kilometres, possibly due to a step-faulted basin margin. Although the simple view that the basin is a half-graben (Leeder 1974, 1982), has been confirmed by seismic reflection data (D. W. Holliday *et al.* pers comm.) it should be noted that both the inferred southern bounding extensional faults, as seen today, are Permian or younger in origin (Leeder *et al.* this volume). They are believed to overlie, or nucleate upon, buried syn-depositional structures present at depth below the post-rift, thermal subsidence fill. The simple half-graben model is also complicated by the presence of intra-basinal faults which define topographic lows.

Rifting began during the Hastarian with the eruption of the alkaline basaltic Birrenswark/Kelso/Cockermouth lavas. The Birrenswark Lavas show elongate NE-SW isopachs, but there is no evidence from magnetic data to indicate that they connect with the Cockermouth Lavas in the south-west part of the basin. Early syn-rift sedimentation was dominated by influxes of mature fluvial siliciclastic detritus from Southern Uplands hanging wall source areas which interdigitate with the widespread schizohaline Cementstone facies of fluvio-lacustrine origin (Leeder 1974) in the Lower Border Group and its correlatives. Seismic reflection profiles across the southern basin margin (D. W. Holliday *et al.* pers. comm.) indicate an extremely thick Lower Border Group sequence in the hanging wall of the Stublick Fault system.

The Ivorian and Chadian Lower Border Group of Bewcastle and Liddesdale, with its little known correlatives around the Cheviot and in south-west Northumberland, comprises numerous peritidal carbonate and siliciclastic deltaic cycles formed by the periodic advance of highly constructive lobate deltas from the north-east (Leeder 1974; Leeder *et al.* this volume). The diachronous advance of a major axial braided fluvial system, also from the north-east, is recorded in the Arundian to Holkerian Middle Border Group. This unit shows evidence for syn-depositional tectonic controls upon alluvial architecture in the central intra-basin lows defined by the Antonstown and Beckhead/Binky Linns faults (Day 1970; Leeder 1987b). The resulting multistorey sandbody (Hodgson 1978) splits and intercalates with marine facies to the south-west (Day 1970), although a suspected correlative to the south-west, the Thirlstane Sandstone, retains its fluvial signature in the Solway Basin (Ord *et al.* 1988).

The Asbian Upper Border Group is composed of Yoredale-type cycles in south-western areas (Lumsden *et al.* 1967), but in the central intra-basin lows around Bewcastle and Bellingham (Day 1970; Frost & Holliday 1980) an abnormal thickness (*c.* 2000 m) of dominantly siliciclastic deltaic facies is found, again deposited as axial drainage systems derived from the north-east (Leeder 1987b, Leeder *et al.* this volume). In Berwickshire and north-east Northumberland the equivalent Scremerston Coal Group is very much thinner and largely composed of delta-top or fluviatile facies with many thick coals.

During the late Asbian, deltaic cycles of Yoredale type were deposited over the whole basin. These conditions continued into the Brigantian, when some increase of cycle thickness from the Alston footwall into the basin suggests continued differential subsidence, although computer modelling of the sequence suggests that differential compaction may have been the cause (Collier, this volume).

2.2. Stainmore Basin (Fig. 3)

The northern margin is drawn along mappable faults such as the Butterknowle — Lunedale — Swindale Beck system which coincides with a belt of steep gravity gradient (Bott 1967). Rapid stratigraphical thickening also occurs across the margin, as revealed by mapping (Burgess & Harrison 1967; Burgess & Mitchell 1976) and by the extremely thick sequence (3100 m) penetrated by the Seal Sands well on the hanging wall side of the Butterknowle Fault system. The southern margin is marked by the Middle Craven Fault and thus defines the basin as a half-graben with progressive southwards onlap onto the Askrigg footwall during the Dinantian (Burgess & Mitchell 1976). Johnson (1967) postulated that the early Dinantian basin was a blind-ended gulf to the west, suggesting increasing throw on the basin margin faults to the east.

The main outcrops of early Dinantian strata occur around Ravenstonedale and provide a more-or-less complete Dinantian succession, mainly in carbonate facies (Garwood 1913; see review in Mitchell *et al.* 1978). The Basement Beds are locally derived, coarse fluvial siliciclastic facies (Kimber & Johnson 1986). Rapid local thickness changes and facies variations are related to local valley-fill processes and to movements upon growth faults such as the Swindale Beck Fault (Burgess & Harrison 1967; Burgess & Holliday 1979). At Ravenstonedale the Pinskey Gill Formation (Ivorian), which was deposited in a nearshore setting, rests directly upon the Lower Palaeozoic basement and is overlain by coarse siliciclastics of alluvial fan aspect. The Stone Gill Beds of the Ravenstonedale Group contain carbonates and thin siliciclastic mudrocks of

peritidal 'gulf' aspect (Barraclough 1983).

Towards the top of the Ravenstonedale Group and in the early Arundian Scandal Beck Limestone of the Orton Group, carbonates of open marine origin occur. Peritidal grainstones are more common in the thinned sequences of the Shap area, towards the presumed northern shoreline of the gulf. The Ashfell Sandstone represents a fluvio-deltaic incursion which probably originated in the Northumberland Basin (Fell Sandstone) and prograded southwards and southwestwards down the Eden/Shap 'low'. Abandonment of this delta during the Holkerian was followed by a marine transgression which deposited a sheet of bioclastic grainstones and led to the development of a carbonate platform. These facies are also characteristic of the Asbian Alston Group. The combined effects of marine transgression and regional subsidence destroyed the former Stainmore gulf as a geomorphic feature.

The Raydale and Beckermonds Scar boreholes to the south (Wilson & Cornwell 1982), reveal a progressive southwards onlap of Ivorian to Asbian carbonate ramp or shelf facies against the footwall high caused by extension across the Middle Craven Fault system. By Brigantian times Yoredale-type deltaic/marine cyclicity was dominant in central and northern areas of the basin, with carbonate sedimentation only on the footwall crest. Cyclicity in the carbonates may be caused by eustacy (Walkden 1987; Horbury, this volume) and/or repeated footwall uplifts of the active North and Middle Craven fault system.

2.3. Southern Lake District High (Fig. 4)

The north and south boundaries of the Southern Lake District High (Grayson & Oldham 1987) are poorly defined because of either erosion, or cover by Permo-Triassic sediments. To the east the high passes abruptly into the Lancaster Fells Basin (Gawthorpe 1987; Lee & Gawthorpe, in prep.) along a line approximately coincident with the Lune Valley, whilst to the west it is probably bounded by the Haverigg Fault (Horbury 1987).

Sedimentation commenced during the Tournaisian with deposition of fluvial conglomerates and sandstones filling topographic lows on the eroded basement (Rose & Dunham 1977). The basement topography continued to influence sedimentation during the Chadian and early Arundian producing facies and thickness variations in these sediments. The basement was finally transgressed during the early Arundian. The Chadian is characterised by tidal flat, beach and lagoonal sediments (Martin Limestone) which pass upwards into subtidal packstones and grainstone shoals (the Arundian Red Hill Oolite) with local framework reefs (Vaughan & Adams 1984; Adams 1984). During the Arundian and Holkerian a carbonate shelf was developed over the whole area (Dalton Beds and Park Limestone). The first indication of differential subsidence occurs in the Arundian in the Furness area where the Dalton Beds increase in thickness from *c.* 120 m to 250 m over a distance of a few kilometres (Mitchell *et al.* 1978).

A major fall in sea level in latest Holkerian to early Asbian, which is thought to be partly tectonic in origin, created a widespread unconformity on the shelf with a relief of at least 20 m (Horbury, this volume). The overlying Asbian Urswick Limestone is composed of 10-20 m thick grainstone-dominated shoaling-up cycles. These major cycles are interpreted to be of tectonic origin and are punctuated by emergent surfaces produced during eustatic sea level falls (Horbury, this

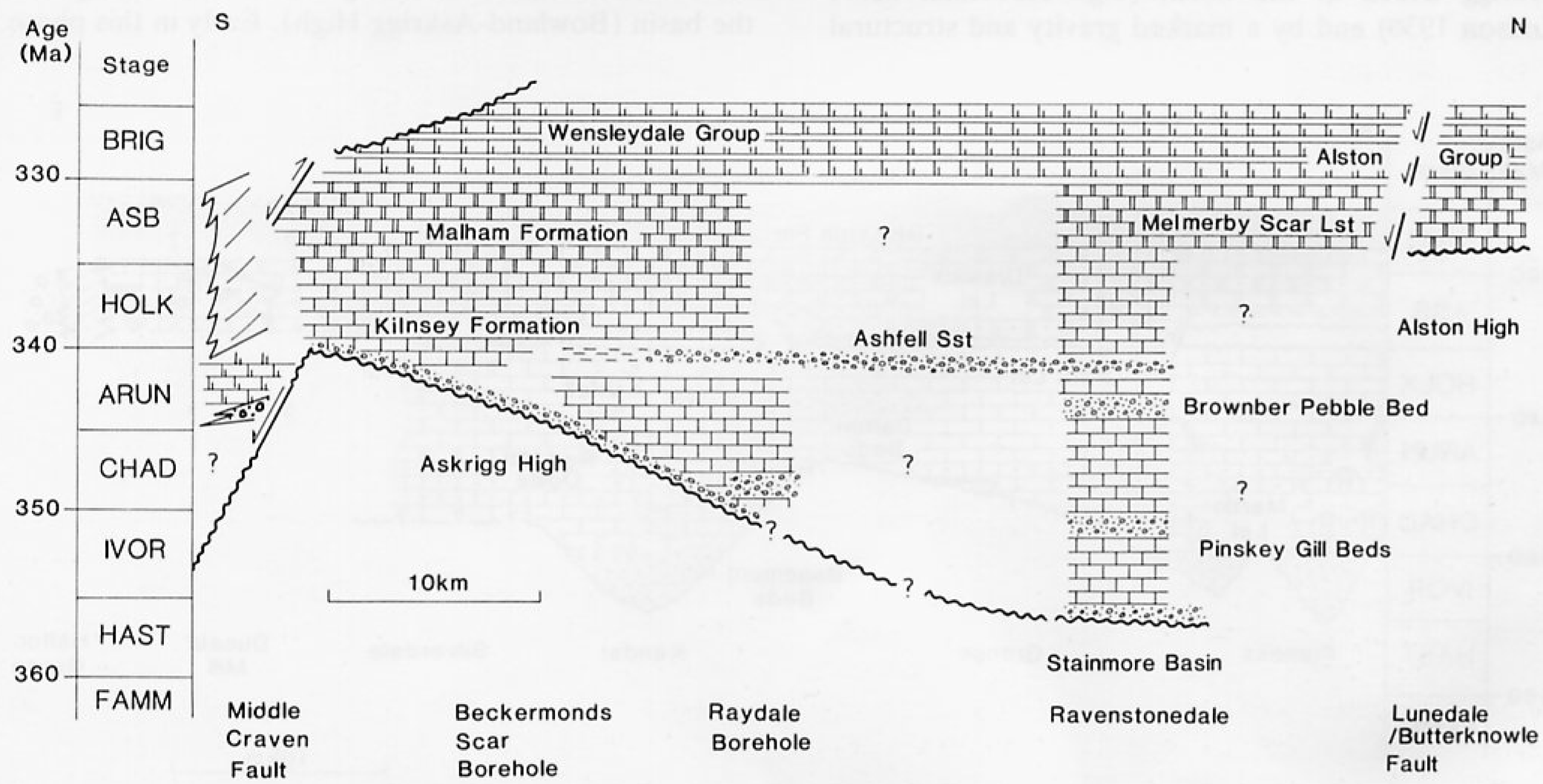


Fig. 3. Chronostratigraphical section across the Stainmore Basin. Location of section is shown in Fig. 1.

volume). Thickness variations in these Asbian cycles suggests that periods of differential subsidence affected the platform. In the east of the area around Dunald Mill, platform margin grainstone shoals are present, while further south-east, at Halton Green, slope deposits consisting of a limestone debris flow and turbidites are exposed. These facies indicate the presence of a major platform margin in the east of the area which, from the geometry of the marginal grainstones, probably accreted vertically with limited easterly-directed progradation. This suggests a footwall location. During the early Brigantian, carbonate production was severely reduced, particularly in the west of the area, by a combination of increased siliciclastic input and subsidence. Carbonates higher in the Brigantian Gleaston Formation are restricted to thin argillaceous limestones interbedded with mudstones and sandstones which show poorly developed cyclicity of distal Yoredale aspect. Facies variations in the Brigantian of the Furness area indicate the presence of a structurally controlled sub-basin (Rose & Dunham 1977).

2.4. Bowland Basin (Fig. 5)

The basin was a half-graben during the Dinantian, as witnessed by major thickness and facies variations. Thus more than 4000 m of Dinantian are indicated by gravity modelling (Lee & Gawthorpe, in prep.), contrasting with 500 m of shallow water carbonates proven by the Holme Chapel Borehole (Ramsbottom 1974; Miller & Grayson 1982) in the central Pennines. These facies and thickness changes indicate a southern fault-bounded basin margin, situated at depth beneath the inversion-related Pendle Monocline (Miller & Grayson 1982; Gawthorpe 1987). The northern margin of the basin is marked by facies and thickness changes onto the Askrigg Block in the north (e.g. Tiddeman 1889; Hudson 1930) and by a marked gravity and structural high (Bowland High) to the north-west of the basin (Gawthorpe 1987).

The basement to the basin has not been penetrated by any well to date, the oldest proven sediments being of Ivorian age. These were penetrated by the Swinden Borehole (Charsley 1984) and consist of sub-wavebase argillaceous wackestones and packstones deposited on a carbonate ramp. This general style of sedimentation continued into the Chadian (Chatburn and Thornton limestones), but with thickness and facies variations suggesting some degree of structural control on sedimentation (Gawthorpe 1987). For example Waulsortian build-ups are commonly associated with the flanks of intra-basin fault-blocks (Miller & Grayson 1982, Lees & Miller 1985).

During the late Chadian / early Arundian there was a marked development of sea floor topography indicated by thickness and facies variations (Gawthorpe 1987). These were associated with the development of local unconformities on the footwall crest of intra-basin faults, expressed now as inversion anticlines (e.g. Clitheroe, Hetton-Eshton and Slaidburn anticlines (Harrison 1982; Arthurton 1984). The succession in the basin (Worston Shales) became dominated by terrigenous mudstone (Gawthorpe 1986) with local developments of siliciclastic turbidites (e.g. Buckbanks Sandstone, Riley 1982), and sedimentary slides (Dunnington 1945; Gawthorpe & Clemmey 1985). In addition Pb-Zn mineralisation, similar in character to Irish-style ore deposits (e.g. Ballinalach, Jones & Bradfer 1981; Navan, Andrews & Ashton 1985) is associated with these events (Gawthorpe 1985).

The succeeding late Arundian to early Asbian sediments show a progressive increase in carbonate sedimentation, resulting from the development of a carbonate-rimmed shelf along the northern margin of the basin (Bowland-Askrigg High). Early in this phase

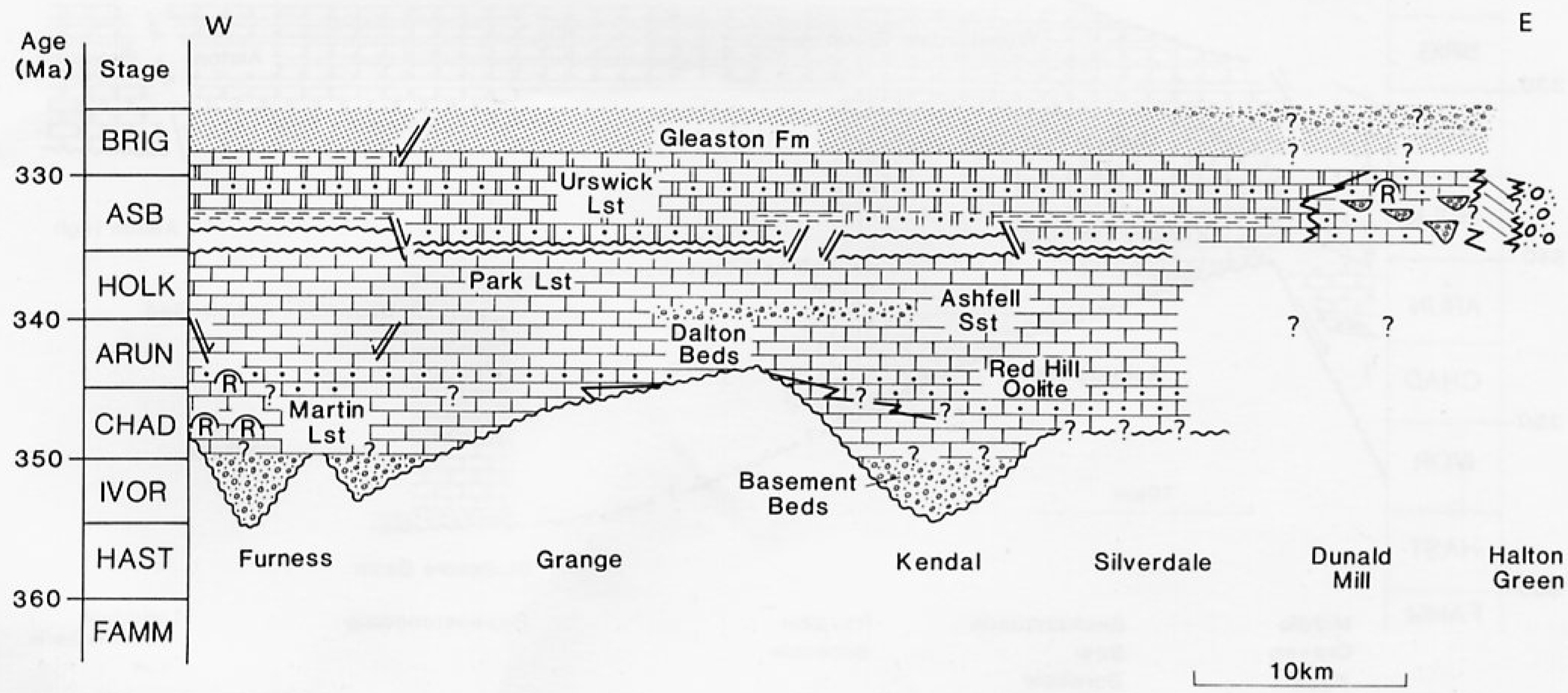


Fig. 4. Chronostratigraphical section across the Southern Lake District High. Location of section is shown in Fig. 1.

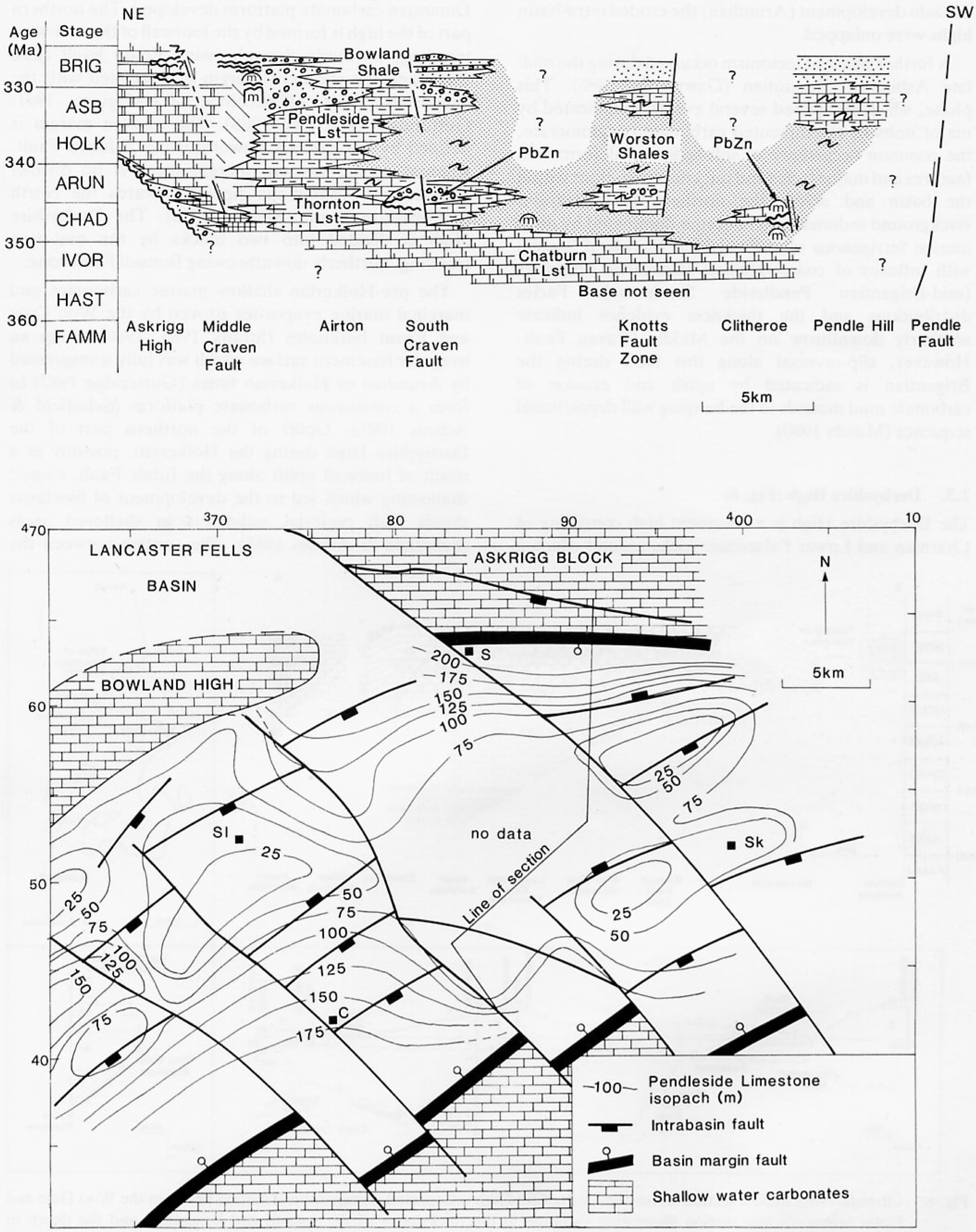


Fig. 5. Chronostratigraphical section across the Bowland Basin and isopach map of Pendleside Limestone (Asbian). Location of section shown in Fig. 1. Compiled from Gawthorpe (1987), Arthurton *et al.* (1988) and Lee & Gawthorpe (in prep). Basement structures are defined by gravity modelling from Lee & Gawthorpe (in prep.). S = Settle, Sk = Skipton, Sl = Slaidburn, C = Clitheroe.

of basin development (Arundian) the eroded intra-basin highs were onlapped.

A further phase of tectonism occurred during the mid/late Asbian to Brigantian (Gawthorpe 1986). This phase, which comprised several events, is indicated by major units of resedimented carbonate conglomerate, the common occurrence of soft-sediment deformation features and major facies and thickness variations within the basin and across the northern basin margin. Background sedimentation became dominated by deep marine terrigenous mud deposition (Bowland Shales) with influxes of coarse-grained siliciclastic turbidites (mid-Brigantian Pendleside Sandstone). Facies distributions and the thickness evidence indicate southerly downthrow on the Middle Craven Fault. However, slip-reversal along this fault during the Brigantian is indicated by uplift and erosion of carbonate mud mounds in the hanging wall depositional sequence (Mundy 1980).

2.5. Derbyshire High (Fig. 6)

The Derbyshire High is a basement high consisting of Charnian and Lower Palaeozoic rocks around which a Dinantian carbonate platform developed. The northern part of the high is formed by the footwall of the east-west trending, northerly downthrowing Edale Fault (Lee 1988) and the southern margin is associated with the Cinderhill Fault (Whitcombe & Maguire 1981; Gutteridge 1987; Lee 1988). The eastern margin is defined by the easterly downthrowing Ashford Fault, whereas at the western margin there is no distinct structure, the basement dipping towards the North Staffordshire Basin (Maroof 1976). The Derbyshire High is divided into two blocks by the east-west trending, northerly downthrowing Bonsall Fault zone.

The pre-Holkerian shallow marine carbonates and marginal marine evaporites proven by the Woo Dale and Eyam boreholes (Strank 1985, 1986) onlap an irregular basement surface which was fully transgressed by Arundian or Holkerian times (Gutteridge 1987) to form a continuous carbonate platform (Schofield & Adams 1985). Uplift of the northern part of the Derbyshire High during the Holkerian, possibly as a result of footwall uplift along the Edale Fault, caused shallowing which led to the development of bioclastic shoals with peritidal sediments in sheltered areas (Schofield & Adams 1985). The contact between the

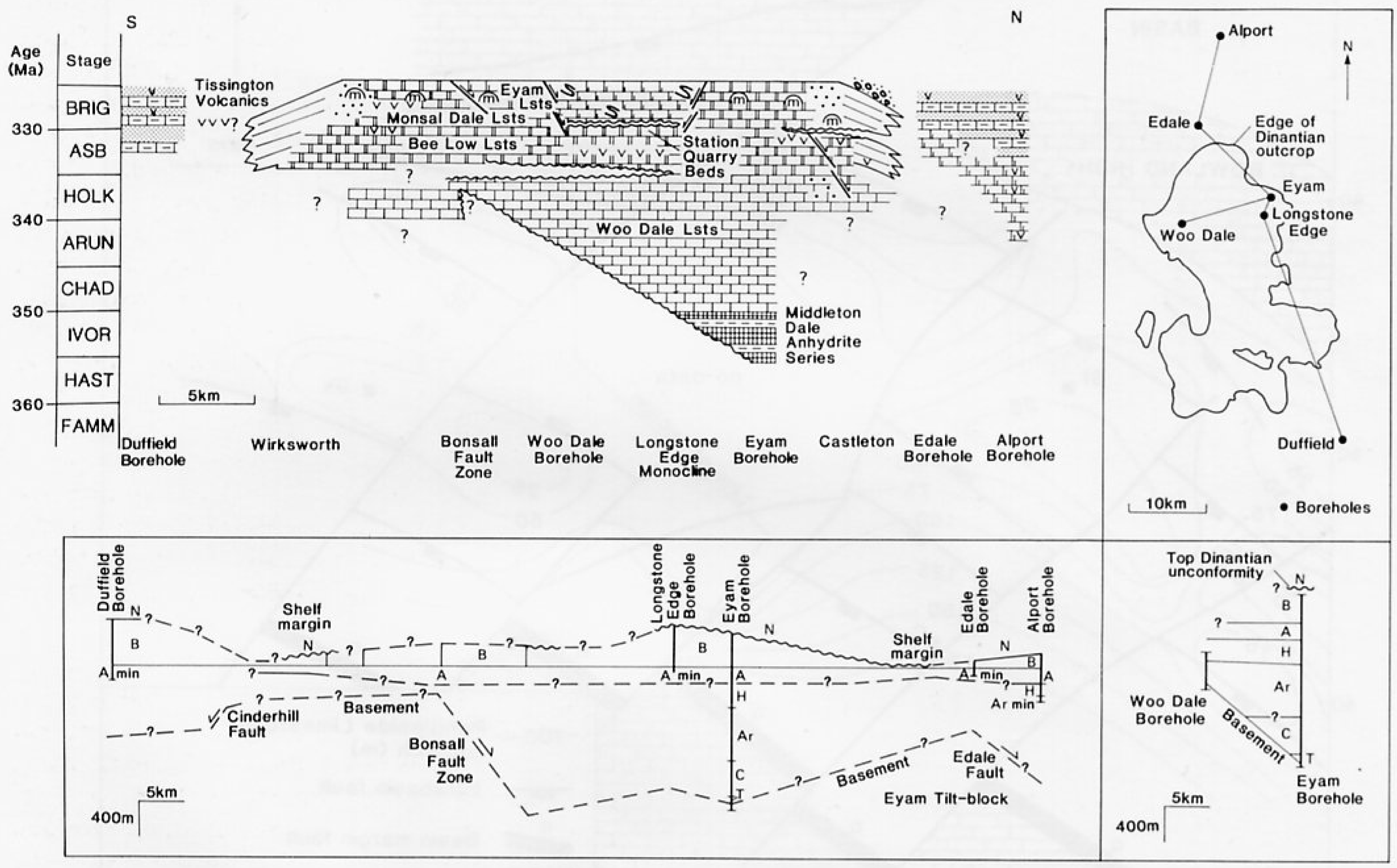


Fig. 6. Chronostratigraphical section across the Derbyshire High interpreted stratigraphical section between the Woo Dale and Eyam boreholes and section illustrating variation in the thicknesses of the Asbian and Brigantian and the depth to basement across the Derbyshire High. Compiled from Hudson & Cotton (1945), Smith *et al.* (1967), Stevenson & Gaunt (1971), Aitkenhead (1977), Weaver & Stanley (1977), Frost & Smart (1979), Whitcombe & Maguire (1981), Walkden (1982), Aitkenhead *et al.* (1985) and Strank (1985, 1986, 1987). Depth to basement is controlled by the Eyam and Woodale boreholes, elsewhere it is inferred from gravity data provided by Lee (pers. comm. 1987). Datum is top Asbian, vertical exaggeration x10. N = Namurian, B = Brigantian, A = Asbian, H = Holkerian, Ar = Arundian, C = Chadian, T = Tournaisian, min = minimum thickness. Location of chronostratigraphical section is shown in Fig. 1.

Woo Dale and the overlying Bee Low Limestones (Asbian) is conformable in the northern part of the Derbyshire High, but end-Holkerian uplift produced an angular unconformity whose stratigraphical separation increases southwards (Schofield & Adams 1985). The origin of this uplift is unknown.

The Bee Low Limestones comprise repeated shallowing-upwards cycles of bioclastic packstones and grainstones capped by emergent surfaces and K-bentonites which were deposited on a carbonate shelf (Walkden 1974, 1987). During the Asbian the Derbyshire High was surrounded by a high-angle rimmed shelf margin (Broadhurst & Simpson 1973; Walkden 1982). Local non-sequences and minor unconformities are present at the northern shelf margin indicating episodic footwall uplift associated with the Edale Fault. The nature of the shelf margin changed at the Asbian-Brigantian boundary into a low-angle margin associated with extensive bioclastic grainstone shoals within 2-3 km of the shelf margin (Walkden 1982).

An intra-shelf basin developed at the beginning of the Brigantian which was caused by reactivation of the Bonsall Fault zone resulting in growth of the Longstone Edge Monocline and the Taddington-Bakewell Anticline (Gutteridge 1987, this volume). The remaining shelf areas accumulated shoaling-upwards carbonates which possess a basal argillaceous bioclastic wackestone or packstone phase normally absent in the preceding Asbian cycles (Bridges 1982; Walkden 1982). Within the intra-shelf basin, uplift caused the development of a local angular unconformity. This uplift acted as a focus for later shallow water sedimentation (Walkden 1977; Gutteridge, this volume). Deposition in the intra-shelf basin was characterised by bioclastic calcisiltites, bioclastic turbidites and slumps derived from surrounding shelf areas. Shallow water sedimentation was periodically re-established over part of the intra-shelf basin by the progradation of surrounding shelf sediments in response to variations in subsidence rate (Gutteridge, this volume). Later in the Brigantian an eastwards-dipping carbonate ramp developed in the central part of the Derbyshire High as a result of footwall collapse of the southern fault block (Gutteridge 1984, 1987).

Reversal of slip on the Ashford Fault during the late Brigantian caused the development of minor north-south trending anticlines at the eastern margin of the Derbyshire High. This resulted in localised shallowing and the development of local unconformities between the Brigantian limestones and the late Brigantian/ Namurian shale-dominated sequence (Gutteridge, this volume).

Basic volcanicity on the Derbyshire High occurred from the Holkerian to the early Brigantian, with a peak of activity around the Asbian/Brigantian boundary (Stevenson & Gaunt 1971; Walters & Ineson 1981) coinciding with the main phase of syn-sedimentary tectonism. Volcanic centres are aligned along NW-SE trends, which suggests that their location was controlled by the underlying basement structure.

2.6. North Staffordshire Basin (Fig. 7)

The North Staffordshire Basin is a deep-water area lying immediately to the west and south-west of the Derbyshire High. Lee (1988) interpreted this basin as a half-graben whose western margin was controlled by the Lask Edge Fault, a major north-south trending fault with eastwards downthrow. The basement rises eastwards towards the Derbyshire High (Maroof 1976) and is displaced by north-south trending antithetic faults to the Lask Edge Fault (Lee 1988).

Sedimentation commenced during the late Devonian or Hastarian with deposition of the Redhouse Sandstones (proven by the Caldon Low Borehole) which thin towards the Derbyshire High (Aitkenhead & Chisholm 1982; Rogers 1983). These alluvial pebbly sandstones and siltstones are overlain by dolomitised peritidal and shallow subtidal limestones interbedded with siltstones, sandstones and breccia-conglomerates (Rue Hill Dolomites) of Hastarian to early Ivorian age (Aitkenhead & Chisholm 1982; Chisholm *et al.* in press).

During the Ivorian to Asbian, distal bioclastic turbidites were deposited in the basin (Milldale and Ecton limestones) with an influx of coarse bioclastic turbidites (Hopedale Limestone) during the Asbian (Prentice 1951; Aitkenhead & Chisholm 1982; Aitkenhead *et al.* 1985). These turbidites were probably sourced from shelf areas to the east and south-west. Carbonate mud mounds within the Milldale Limestones were probably deposited at water depths between 220 m and 280 m (Bridges & Chapman 1988). Several local non-sequences and angular unconformities within the Milldale Limestones (Aitkenhead & Chisholm 1982) are probably of tectonic origin, but cannot be dated owing to poor biostratigraphical resolution. Siliciclastic input to the basin increased during the Brigantian with the deposition of basinal shales interbedded with the turbiditic Onecote Sandstone and distal turbiditic bioclastic limestones (Mixon Limestone-Shales) (Morris 1969; Aitkenhead *et al.* 1985).

In the footwall of the Lask Edge Fault, the Astbury inlier contains Asbian shelf limestones and Brigantian shallow marine carbonates interbedded with subaerial and marginal marine siliciclastics up to 90 m in thickness (Evans *et al.* 1968). The hanging wall, in contrast, contains Asbian and Brigantian resedimented carbonates and basinal shales 210 m thick proven by the Gun Hill Borehole (Hudson & Cotton 1945). These facies and thickness variations across the Lask Edge Fault indicate that it was active at least during the Asbian and Brigantian.

Basic volcanics are present in the North Staffordshire Basin; the Gun Hill Borehole found tuffs of Holkerian and Asbian ages, and tuffs of Brigantian age are present

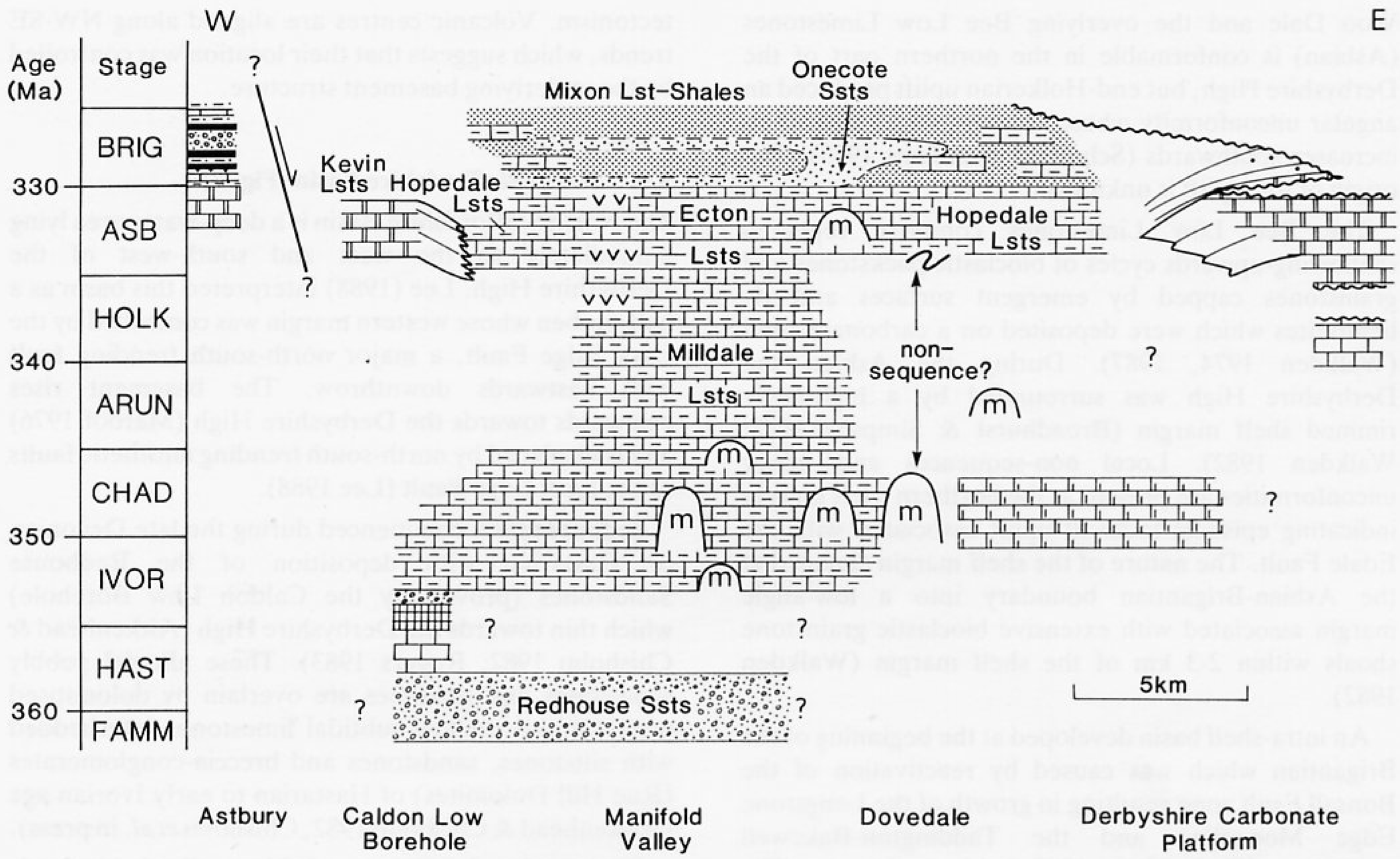


Fig. 7. Chronostratigraphical section across the North Staffordshire Basin. Location of section is shown in Fig. 1.

in the Astbury inlier (Hudson & Cotton 1945; Evans *et al.* 1968). However, only one volcanic centre in the North Staffordshire Basin has been identified (Aitkenhead 1984).

2.7. North Wales Shelf (Fig. 8)

The North Wales Shelf formed part of the carbonate platform which fringed the northern margin St George's Land now outcropping in a discontinuous band between Anglesey and Oswestry. Dinantian sedimentation represents the progressive burial of the Lower Paleozoic basement, which was divided into a series of topographic lows (referred to as gulfs or embayments) and highs by a number of NE-SW to E-W trending faults (e.g. Berw, Dinorwic and Bala faults).

The base of the Dinantian sequence is marked by locally derived siliciclastic sediments which rest on basement. Late Chadian to early Asbian limestones were deposited either on a carbonate shelf or the shallow part of a ramp with occasional siliciclastic input from St George's Land (Davies 1983; Somerville & Strank 1984a; Walkden & Davies 1983; Somerville *et al.* 1986). Holkerian to Brigantian sediments consist of repeated shallowing-upwards cycles. Asbian shelf cycles are grain-supported limestones capped by peritidal facies with emergence surfaces which resulted from the repeated progradation of high energy shoals (Power & Somerville 1975; Gray 1981; Davies 1983). Asbian cycles thicken across the Bala Fault into the Mold Gulf, indicating that the Mold Gulf was subsiding relative to the Cyrn-yr-Brain High at least during the Asbian. Thickening of Asbian cycles also occurs down the flanks of the Cyrn-yr-Brain and Berwyn highs towards the Llangollen and Oswestry embayments. For example, the Eglwyseg Formation (late Asbian) thickens from 46 m overlying the flank of the Cyrn-yr-Brain High to 148 m in the Llangollen embayment (Gray 1981), clearly indicating differential subsidence. Higher rates of subsidence within the lows are also indicated by the development of a basal argillaceous subtidal phase within the shelf cycles, not present on the highs (Somerville 1979a; Gray 1981). Brigantian cycles develop a basal argillaceous phase (Somerville 1979b; Somerville & Strank 1984b) similar to Brigantian shelf cycles deposited on the Derbyshire High and to Asbian cycles in areas of higher subsidence on the North Wales Shelf. This may suggest that the subsidence rates of the North Wales Shelf, and possibly also of the Derbyshire High, were higher during the Brigantian than during the Asbian.

An angular unconformity within early Brigantian limestones over the Cyrn-yr-Brain High indicates that this high underwent relative uplift during the early Brigantian (Gray 1981). There are no thickness changes in late Brigantian sediments deposited to the east of the Bala Fault, indicating that there was no further differential subsidence of the highs and embayments. Increased siliciclastic input to the North Wales Shelf

during the late Brigantian / Namurian is represented by the Sandy Passage Beds which consist of shales and sandstones with thin bioclastic limestones deposited in a shallow marine shelf environment (Banerjee 1969; Oldershaw 1969).

3. DISCUSSION

3.1. Controls on sedimentation

Analysis of the statigraphy and sedimentation of the basins and highs described in the previous section indicates several widespread phases of tectonic activity. Four main phases of syn-sedimentary faulting can be recognised, separated by intervals of relative tectonic quiescence (Fig. 9):

1. late Devonian - early Tournaisian,
2. late Chadian - early Arundian,
3. mid/late Asbian,
4. Brigantian.

Although beyond the scope of this paper, an additional phase of tectonic activity during the Pendleian (Namurian) has been recognised along the line of the Middle and South Craven faults in Bowland and along the margins of the Derbyshire High (Stevenson & Gaunt 1971; Dunham & Wilson 1985).

The intervals of enhanced tectonism proposed above equate with some of the phases of 'earth movement' recognised principally by Hudson and co-workers in the 1930s (e.g. Hudson & Turner 1933) and Parkinson in the 1940s and 1950s (e.g. Parkinson 1944) from the Bowland and Derbyshire regions. The evidence presented here supports an underlying tectonic influence on Dinantian sedimentation as suggested by these workers. These deductions do not rule out eustatic influences on sedimentation (e.g. Ramsbottom 1973, 1981) which may have had an important control on facies cyclicity during tectonically quiescent periods.

Basin initiation occurred at the onset of a major regional phase of extensional tectonics which began during the late Devonian to early Tournaisian. The exact timing of this episode of basin initiation in the United Kingdom is poorly known due to limited exposure and well penetration. In the better-exposed Munster and Dublin basins, Ireland, this early phase of basin development is better constrained with rifting episodes recognised during the middle Devonian, late Devonian and Tournaisian (Williams *et al.* this volume; Nolan, this volume).

Two phases of fault reactivation can be recognised throughout northern England and North Wales. A

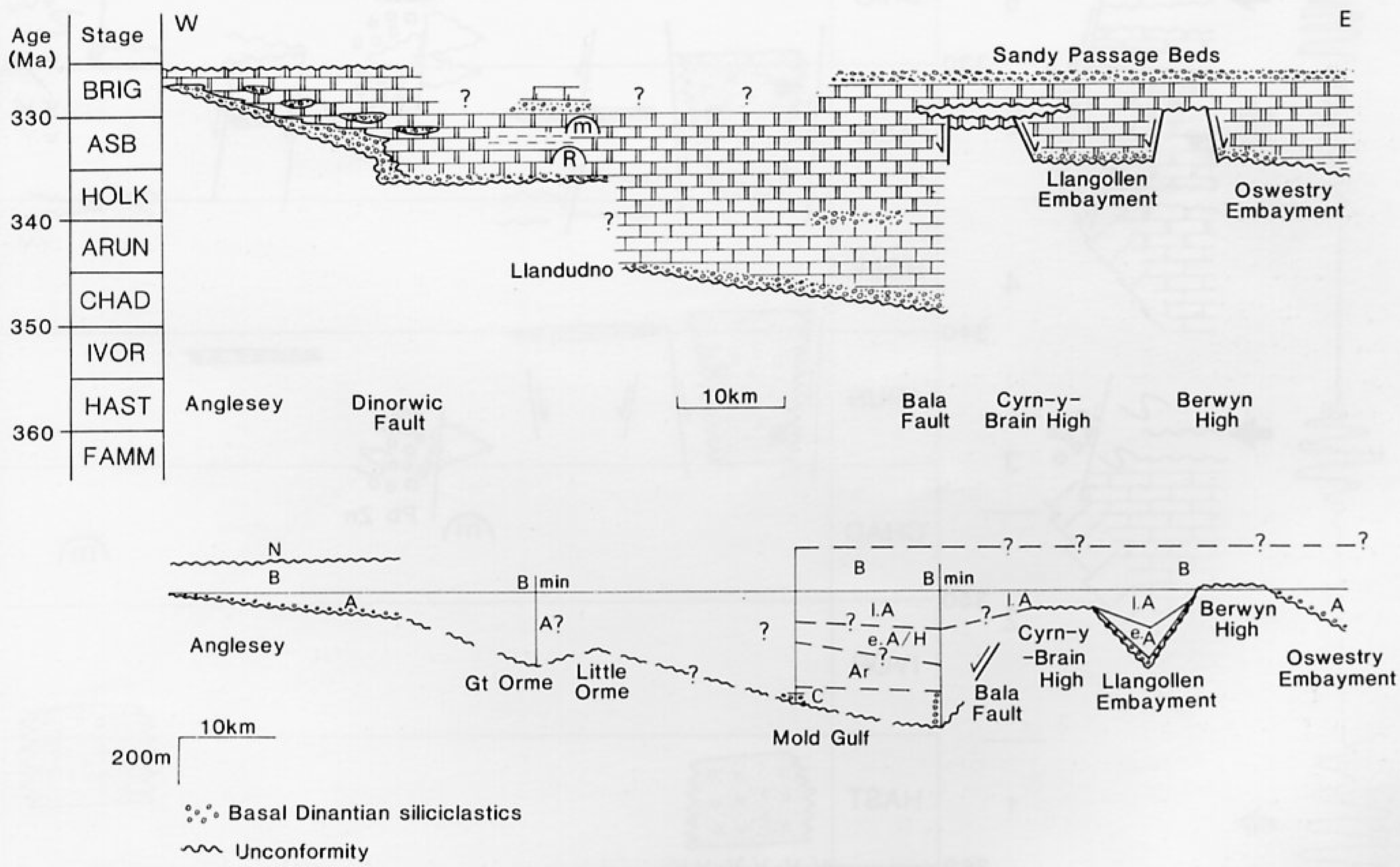


Fig. 8. Chronostratigraphical and thickness sections across the North Wales Shelf. Location of section shown in Fig. 1. Thickness data compiled from Somerville (1979a), Gray (1981), Davies (1983), Somerville & Strank (1984a,b), Warren *et al.* (1984) and Somerville *et al.* (1986). Datum is top Asbian, vertical exaggeration x50. lA = late Asbian, eA = early Asbian, eA/H = early Asbian and Holkerian. Other abbreviations as in Figure 6. The position of the Asbian/Holkerian boundary is uncertain owing to poor biostratigraphic resolution. Thickness of the Brigantian to the south-east of the Bala Fault is uncertain, but Gray (1981) indicates that it is constant over the highs and embayments.

major phase occurred during late Chadian to early Arundian and a subordinate phase during the mid to late Asbian. Structural confinement and vertical stacking of coarse siliciclastics and resedimented carbonates in hanging wall sequences, together with unconformities and condensed sequences within footwalls (e.g. Northumberland and Bowland; Leeder *et al.* this volume; Gawthorpe 1987) suggest that phases of fault reactivation had a high extensional component. Similar phases of active faulting have also been recognised from the Dublin basin in Ireland (Nolan, this volume).

During the mid to late Brigantian, a complex, but more localized phase of reactivation occurred. Both this, and the subsequent Pendleian phase are not apparent in the Northumberland Basin, but are recognised further to the south and to the west in Ireland (Dublin Basin, Nolan *op. cit.*). Although most of the stratigraphic evidence indicates extensional or transtensional reactivation, there is some local evidence of slip-reversal. This is mainly associated with E-W-trending faults (e.g. Middle Craven Fault), although the throw along N-S Ashford Fault may also have been reversed during the Brigantian.

We propose that the evolution of Dinantian basins was marked by an alternation of episodes of active faulting with intervals of relative tectonic quiescence. If regional variations in sediment supply are taken into account (e.g. proximity to clastic sources and variations in carbonate productivity) some general conclusions about the style of sedimentation during tectonically active and quiescent periods can be drawn. The tectonically active intervals are characterised by major influxes of siliciclastic sediment resulting from the rejuvenation of source areas or, more likely, structurally-controlled changes in sediment transfer (the term 'topographic funnelling' has been used to describe this effect - H. Clemmey, pers. comm.). The influx of siliciclastic sediment is most apparent in areas closer to source (e.g. Northumberland Basin), and is commonly represented by the progradation of fluvio-deltaic facies.

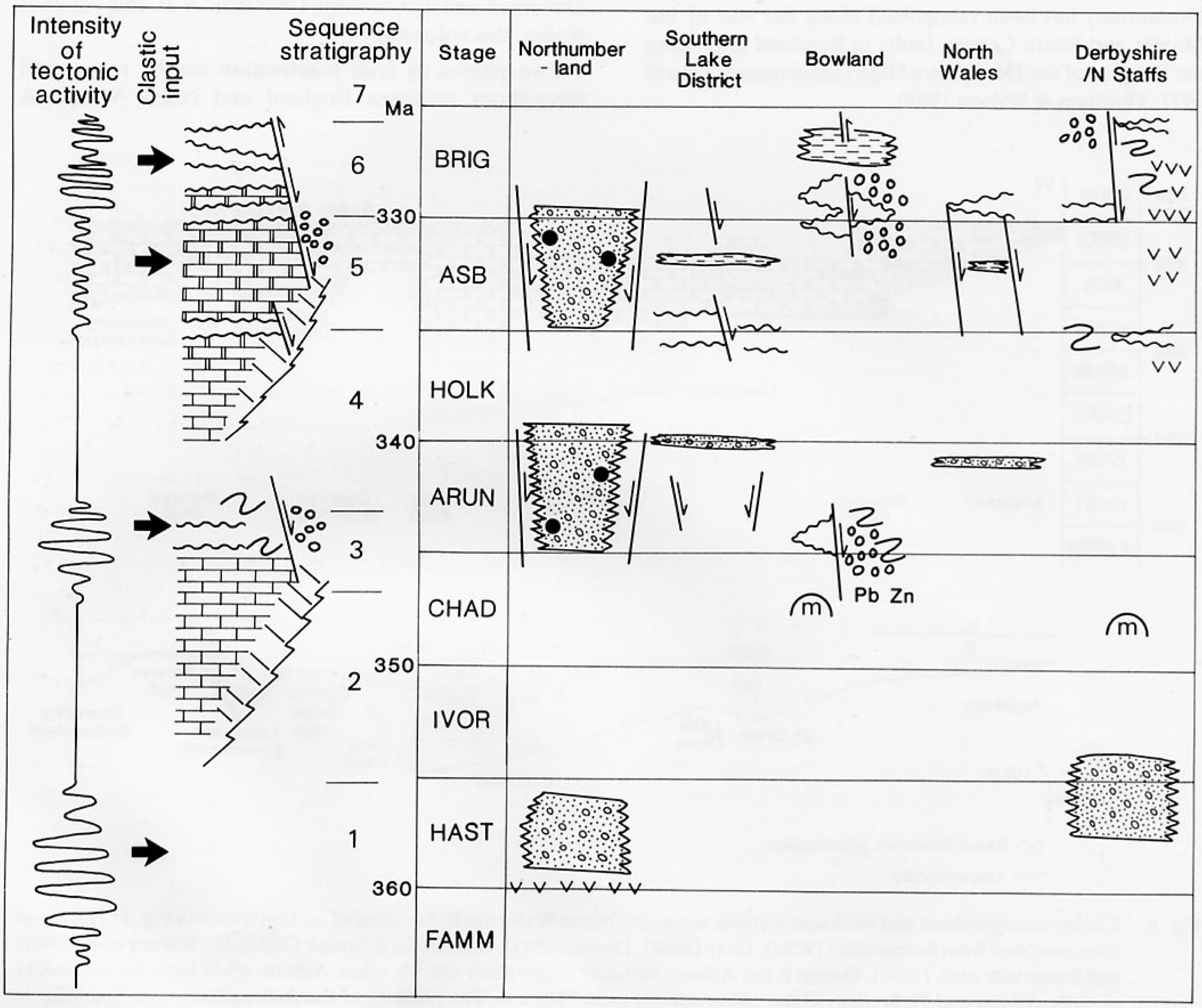


Fig. 9. Summary of tectono-sedimentary events in late Devonian/Dinantian basin evolution in northern England and North Wales. Key is given in Table 1.

In more distant areas the only indication of siliciclastic influx is often an increase in the percentage of terrigenous mud. During the most active phases of fault reactivation, carbonate production was retarded by inundation of hanging wall areas and subaerial emergence of footwalls. Thus, the size of carbonate ramps and/or rimmed shelves decreased. However, where the intensity of tectonic activity was low and carbonate production was high, for example the mid to late Asbian of the North Wales Shelf, carbonate production could mask tectonic effects. In addition to these sedimentary responses to faulting, igneous activity (e.g. Asbian/Brigantian, Derbyshire High) and base metal mineralisation (e.g. late Chadian/Arundian, Bowland Basin) may characterise these active phases in basin evolution.

By way of contrast, intervals of relative tectonic quiescence were characterised by increased carbonate production resulting in vertical accretion or progradation of carbonate rimmed shelves down hanging wall dip-slopes (e.g. northwestern margin of the Bowland Basin and the northern margin of the Widmerpool Basin). Carbonate rimmed shelves in footwall settings (e.g. northern margin of the Derbyshire High) show vertical accretion, with progradation limited by the large change in water depth across major fault zones.

3.2. Structural setting

The basin evolution diagrams and cross-sections in Section 2, show that the dominant structural style of the Dinantian basins is that of asymmetric grabens and half-grabens. The thickness and facies variations in this type of basin are at variance with those predicted by the block and basin model for late Devonian and Dinantian sedimentation (Bott 1967; Johnson 1967). The alternative tilt-block hypothesis (Miller & Grayson 1982; Grayson & Oldham 1987), although describing general basinal structural style, fails to take account of the genetic relationships between the active fault segments and their control on sedimentation. The two major basins exposed in northern England (Northumberland and Bowland) show that the overall form of the basins is the result of asymmetric subsidence towards a major bounding fault, tens of kilometres in length, with a displacement of several kilometres (e.g. Pendle Fault, Gawthorpe 1987; Stublick Fault, Holliday *et al.* pers. comm.). In addition to these main faults, there are a number of synthetic and antithetic faults, kilometres to tens of kilometres in length, with a displacement of tens to hundreds of metres which form small intra-basin fault blocks and clearly result from accommodation of extension in the hanging wall to the boundary faults (Gibbs 1984). Other structures, which form at high angles to the main boundary fault, act as transfer zones linking displacement on two or more fault segments. These structures are not predicted by the tilt-block model yet are of major importance in the structural and sedimentary evolution of the basins. Such a linked structural geometry is characteristic of many rift zones throughout the world (e.g. UKCS, Harding 1984; Cheadle *et al.* 1987; East Greenland, Surlyk 1977; Larsen 1988; Aegean, Jackson *et al.* 1982; East Africa, Rosendahl *et al.* 1986).

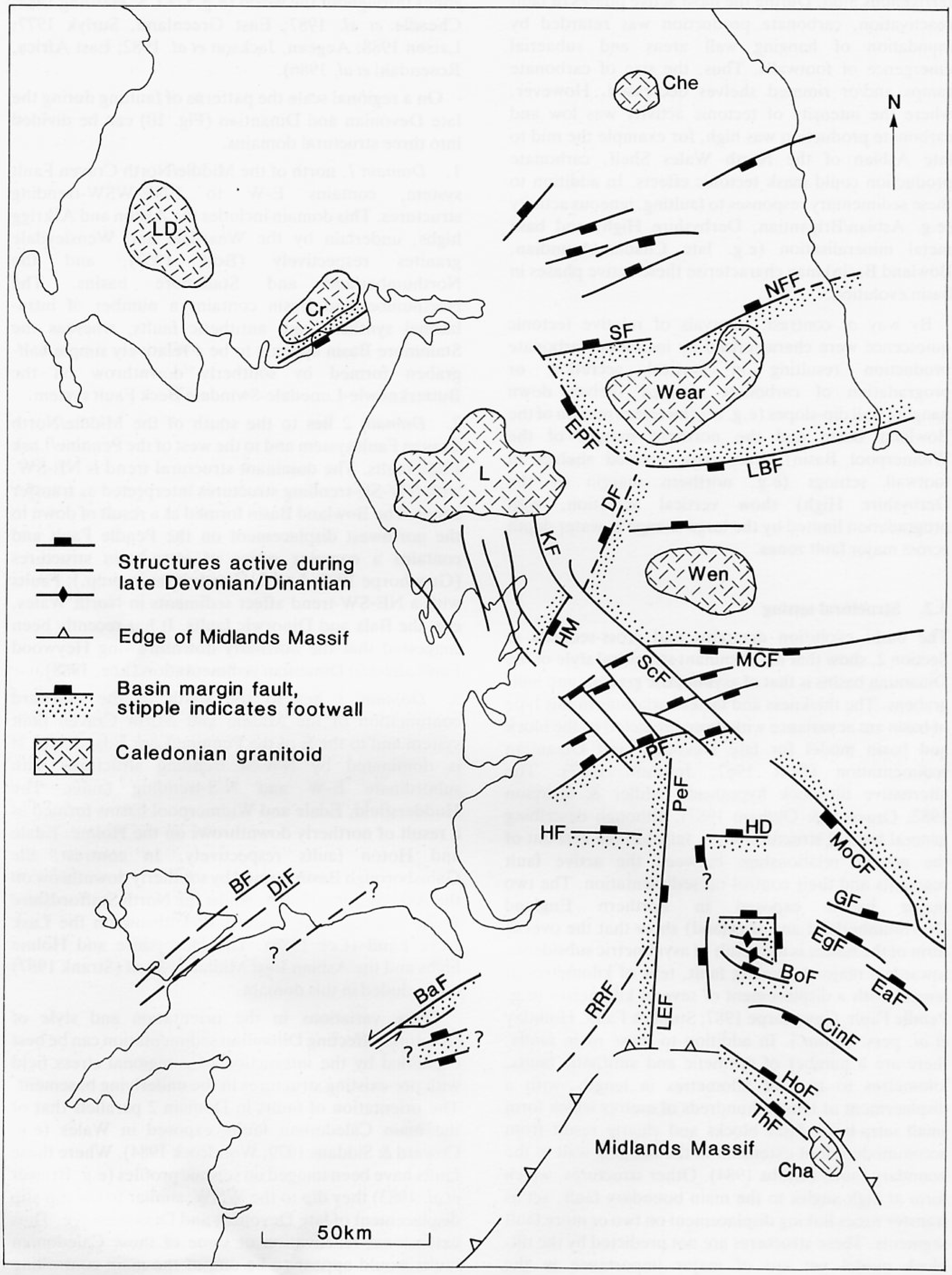
On a regional scale the patterns of faulting during the late Devonian and Dinantian (Fig. 10) can be divided into three structural domains.

1. *Domain 1*, north of the Middle/North Craven Fault system, contains E-W to ENE-WSW-trending structures. This domain includes the Alston and Askrigg highs, underlain by the Weardale and Wensleydale granites respectively (Bott 1967), and the Northumberland and Stainmore basins. The Northumberland Basin contains a number of intra-basinal synthetic and antithetic faults, whereas the Stainmore Basin appears to be a relatively simple half-graben formed by southerly downthrow on the Butterknowle-Lunedale-Swindale Beck Fault system.

2. *Domain 2* lies to the south of the Middle/North Craven Fault system and to the west of the Pennine/Lask Edge faults. The dominant structural trend is NE-SW, with NW-SE-trending structures interpreted as transfer zones. The Bowland Basin formed as a result of down to the northwest displacement on the Pendle Fault and contains a complex series of intra-basin structures (Gawthorpe 1987; Lee & Gawthorpe, in prep.). Faults with a NE-SW-trend affect sediments in North Wales, e.g. the Bala and Dinorwic faults. It has recently been suggested that the northerly downthrowing Heywood Fault affected Dinantian sedimentation (Lee, 1988).

3. *Domain 3* lies to the south of the eastward continuation of the Middle and North Craven fault system and to the E of the Pennine/Lask Edge faults. It is dominated by NW-SE-trending structures with subordinate E-W and N-S-trending faults. The Huddersfield, Edale and Widmerpool basins formed as a result of northerly downthrows on the Holme, Edale and Hoton faults respectively. In contrast, the Gainsborough Basin formed by southerly downthrow on the Askern-Spittal Fault, whilst the North Staffordshire Basin resulted from easterly downthrow on the Lask Edge Fault (Lee 1988). The Derbyshire and Holme highs and the Asbian East Midlands Shelf (Strank 1987) are included in this domain.

These variations in the orientation and style of structures affecting Dinantian sedimentation can be best explained by the interaction of a regional stress field with pre-existing structures in the underlying basement. The orientation of faults in Domain 2 parallels that of the main Caledonian faults exposed in Wales (e.g. Coward & Siddans 1979; Woodcock 1984). Where these faults have been imaged on seismic profiles (e.g. Brewer *et al.* 1983) they dip to the WNW, similar to the dip-slip displacement of late Devonian and Dinantian age. Thus extensional reactivation of some of these Caledonian faults would appear to be one of the main controlling


Che
N
LD
Cr
NFF
SF
Wear
EPF
LBF
L
DF
KF
Wen
Structures active during
late Devonian/Dinantian
Edge of Midlands Massif
Basin margin fault,
stipple indicates footwall
Caledonian granitoid
HM
MCF
ScF
PF
PeF
HF
HD
MoCF
BF
DiF
GF
EgF
BoF
EaF
BaF
RRF
LEF
CinF
HoF
ThF
Midlands Massif
Cha
50km

factors on the location and geometry of the Dinantian basins in Domain 2.

Evidence concerning the deep structure of the East Midlands is, by contrast, relatively sparse. However, a buried Caledonian fold-belt is suggested trending NW-SE (Turner 1949; Kent 1968; Wills 1973, 1978; Smith *et al.* 1985; Smith 1987). Reactivation of these structures under an extensional stress regime during the late Devonian to early Carboniferous may also explain the dominant style of basin formation in this domain. The general E-W trend to the faults within Domain 1, and in Domains 2 and 3 adjacent to the Pennine Fault, may be a function of their position in the structural arc linking the Welsh and East Midlands Caledonides which resulted from northward indentation of the Midlands Massif during the early Devonian (Turner 1949; Soper *et al.* 1987).

The marked control on late Devonian and Dinantian basin development exerted by basement structures makes the orientation of the applied stress field difficult to determine. Three possible stress fields have been proposed to account for late Devonian and Dinantian basin development: (i) large-scale dextral shear (e.g. Arthaud & Matte 1977; Badham 1982; Arthurton 1984), (ii) E-W extension (e.g. Russell 1971, 1976; Haszeldine 1984, 1988, this volume; Haszeldine & Russell 1987) (iii) N-S extension (e.g. Leeder 1976, 1982, 1987a; Bott 1987; Gawthorpe 1987; Lee 1988). Models involving large strike-slip deformations are not considered applicable for the following reasons: (i) there is no evidence for major lateral off-sets across faults, (ii) structures resulting from dextral shear (e.g. Ribblesdale Fold Belt) appear to have formed during the late Carboniferous rather than during the late Devonian or Dinantian (e.g. Gawthorpe 1987), (iii) major depocentres are not located at fault segments that would have been releasing bends under a dextral shear regime, (iv) basaltic volcanism is rarely associated with strike-slip regimes (Ballance & Reading 1980; Mitchell & Reading 1986). Hypotheses involving E-W extension which exploited N-S crustal lineaments, or 'geofractures', are also questioned for two main reasons: (i) the dominant influence of NE-SW, NW-SE and E-W faults on late Devonian to Dinantian basin development as indicated by stratigraphical, sedimentological and structural data has been described in this paper for northern England and North Wales, and for the Munster and Dublin Basins, by (Williams *et al.*, this volume; Nolan, this volume). Only two N-S-trending structures (Pennine/Lask Edge and Ashford Faults) were demonstrably active during the late Devonian and Dinantian in northern England. (ii) E-W-trending faults have dip-slip displacements of up to several kilometres of vertical throw. These faults do not display evidence for large strike-slip displacements that would be required under an E-W extensional stress regime. Therefore, to account for the development of the late Devonian and Dinantian sedimentary basins, we propose that a predominantly N-S oriented extensional stress field reactivated basement fault zones, with E-W-trending basement structures acting as dip-slip fault segments and structures on other trends responding by varying amounts of oblique movement.

An important area for future study concerns the possible identification of syn-extensional rotation of Dinantian fault-bounded crustal segments about vertical axes. Recent palaeomagnetic studies in the Aegean extensional terrane have established large magnitude rotations of up to 50° in the past 10 Ma (Kissel *et al.* 1986) and an elegant extensional model has been proposed to account for such rotations (McKenzie & Jackson 1986). We predict that such rotations ought to have occurred during the Dinantian evolution of the British Isles and that these may in future be detected by palaeomagnetic studies.

4. CONCLUSIONS

This synthesis of the late Devonian and Dinantian sequences exposed in northern England and North Wales has resolved four main tectonically active phases of basin evolution that punctuated intervals of relative tectonic quiescence. The first and most significant tectonic phase occurred during the late Devonian to early Tournaisian and marked the initiation of major half-grabens and asymmetric grabens whose orientation was controlled by Caledonian basement structures. Two further widespread phases of reactivation occurred during the late Chadian/early Arundian and in the mid to late Asbian, the latter being most significant in the north of the area. The fourth more localized period of reactivation occurred south of the Askrigg High during the Brigantian and involved a phase of inversion.

Fig. 10. Distribution of active structures which influenced late Devonian/Dinantian basin development. Map compiled from data referred to in the text and Eden *et al.* (1957), Edwards (1967), Smith *et al.* (1967), Kent (1968), Stevenson & Gaunt (1971), Smith *et al.* (1973), Wills (1973), Frost & Smart (1979), Whitcombe & Maguire (1981), Aitkenhead *et al.* (1985), Smith *et al.* (1985), Strank (1987), Lee (1988) and Gutteridge (this volume) for Domain 3.

Late Caledonian granoitoids: LD = Loch Doon, Che = Cheviot, Wear = Weardale, Wen = Wensleydale, L = Lake District, Cha = Charnwood Forest Igneous Province.

Structures: NFF = Ninety Fathom Fault, SF =Stublick Fault, EPF = Eden-Pennine Fault, LBF = Lunedale – Butterknowle Fault, DF = Dent Fault, KF = Kendal Fault, HM = Hutton Monocline, MCF = Mid Craven Fault, SCF = South Craven Fault, PF = Pendle Fault, HF = Heywood Fault, PeF = Pennine Fault, HD = Holme Disturbance, MoCF = Morley – Campsall Fault, GF = Gainsborough Fault, EgF = Egmanton Fault, EaF = Eakring Fault, BoF = Bonsall Fault, CinF = Cinderhill Fault, HoF = Hoton Fault, ThF = Thringston Fault, LEF = Lask Edge Fault, RRF = Red Rock Fault, BaF = Bala Fault, DiF =Dinorwic Fault, BF = Berw Fault.

However, major problems still remain concerning the origin of these phases of basin evolution and their precise geographic distribution and duration. Crucial to future work is the ability to correlate the 'signals' observed in the basin fill on an inter- and intra-basin scale. Existing biostratigraphic zonation schemes require careful evaluation, especially with respect to facies control on faunas. Alternative correlation methods could also be employed, such as cement stratigraphy, palaeomagnetism and seismic sequence analysis. Cement stratigraphies developed from regional diagenetic studies and linked to burial history, mineralisation and vein sets can be used as a correlation technique and to help identify phases of tectonism. For example, the use of zoned calcite cements associated with phases of meteoric diagenesis can provide high-resolution correlations on carbonate platforms (e.g. Meyers 1974; Horbury 1987). Palaeomagnetic studies may also aid correlation by means of magnetic polarity stratigraphy (e.g. Turner *et al.* 1979), but care is needed in identifying post-depositional remagnetisation. Palaeomagnetic studies may also be used to constrain tectonic rotations (e.g. Hornafius 1985, Western Transverse Ranges, California; Kissel *et al.* 1986, Greek Aegean) and thus help constrain regional tectonic models.

Perhaps one of the most fruitful developments would be the integration of field data, as presented in this paper, with seismic reflection data. The alternation of tectonically active and quiescent phases of basin development is likely to produce correlatable seismic sequence boundaries, bounding sequences with distinctive form and internal configurations. Mapping sequences will not only help refine present late Devonian and Dinantian basin evolution models based on outcrop data and extend such analyses into the subsurface, but will also develop an exploration philosophy for what are presently poorly defined late Devonian and Dinantian hydrocarbon and base metal play fairways.

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References

[illegible]MS, A. E. 1984. Development of algal-foraminiferal-coral [illegible] in the Lower Carboniferous of Furness, [illegible] *thaia* **17**, 233-249.

AITKENHEAD, N. 1977. The Institute of Geological Sciences borehole at Duffield, Derbyshire. *Bulletin of the Geological Survey of Great Britain* **59**, 1-38.

AITKENHEAD, N. 1984. Volcanoes in the late Dinantian of Derbyshire, England with particular reference to the Widmerpool Gulf. *European Dinantian Environments 1st Meeting 1984, Abstracts.* Open University, p.33.

AITKENHEAD, N. & CHISHOLM, J. I. 1982. *A standard nomenclature for the Dinantian formations of the Peak District of Derbyshire and Staffordshire.* Report of the Institute of Geological Sciences **82/8**.

AITKENHEAD, N., CHISHOLM, J. I. & STEVENSON, I. P. 1985. *Geology of the country around Buxton, Leek and Bakewell.* Memoir of the British Geological Survey.

ALEXANDER, J. & LEEDER, M. R. 1987. Active tectonic control on alluvial architecture. Pp. 243-252. in ETHERIDGE, F. G., FLORES, R. M. & HARVEY, M. D. (editors) *Recent Developments in Fluvial Sedimentology.* Society of Economic Paleontologists and Mineralogists Special Publication **39**.

ANDREWS, C. J. & ASHTON, J. H. 1985. Regional setting, geology and metal distribution patterns of the Navan orebody, Ireland. *Transactions of the Institute of Mining & Metallurgy* **94**, B66-93.

ARTHAUD, F. & MATTE, R. 1977. Late Palaeozoic strike-slip faulting in southern Europe and North Africa: a result of a right-lateral shear zone between the Appalachians and the Urals. *Bulletin of the Geological Society of America* **88**, 1305-1320.

ARTHURTON, R. S. 1984. The Ribblesdale Fold Belt. Pp. 131-138 in HUTTON, D. H. W. & SANDERSON, D. J. (editors) *Variscan Tectonics of the North Atlantic Region.* Geological Society of London Special Publication **14**.

ARTHURTON, R. S., JOHNSON, E. W. & MUNDY, D. J. C. 1988. *Geology of the country around Settle.* Memoir of the British Geological Survey.

BADHAM, J. P. N. 1982. Strike-slip orogens — an explanation for the Hercynides. *Journal of the Geological Society* (London) **139**, 495-506.

BADLEY, M. E., EGEBERG, T. & NIPEN, O. 1984. Development of rift basins illustrated by the structural evolution of the Oseberg feature, Block 30/6, offshore Norway. *Journal of the Geological Society* (London) **141**, 639-649.

BALLANCE, P. F. & READING, H. G. 1980. *Sedimentation in Oblique-Slip Mobile Zones.* Blackwell Scientific Publications, Oxford.

BANERJEE, A. 1969. Carboniferous lithofacies, Rhydmwyn to Erryrys, North Wales, *Geological Journal* **6**, 181-184.

BARR, D. 1987. Lithospheric stretching, detached normal faulting and footwall uplift. Pp. 75-94 in COWARD, M. P., DEWEY, J. F. & HANCOCK, P. L. (1987) q.v.

BARRACLOUGH, R. 1983. *Tectonic versus eustatic ses level changes in the Lower Carboniferous of northern England: a sedimentary study.* Unpublished Ph.D. thesis, University of Leeds.

BESLY, B. M. & KELLING, G. (editors) 1988. *Sedimentation in a syn-orogenic basin complex: the Carboniferous of northwest Europe.* Blackie & Son.

BOTT, M. H. P. 1967. Geophysical investigations of the northern Pennine basement rocks. *Proceedings of the Yorkshire Geological Society* **36**, 139-168.

BOTT, M. H. P. 1976. Formation of sedimentary basins of graben type by extension of the continental crust. *Tectonophysics* **36**, 77-86.

BOTT, M. H. P. 1987. Subsidence mechanisms of Carboniferous basins in northern England. Pp. 21-32 in MILLER, J., ADAMS, A. E. & WRIGHT, V. P. (1987) q.v.

BOTT, M. H. P. & JOHNSON, G. A. L. 1967. The controlling mechanism of Carboniferous cyclic sedimentation. *Quarterly Journal of the Geological Society of London* **122**, 421-441.

BOTT, M. H. P. & MASSON-SMITH, D. J. 1957. The geological interpretation to a gravity survey of the Alston Block and Durham Coalfield. *Quarterly Journal of the Geological Society of London* **113**, 93-117.

BOTT, M. H. P., SWINBURN, P. M. & LONG, R. E. 1984. Deep structure and origin of the Northumberland and Stainmore troughs. *Proceedings of the Yorkshire Geological Society* **44**, 479-496.

BREWER, J. A., MATTHEWS, D. H., WARNER, M. R., HALL, J., SMYTHE, D. K. & WHITTINGTON, R. J. 1983. BIRPS deep seismic reflection studies of the British Caledonides. *Nature* **305**, 206-210.

BRIDGES, P. H. 1982. The origin of cyclothems in the late Dinantian platform carbonates at Crich, Derbyshire. *Proceedings of the Yorkshire Geological Society* **44**, 159-180.

BRIDGES, P. H. 1984. The south-west margin of the Dinantian carbonate platform of Derbyshire, UK. A preliminary study. *5th European Sedimentology Meeting, Abstracts*. p.79.

BRIDGES, P. H. & CHAPMAN, A. J. 1988. The anatomy of a deepwater mud-mound complex to the southwest of the Dinantian platform in Derbyshire, U.K. *Sedimentology* **35**, 139-162.

BRIDGE, J. S. & LEEDER, M. R. 1979. A simulation model of alluvial stratigraphy. *Sedimentology* **26**, 617-644.

BROADHURST, F. M. & SIMPSON, I. P. 1973. Bathymetry on a Carboniferous reef. *Lethaia* **6**, 367-381.

BURGESS, I. C. & HARRISON, R. K. 1967. Carboniferous basement beds in the Roman Fell district, Westmoreland. *Proceedings of the Yorkshire Geological Society* **36**, 203-225.

BURGESS, I. C. & HOLLIDAY, D. W. 1979. *Geology of the country around Brough-Under-Stainmore*. Memoir of the Geological Survey of Great Britain.

BURGESS, I. C. & MITCHELL, M. 1976. Viséan lower Yoredale limestones on the Alston and Askrigg blocks and the base of the D_2 Zone in northern England. *Proceedings of the Yorkshire Geological Society* **40**, 613-630.

CHARSLEY, T. J. 1984. Early Carboniferous rocks in the Swinden No. 1 Borehole, west of Skipton. *Report of the British Geological Survey* **16/1**, 5-12.

CHEADLE, M. J., MCGEARY, S., WARNER, M. R. & MATTHEWS, D. H. 1987. Extension structures on the western UK continental shelf: a review of evidence from deep seismic profiling. Pp. 445-465 in COWARD, M. P., DEWEY, J. F. & HANCOCK, P. L. (1988) q.v.

CHISHOLM, J. I., CHARSLEY, T. J., AITKENHEAD, N. & STEVENSON, I. P. in press. *Geology of the country around Ashbourne and Cheadle*. Memoir of the British Geological Survey.

COWARD, M. P., DEWEY, J. F. & HANCOCK, P. L. (editors) 1987. *Continental Extensional Tectonics*. Geological Society of London Special Publication **28**.

COWARD, M. P. & SIDDANS, A. W. B. 1979. The tectonic evolution of the Welsh Caledonides. Pp. 187-198 in HARRIS, A. L., HOLLAND, C. H. & LEAKE, B. E. (editors) *Caledonides of the British Isles — reviewed*. Geological Society of London Special Publication **8**.

DAVIES, J. 1983. *Stratigraphy, sedimentology and palaeontology of the Lower Carboniferous of Anglesey*. Unpublished Ph.D. thesis, University of Keele.

DAY, J. B. W. 1970. *Geology of the country around Bewcastle*. Memoir of the Geological Survey of Great Britain.

DEWEY, J. F. 1982. Plate tectonics and the evolution of the British Isles. *Journal of the Geological Society* (London) **139**, 371-412.

DUNHAM, K. C. & WILSON, A. A. 1985. *Geology of the Northern Pennine Orefield: Volume 2, Stainmore to Craven*. Economic Memoir of the British Geological Survey.

DUNNINGTON, H. V. 1945. Contemporaneous slumping in the Embsay Limestone series of the Skipton Anticline. *Proceedings of the Yorkshire Geological Society* **25**, 239-247.

EDEN, R. A., STEVENSON, I. P. & EDWARDS, W. 1957. *Geology of the country around Sheffield*. Memoir of the Geological Survey of Great Britain.

EDWARDS, W. 1967. *Geology of the country around Ollerton*. Memoir of the Geological Survey of Great Britain.

EVANS, W. B., WILSON, A. A., TAYLOR, B. J. & PRICE, D. 1968. *Geology of the country around Macclesfield, Congleton, Crewe and Middlewich*. Memoir of the Geological Survey of Great Britain.

FALCON, N. L. & KENT, P. E. 1960. *Geological results of petroleum exploration in Britain, 1945-1957*. Memoir of the Geological Society of London **2**.

FROST, D. V. & HOLLIDAY, D. W. 1980. *Geology of the Bellingham district*. Memoir of the Geological Survey of Great Britain.

FROST, D. V. & SMART, J. G. O. 1979. *Geology of the country north of Derby*. Memoir of the Geological Survey of Great Britain.

GARWOOD, E. J. 1913. The Lower Carboniferous succession in the northwest of England. *Quarterly Journal of the Geological Society of London* **68**, 449-586.

GAWTHORPE, R. L. 1985. *Sedimentation, tectonics and diagenesis: the Dinantian sequence of the Bowland Basin, northern England*. Unpublished Ph.D. thesis, University of Leeds.

GAWTHORPE, R. L. 1986. Sedimentation during carbonate ramp-to-slope evolution in a tectonically active area: Bowland Basin (Dinantian), N. England. *Sedimentology* **33**, 185-206.

GAWTHORPE, R. L. 1987. Tectono-sedimentary evolution of the Bowland Basin, N. England, during the Dinantian. *Journal of the Geological Society* (London) **144**, 59-71.

GAWTHORPE, R. L. & CLEMMEY, H. 1985. Geometry of submarine slides in the Bowland Basin (Dinantian) and their relation to debris flows. *Journal of the Geological Society* (London) **142**, 555-565.

GEORGE, T. N. 1958. Lower Carboniferous palaeogeography of the British Isles. *Proceedings of the Yorkshire Geological Society* **31**, 227-318.

GEORGE, T. N. 1978. Eustacy and tectonics: sedimentary rhythms and stratigraphical units in British Dinantian correlations. *Proceedings of the Yorkshire Geological Society* **42**, 229-262.

GEORGE, T. N., JOHNSON, G. A. L., MITCHELL, M., PRENTICE, J. E., RAMSBOTTOM, W. H. C., SEVASTOPULO, G. D. & WILSON, R. B. 1976. *A correlation of Dinantian rocks in the British Isles.* Geological Society of London Special Report **7**.

GIBBS, A. D. 1984. Structural evolution of extensional basin margins. *Journal of the Geological Society* (London) **141**, 609-620.

GIBBS, A. D. 1987. Development of extensional and mixed-mode sedimentary basins. Pp. 19-33 in COWARD, M. P., DEWEY, J. F. & HANCOCK, P. L. (1987) q.v.

GRAY, D. I. 1981. *Lower Carboniferous palaeoenvironments in North Wales.* Unpublished Ph.D. thesis, University of Newcastle upon Tyne.

GRAYSON, R. F., & OLDHAM, L. 1987. A new structural framework for the northern British Dinantian as a basis for oil, gas and mineral exploration. Pp. 33-59 in MILLER, J., ADAMS, A. E. & WRIGHT, V. P. (1987) q.v.

GUTTERIDGE, P. 1984. Sedimentation of the Eyam Limestone Formation, (Derbyshire). *European Dinantian Environments 1st Meeting 1984. Open University.* Pp. 128-130.

GUTTERIDGE, P. 1987. Dinantian sedimentation and the basement structure of the Derbyshire Dome. *Geological Journal* **22**, 25-41.

GUTTERIDGE, P. this volume. Controls on carbonate sedimentation in a Brigantian intrashelf basin, Derbyshire.

HARDING, T. P. 1984. Graben hydrocarbon occurrences and structural style. *Bulletin of the American Association of Petroleum Geologists* **68**, 333-362.

HARRISON, D. J. 1982. *The limestone resources of the Craven Lowlands: description of parts of 1:50000 geological sheets 59, 60, 68 & 69.* Mineral Assessment Report Institute of the Geological Sciences **116**.

HASZELDINE, R. S. 1984. Carboniferous North Atlantic palaeogeography: stratigraphic evidence for rifting, not megashear or subduction. *Geological Magazine* **121**, 443-463.

HASZELDINE, R. S. 1988. Crustal lineaments in the British Isles: their relationship to Carboniferous basins. Pp. 53-68 in BESLY, B. M. & KELLING, G. (1988) q.v.

HASZELDINE, R. S. this volume. Evidence against crustal stretching, north-south tension and Hercynian collision, forming British Carboniferous basins.

HASZELDINE, R. S. & RUSSELL, M. J. 1987. The late Carboniferous North Atlantic Ocean: implications for hydrocarbon exploration from Britain to the Arctic. Pp. 1163-1177 in BROOKS, J. & GLENNIE, K. (editors) *Petroleum Geology of North West Europe.* Graham & Trotman, London.

HODGSON, A. V. 1978. Braided river bedforms and related sedimentary structures in the Fell Sandstone Group (Lower Carboniferous) of North Northumberland. *Proceedings of the Yorkshire Geological Society* **41**, 509-532.

HORBURY, A. D. 1987. *Sedimentology of the Urswick Limestone in South Cumbria and North Lancashire.* Unpublished Ph.D. thesis, University of Manchester.

HORBURY, A. D. this volume. The relative roles of tectonism and eustacy in the deposition of the Urswick limestone in South Cumbria and North Lancashire.

HORNAFIUS, J. S. 1985. Neogene tectonic rotation of the Santa Ynez Range, Western Transverse Ranges, California, suggested by paleomagnetic investigation of the Monterey Formation. *Journal of Geophysical Research* **90**, 12503-12522.

HUDSON, R. G. S. 1930. The Carboniferous of the Craven Reef Belt: the Namurian unconformity of Scaleber, near Settle. *Proceedings of the Geologists' Association* **41**, 290-322.

HUDSON, R. G. S. 1936. Sudetic earth-movements in the Craven area. *Report of the British Association for the Advancement of Science, Blackpool* p.350.

HUDSON, R. G. S. & COTTON, G. 1945. The Lower Carboniferous in a boring at Alport, Derbyshire. *Proceedings of the Yorkshire Geological Society* **25**, 254-330.

HUDSON, R. G. S. & MITCHELL, G. H. 1937. The Carboniferous rocks of the Skipton anticline. *Summary of Progress of the Geological Survey of Great Britain 1935, Part 2,* 1-45.

HUDSON, R. G. S. & TURNER, S. 1933. Early and mid-Carboniferous earth movements in Great Britain. *Proceedings of the Leeds Philosophical Society (Science Section)* **2**, 455-66.

JACKSON, J. A., KING, G. & VITA-FINZI, C. 1982. The neotectonics of the Aegean: an alternative view. *Earth and Planetary Science Letters* **61**, 303-318.

JACKSON, J. A. & MCKENZIE, D. 1983. The geometric evolution of normal fault systems. *Journal of Structural Geology* **5**, 471-481.

JOHNSON, G. A. L. 1960. Palaeogeography of the northern Pennines and part of NE England during deposition of Carboniferous cyclothemic deposits. *International Geological Congress XXI Session, Norden* **12**, 118-128.

JOHNSON, G. A. L. 1967. Basement control of Carboniferous sedimentation in northern England. *Proceedings of the Yorkshire Geological Society* **36**, 175-94.

JONES, G. V. & BRADFER, N. 1981. The Ballinalack deposit, Co. Westmeath, Ireland. Pp. 47-62 in BROWN, A. G. & PYNE, J. (editors) *Mineral Exploration in Ireland: Progress and developments 1971-1981 (Wexford Conference 1981).* Irish Association of Economic Geologists, Dublin.

KENT, P. E. 1966. Structure of the concealed Carboniferous rocks of NE England. *Proceedings of the Yorkshire Geological Society* **35**, 323-352.

KENT, P. E. 1968. The buried floor of eastern England. Pp. 138-148 in SYLVESTER-BRADLEY, P. C. & FORD, T. D. (editors) *The Geology of the East Midlands.* Leicester University Press.

KIMBER, R. N. & JOHNSON, G. A. L. 1986. Lake District Highlands and Islands during the Upper Palaeozoic. *Proceedings of the Cumberland Geological Society* **4**, 377-390.

KISSEL, C., LAJ, C., POISSON, A., SAVASCIN, Y., SIMEAKIS, K. & MERCIER, J. L. 1986. Paleomagnetic evidence for Neogene rotational deformations in the Aegean Domain. *Tectonics* **5**, 783-795.

LARSEN, P. H. 1988. Relay structures in a Lower Permian basement-involved extensional system, East Greenland. *Journal of Structural Geology* **10**, 3-8.

LEE, A. G. 1988. Carboniferous basin configuration of central England, modelled using gravity data. Pp. 69-84 in BESLY, B. M. & KELLING, G. (1988) q.v.

LEE, A. G. & GAWTHORPE, R. L. in prep. Geophysical analysis of the structure and evolution of the Bowland Basin, northern England.

LEEDER, M. R. 1974. Lower Border Group (Tournaisian) fluvio-deltaic sedimentation and the palaeogeography of the Northumberland Basin. *Proceedings of the Yorkshire Geological Society* **40**, 129-180.

LEEDER, M. R. 1976. Sedimentary facies and the origins of basin subsidence along the northern margin of the supposed Hercynian ocean. *Tectonophysics* **36**, 167-179.

LEEDER, M. R. 1982. Upper Palaeozoic basins of the British Isles - Caledonide inheritance versus Hercynian plate margin processes. *Journal of the Geological Society* (London) **139**, 479-491.

LEEDER, M. R. 1987a. Tectonic and palaeogeographic models for Lower Carboniferous Europe. Pp. 1-19 in MILLER, J., ADAMS, A. E. & WRIGHT, V. P. (1987) q.v.

LEEDER, M. R. 1987b. Sediment deformation structures and palaeo-tectonic analysis of extensional sedimentary basins. Pp. 137-146 in JONES, M. & PRESTON, R. M. F. (editors) *Deformation of Sediments and Sedimentary Rocks*. Special Publication of the Geological Society **29**.

LEEDER, M. R., & GAWTHORPE, R. L. 1987. Sedimentary models for extensional tilt block/half graben basins. Pp. 139-152 in COWARD, M. P., DEWEY, J. F. & HANCOCK, P. L. (1987) q.v.

LEEDER, M. R., FAIRHEAD, D., LEE, A. G., STUART, G., CLEMMEY, H., GREEN, C. & AL-HADDEH, B. this volume. The Northumberland Basin: an inverted Carboniferous extensional basin.

LEEDER, M. R. & MCMAHON, A. H. 1988. Upper Carboniferous (Silesian) basin subsidence in northern Britain. Pp. 43-52 in BESLY, B. M. & KELLING, G. (1988) q.v.

LEES, A. & MILLER, J. 1985. Facies variation in Waulsortian buildups, Part 2; Mid-Dinantian buildups from Europe and North America. *Geological Journal* **20**, 159-180.

LUMSDEN, G. I., TULLOCH, W., HOWELLS, M. F. & DAVIES, A. 1967. *The geology of the neighbourhood of Langholm*. Memoir of the Geological Survey of Great Britain.

MAROOF, S. I. 1976. The structure of the concealed pre-Carboniferous basement of the Derbyshire Dome from gravity data. *Proceedings of the Yorkshire Geological Society* **41**, 56-69.

MCKENZIE, D. & JACKSON, J. 1986. A block model of distributed deformation by faulting. *Journal of the Geological Society* (London) **143**, 349-353.

MEYERS, W. J. 1974. Carbonate cement stratigraphy of the Lake Valley Formation (Mississippian) Sacramento Mountains, New Mexico. *Journal of Sedimentary Petrology* **44**, 837-861.

MILLER, J., ADAMS, A. E. & WRIGHT, V. P. (editors) 1987. *European Dinantian Environments*. John Wiley and Sons, Chichester.

MILLER, J. & GRAYSON, R. F. 1982. The regional context of Waulsortian facies in northern England. Pp. 17-30 in BOLTON, K., LANE, H. R. & LEMONE, D. U. (editors) *Symposium on the palaeoenvironmental setting and distribution of the Waulsortian facies*. The El Paso Geological Society and University of Texas at El Paso.

MITCHELL, A. H. G. & READING, H. G. 1986. Sedimentation and tectonics. Pp. 417-519 in READING, H. G. (editor) *Sedimentary Environments and Facies*. 2nd edition. Blackwell Scientific Publications, Oxford.

MITCHELL, M., TAYLOR, B. J. & RAMSBOTTOM, W. H. C. 1978. Carboniferous. Pp. 168-188 in MOSELEY, F. (editor). *The Geology of the Lake District*. Yorkshire Geological Society Occasional Publication **3**.

MORRIS, P. G. 1969. Dinantian and Namurian stratigraphy east and south-east of Leek, North Staffordshire. *Proceedings of the Geologists' Association* **80**, 145-175.

MUNDY, D. J. C. 1980. *Aspects of the Palaeoecology of the Craven Reef Belt (Dinantian) of North Yorkshire*. Unpublished Ph.D. thesis, University of Manchester.

NOLAN, S. C. this volume. The style and timing of Dinantian syn-sedimentary tectonics in the eastern part of the Dublin Basin, Ireland.

OLDERSHAW, A. E. 1969. Carboniferous lithofacies, Halkyn Mountain, North Wales. *Geological Journal* **6**, 185-192.

ORD, D. M., CLEMMEY, H. & LEEDER, M. R. 1988. Palaeotectonic analysis of faults in the Carboniferous Solway Basin, SW Scotland. *Journal of the Geological Society* (London) **145**, 249-259.

PARKINSON, D. 1944. The origin and structure of the Lower Viséan reef-knolls of the Clitheroe district, Lancashire. *Quarterly Journal of the Geological Society of London* **99**, 155-168.

POWER, G. & SOMERVILLE, I. D. 1975. A preliminary report on the occurrence of minor sedimentary cycles in the "Middle White Limestone" (D_1), Lower Carboniferous of North Wales. *Proceedings of the Yorkshire Geological Society* **28**, 491-497.

PRENTICE, J. E. 1951. The Carboniferous Limestone of the Manifold Valley region, North Staffordshire. *Quarterly Joural of the Geological Society of London* **106**, 171-210.

RAMSBOTTOM, W. H. C. 1973. Transgressions and regressions in the Dinantian: a new synthesis of British Dinantian stratigraphy. *Proceedings of the Yorkshire Geological Society* **39**, 567-607.

RAMSBOTTOM, W. H. C. 1974. Dinantian. Pp. 47-73 in RAYNER, D. H. & HEMINGWAY, J. E. (editors) *The Geology and Mineral Resources of Yorkshire*. Yorkshire Geological Society.

RAMSBOTTOM, W. H. C. 1981. Eustacy, sea level and local tectonics, with examples from the British Carboniferous. *Proceedings of the Yorkshire Geological Society* **43**, 473-482.

RAMSBOTTOM, W. H. C. & MITCHELL, M. 1980. The recognition of the Tournaisian Series in Britain. *Journal of the Geological Society* (London) **137**, 61-63.

RIDD, M. F., WALKER, D. B. & JONES, J. M. 1970. A deep borehole at Harton on the margin of the Northumberland Trough. *Proceedings of the Yorkshire Geological Society* **38**, 75-103.

RILEY, N. J. 1982. *Early Viséan trilobite and ammonoid faunas in the western part of the Craven Basin*. Unpublished Ph.D. thesis, University of Bristol.

ROGERS, D. E. 1983. *Seismic studies on the Derbyshire Dome*. Unpublished Ph.D. thesis, University of Leeds.

ROSENDAHL, B. R., REYNOLDS, D. J., LORBER, P. M., BURGESS, C. F., MCGILL, J., SCOTT, D., LAMBIASE, J. J. & DERKSEN, S. J. 1986. Structural expressions of rifting: lessons from Lake Tanganyika, Africa. Pp. 29-44 in FROSTICK, L. E., RENTANT, R. W., REID, I. & TIERCELIN, J. J. (editors) *Sedimentation in the African Rifts*. Geological Society of London Special Publication **25**.

ROSE, W. C. C., & DUNHAM, SIR K. C. 1977. *Geology and hematite deposits of South Cumbria*. Economic Memoir Geological Survey of Great Britain.

RUSSELL, M. J. 1971. North-south geofractures in Scotland and Ireland. *Scottish Journal of Geology* **8**, 75-84.

RUSSELL, M. J. 1976. A possible lower Permian age for the onset of ocean floor spreading in the northern North Atlantic. *Scottish Journal of Geology* **13**, 315-323.

SCHOFIELD, K. & ADAMS, A. E. 1985. Stratigraphy and depositonal environments of the Woo Dale Limestone Formation (Dinantian), Derbyshire. *Proceedings of the Yorkshire Geological Society* **45**, 225-233.

SMITH, E. G., RHYS, G. H. & EDEN, R. A. 1967. *Geology of the country around Chesterfield, Matlock and Mansfield*. Memoir of the Geological Survey of Great Britain.

SMITH, E. G., RHYS, G. H. & GOOSENS, R. F. 1973. *Geology of the country around East Retford, Worksop and Gainsborough*. Memoir of the Geological Survey of Great Britain.

SMITH, N. J. P. 1987. The deep geology of central England: the prospectivity of the Palaeozoic rocks. Pp. 217-224 in BROOKS, J. & GLENNIE, K. (editors) *Petroleum Geology of North West Europe*. Graham & Trotman, London.

SMITH, N. J. P., JACKSON, D. I., ARMSTRONG, E. J., MULHOLLAND, P., JONES, S., AULD, H. A., BULAT, J., SWALLOW, J. L., QUINN, M. F., OATES, N. K. & BENNETT, J. R. P. 1985. *Map 1. Pre-Permian Geology of the United Kingdom (South)*. British Geological Survey.

SOMERVILLE, I. D. 1979a. Minor sedimentary cyclicity in late Asbian (D_1) limestones east of the Llangollen district of North Wales. *Proceedings of the Yorkshire Geological Society* **42**, 317-341.

SOMERVILLE, I. 1979b. A cyclicity in the early Brigantian (D_2) limestones east of the Clwydian Range, North Wales and its use in correlation. *Geological Journal* **14**, 69-86.

SOMERVILLE, I. D., MITCHELL, M. & STRANK, A. R. E. 1986. An Arundian fauna from the Dyserth area, North Wales and its correlation within the British Isles. *Proceedings of the Yorkshire Geological Society* **46**, 57-75.

SOMERVILLE, I. D. & STRANK, A. R. E. 1984a. Discovery of Arundian and Holkerian faunas from a Dinantian platform succession in North Wales. *Geological Journal* **19**, 85-104.

SOMERVILLE, I. D. & STRANK, A. R. E. 1984b. The recognition of the Asbian/Brigantian boundary fauna and marker horizons in the Dinantian of North Wales. *Geological Journal* [illegible], 227-237.

[illegible] & WOODCOCK, N. H. 1987. Late [illegible] transpression in north-west [illegible]etry and geotectonic [illegible] *Yorkshire Geological*

STEVENSON, I. P. & GAUNT, G. D. 1971. *Geology of the country around Chapel en le Frith*. Memoir of the Geological Survey of Great Britain.

STRANK, A. R. E. 1985. The Dinantian biostratigraphy of a deep borehole near Eyam, Derbyshire. *Geological Journal* **20**, 227-237.

STRANK, A. R. E. 1986. Foraminiferal biostratigraphy of the Woo Dale Borehole, Derbyshire and the age of the Dinantian-Basement unconformity. *Journal of Micropalaeontology* **5**, 1-4.

STRANK, A. R. E. 1987. The stratigraphy and structure of Dinantian strata in the East Midlands, U.K. Pp. 157-175 in MILLER, J., ADAMS, A. E. & WRIGHT, V. P. (1987) q.v.

SURLYK, F. 1977. Mesozoic faulting in East Greenland. Pp. 311-327 in FROST, R. T. C. & DIKKERS, A. J. (editors) *Fault tectonics in NW Europe*. Geologie en Mijnbouw **56**.

TIDDEMAN, R. H. 1889. On concurrent faulting and deposition in Carboniferous times in Craven, Yorkshire, with a note on Carboniferous reefs. *Report British Association for the Advancement of Science, Newcastle* 600-603.

TROTTER, F. M. & HOLLINGWORTH, S. E. 1932. *The geology of the Brampton district*. Memoir of the Geological Survey of Great Britain.

TURNER, J. S. 1949. The deeper structure of central and northern England. *Proceedings of the Yorkshire Geological Society* **27**, 280-297.

TURNER, P., METCALFE, I. & TARLING, D. H. 1979. Palaeomagnetic studies of some Dinantian limestones from the Craven Basin and a contribution to Asbian magnetostratigraphy. *Proceedings of the Yorkshire Geological Society* **42**, 371-396.

VAUGHAN, R. D. & ADAMS, A. E. 1984. Chadian and Arundian sedimentation in the Furness and Millom areas, South Cumbria. *European Dinantian Enviroments 1st Meeting 1984. Abstracts. Open University*. Pp. 120-123.

WALKDEN, G. M. 1974. Palaeokarstic surfaces in the Upper Viséan (Carboniferous) limestones of the Derbyshire Block, England. *Journal of Sedimentary Petrology* **44**, 1232-1247.

WALKDEN, G. M. 1977. Volcanic and erosive events on an Upper Viséan carbonate platform, north Derbyshire. *Proceedings of the Yorkshire Geological Society* **41**, 347-366.

WALKDEN, G. M. 1982. *Field guide to the Lower Carboniferous rocks of the south east margin of the Derbyshire Block: Wirksworth to Grangemill*. Publication of the Department of Geology and Mineralogy, University of Aberdeen.

WALKDEN, G. M. 1987. Sedimentary and diagenetic styles in late Dinantian carbonates of Britain. Pp. 131-155 in MILLER, J., ADAMS, A. E. & WRIGHT, V. P. (1987) q.v.

WALKDEN, G. M. & DAVIES, J. 1983. Polyphase erosion of subaerial omission surfaces in the late Dinantian of Anglesey, North Wales. *Sedimentology* **30**, 861-878.

WALTERS, S. G. & INESON, P. R. 1981. A review of the distribution and correlation of igneous rocks in Derbyshire, England. *Mercian Geologist* **8**, 81-132.

WARREN, P. T., PRICE, D., NUTT, M. J. C. & SMITH, E. G. 1984. *Geology of the country around Rhyl and Denbigh*. Memoir of the British Geological Survey.

WEAVER, J. D. & STANLEY, M. F. 1977. Exposures of the Widmerpool Formation (Dinantian) in South Derbyshire. *Mercian Geologist* **6**, 103-117.

WHITCOMBE, D. N. & MAGUIRE, P. K. H. 1981. Seismic refraction evidence for a basement ridge between the Derbyshire Dome and Charnwood Forest. *Journal of the Geological Society* (London) **138**, 653-659.

WILLIAMS, E. A., BAMFORD, M. K. F., COOPER, M. A., EDWARDS, H. E., FORD, M., GRANT, G. G., MACCARTHY, I. A. J., MCAFEE, A. M. & O'SULLIVAN, M. J. this volume. Tectonic controls and sedimentary response in the Devonian-Carboniferous Munster Basin, south-west Ireland.

WILLS, L. J. 1973. *A palaeogeographic map of the Palaeozoic floor beneath the Permian and Mesozoic formations in England and Wales*. Memoir of the Geological Society of London **7**.

WILLS, L. J. 1978. *A palaeogeographic map of the Lower Palaeozoic floor below the cover of Upper Devonian, Carboniferous and later formations*. Memoir of the Geological Society of London **8**.

WILSON, A. A. & CORNWELL, J. D. 1982. The Institute of Geological Sciences borehole at Beckermonds Scar, North Yorkshire. *Proceedings of the Yorkshire Geological Society* **44**, 59-88.

WOODCOCK, N. H. 1984. The Pontesford Lineament. *Journal of the Geological Society* (London) **141**, 1001-1014.

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