9 Carboniferous: extensional basins, advancing deltas and coal swamps

C. N. WATERS & S. J. DAVIES

The structural evolution of England and Wales during the Carboniferous was primarily a consequence of an oblique (dextral) collision between Gondwana and Laurussia (Warr 2000). Several phases can be recognized. The Rhenohercynian Ocean opened during Early–Mid Devonian regional back-arc transtension between Avalonia and Armorica (Fig. 9.1), possibly associated with northward-directed subduction along the southern margin of Armorica. A narrow seaway floored by oceanic crust developed, extending across southwest England, northern France and Germany. Cessation of the subduction, associated with the Ligerian orogenic phase of central Europe, resulted from the collision of the Iberian and Armorican microplates (Fig. 9.1). During the Late Devonian, transpressive closure of this restricted ocean, associated with the Bretonian orogenic phase, may have occurred in response to short-lived southward-directed subduction of the Rhenohercynian oceanic plate beneath Armorica.

A return to northward-directed subduction of the Theic oceanic plate along the southern margin of Iberia/Armorica (Fig. 9.1) resulted in a Late Devonian–Early Carboniferous phase of back-arc extension within the Avalonian part of the Laurussian plate (Warr 2000). The resultant N–S rifting affected all of central and northern England and North Wales, initiating development of a series of graben and half-grabens, separated by platforms and tilt-block highs (Leeder 1982, 1988). The orientations of the bounding faults, and hence of the basins, was inherited from structures within the pre-Carboniferous basement (Fraser *et al.* 1990; Fraser & Gawthorpe 2003). Principal amongst the basement areas is the Midlands Microcraton, a triangular terrane of Neoproterozoic rocks overlain by relatively undeformed early Palaeozoic strata.

Northern England, north of the Craven Fault System (Fig. 9.2a) comprises a 'Block and Basin' province dominated by the Northumberland Trough-Solway Basin and Stainmore Trough, and by the Alston and Askrigg blocks (Figs 9.2 & 9.3), persistent fault-bound highs associated with buoyant late Caledonian granites. To the west, the volcanic remnants of the Caledonian Orogeny persisted as the Lake District High during the Dinantian. The Southern Uplands High and its offshore continuation into the Mid North Sea High, broadly separated the Northumberland Trough–Solway Basin from the Midland Valley of Scotland. The barrier was breached by a series of narrow NNW-trending basins. At various times the basins may have been connected during sea-level highstands or possibly via through-drainage during periods of low sea level.

To the south of the Craven Fault System, the generally high subsidence rates created a province dominated by basinal facies. A series of half-grabens, including the Gainsborough Trough and Widmerpool Gulf of the East Midlands (Fig. 9.4), the Craven Basin of Lancashire and Harrogate Basin of Yorkshire, formed connected narrow embayments. The intervening platforms include the linked East Midlands Shelf and Derbyshire High, the Holme High, Hathern Shelf and the North Wales Shelf (Fig. 9.2). These platform areas represent the northern margin of the Wales–Brabant High, which formed a persistent topographical feature throughout the Carboniferous.

Along the southern margin of the Wales–Brabant High there is a gradual change southward from a shelf in the South Wales and Bristol region into a deep marine back-arc seaway of the Culm Basin of Cornwall and Devon (Fig. 9.2), that developed from the Late Devonian to Silesian times (see Chapter 10).

By late Dinantian time the magnitude of regional N–S extension had greatly reduced. The positive thermal anomaly generated in the lithosphere during the main phase of extension gradually decayed with time and thermal relaxation subsidence became the dominant structural control on basin evolution in England and Wales during the late Carboniferous (Leeder 1988). The Pennine Basin evolved through Namurian and Westphalian times as a broad region of subsidence between the Southern Uplands and Wales–Brabant High, with a depocentre from south Lancashire to north Staffordshire. The thermal subsidence co-existed with small-scale, pulsatory phases of localized extension and compression, which reactivated basement lineaments (Waters *et al.* 1994).

Closure of the Theic Ocean and initial collision of Gondwana and Iberia/Armorica during the Late Carboniferous (Fig. 9.1) resulted in the Sudetian orogenic phase of crustal thickening, with foreland basin development along the northern margin of the orogenic belt, including SW England and South Wales (Warr 2000). The end Carboniferous late collisional stages, the Asturian orogenic phase, is associated with the northward advance of the Variscan thrust-fold belt into the foreland basin.

The Wales–Brabant High appears to have formed a buttress that prevented further propagation of the NNW-directed thrusting that affected southern England and South Wales (see Chapter 10). During the late Carboniferous Variscan crustal compression culminated in the regional uplift of the Pennine Basin, and erosion of the basin fill formed a major angular unconformity beneath Permo-Triassic deposits. The Variscan compression appears to have reactivated the major basement structures, resulting in the wide range of Variscan structural orientations (Fig. 9.5) and Dinantian basin-bounding normal faults became partially inverted as reverse or obliquely reverse faults. Typically, the faults maintain net normal displacements at depth, whereas, at higher structural levels, local reverse faults, anticlines and monoclines developed. In northern England a deformation phase, prior to Stephanian intrusion

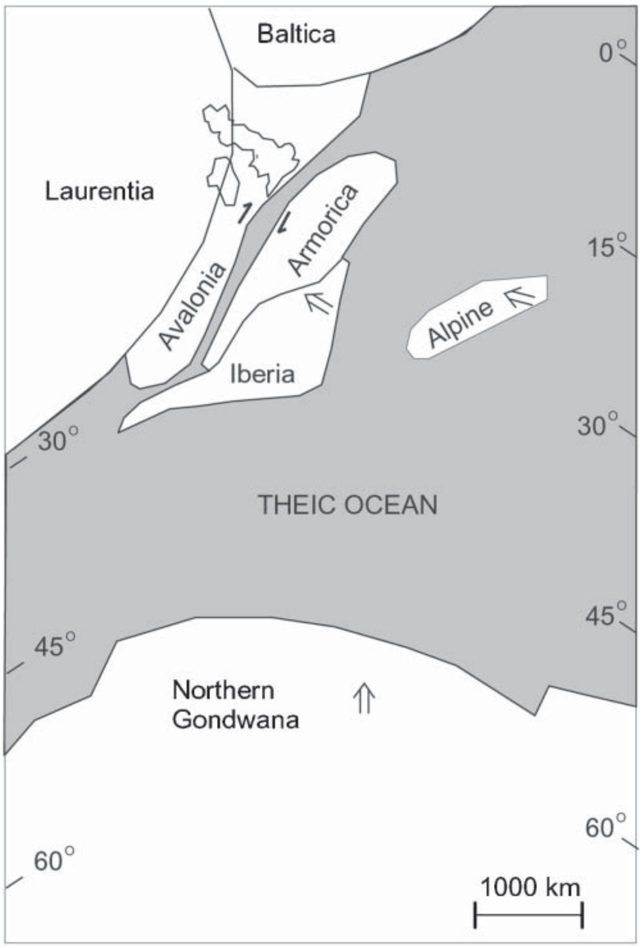

Fig. 9.1. Plate tectonic model for the Mid to Late Devonian (Warr 2000).

of the Whin dykes, resulted in N-trending anticlines and ENE-trending dextral wrench faults in the Northumberland Trough and thrusts along the western margin of the Alston block (Critchley 1984). Intrusion of the Whin Sill is associated with a phase of uplift of the Alston Block and development of conjugate ENE and NNW normal faults, with the former fault set associated with the principal ore veins in the region. Following intrusion of the Whin Sill, a subsequent phase of east–west early Permian compression resulted in the formation of ESE-trending mineral veins associated with sinistral strike-slip movements (Critchley 1984). North-trending structures include the reverse Dent Fault, forming the western margin of the Askrigg Block, and the Pennine Line, a west-verging asymmetrical anticline (Fig. 9.5). Inversion of the Dinantian Craven Basin resulted in the development of ENE-trending anticlines of the Ribblesdale Fold Belt and reactivation of the bounding Pendle Fault to form the Pendle Monocline (Fig. 9.5). The Edale Basin, Widmerpool Gulf, Gainsborough Trough and East Midlands Shelf are associated with NW-trending anticlines and monoclines, which developed in response to reverse reactivation of smaller intra-basinal faults (Aitkenhead *et al.* 2002). In the West Midlands Variscan deformation is associated with east–west compression, reactivation of basement lineaments and development of local unconformities ranging from Bolsovian to Permian age (Waters *et al.* 1994).

Climate

Palaeomagnetic evidence suggests that Britain was situated in near equatorial latitudes in Dinantian times (Scotese & McKerrow 1990). Tournaisian terrestrial strata, laid down in small isolated basins across northern and central England and North Wales, contain calcareous and dolomitic pedogenic horizons ('cornstones'), suggesting a semi-arid climate (Wright 1990). In the Northumberland Trough interbedded mudstone, sandstone and dolostone ('cementstone') developed on marginal marine flats that were subject to periodic desiccation and fluctuating salinity. The early Viséan climate was probably semi-arid with seasonal, possibly monsoonal wetting (Fig. 9.6). Evidence includes growth rings in fossil wood (Falcon-Lang 1999) and the development of arid phase mature calcrete palaeosols, with intermittent development of humid phase palaeokarsts and leached vertisols (Wright 1990). Worldwide facies distributions indicate that during the late Viséan Britain occupied an arid climatic zone present to the south of a humid equatorial belt (Witzke 1990). The regular superposition of calcretes and palaeokarsts can be interpreted as a probable cyclical fluctuation from semi-arid to humid conditions during Asbian and Brigantian times (Wright & Vanstone 2001).

During the Silesian, the British part of Laurentia lay within humid equatorial latitudes (Scotese & McKerrow 1990; Witzke 1990). By late Dinantian times the pole-to-equator temperature gradient began to increase (Raymond *et al.* 1989) and large ice sheets extended across Gondwana in the later Carboniferous. Intense glaciations may have brought about short-term seasonally drier climates, whereas ice melting resulted in sea-level rises and a potentially wetter equatorial climate (Fig. 9.6). During the late Westphalian and Stephanian increasingly arid conditions developed across Laurussia. Initially, Bolsovian primary red-bed facies developed on the flanks of the Wales–Brabant High in response to a lowering of water tables due to tectonic uplift or sediment aggradation, rather than as a consequence of increased aridity (Besly 1988*b*). Subsequent Westphalian D and Stephanian red-beds contain calcretes, evidence for a semi-arid climate. The increasing aridity may reflect a rain-shadow developed to the NW of the evolving Variscan mountain belt (Leeder 1988).

Global eustasy and sediment cyclicity

The Carboniferous was a period of glacial eustasy and therefore sea-level fluctuations were likely to have played a significant role in the development of sedimentary successions. Geographically widespread marine bands have long been accepted as the products of glacio-eustatic transgressions (Ramsbottom 1973).

Significant land-ice probably began to develop during the Dinantian. The Tournaisian–Viséan boundary is marked by a major hiatus in the Bristol area (Fig. 9.6) inferred to represent a large and rapid sea-level fall (Holdsworth & Collinson 1988; Martinsen 1990). Evidence from stable isotope analyses of brachiopods suggests a late Tournaisian phase of glacial activity (Bruckschen & Veizer 1997). Sea-level fall in late Chadian–Arundian times (Fig. 9.6) is suggested by the development of marked non-sequences within the platform carbonates of northern England, Derbyshire High, North Wales and South Wales. This was followed by a phase of late Arundian–Holkerian marine transgression (Ramsbottom 1973).

The onset of the main phase of glaciation began in the early Namurian and peaked in the late Westphalian and Stephanian (Gonzalez-Bonorino & Eyles 1995). At the peak, an ice sheet of approximately the same dimensions as the Pleistocene ice sheet is thought to have developed across large areas of the Gondwanan supercontinent (Caputo & Crowell 1985; Veevers & Powell 1987; Crowley & Baum 1991).

As in the Quaternary (Morton & Suter 1996), Carboniferous ice sheets are believed to have accumulated slowly, but wasted rapidly, producing an asymmetric sea-level curve (Church & Gawthorpe 1994; Brettle 2001). High-magnitude, high-frequency glacio-eustatic sea-level change is considered to be an important characteristic of the Carboniferous (Hampson *et al.* 1997). Wright & Vanstone (2001) use Asbian–early

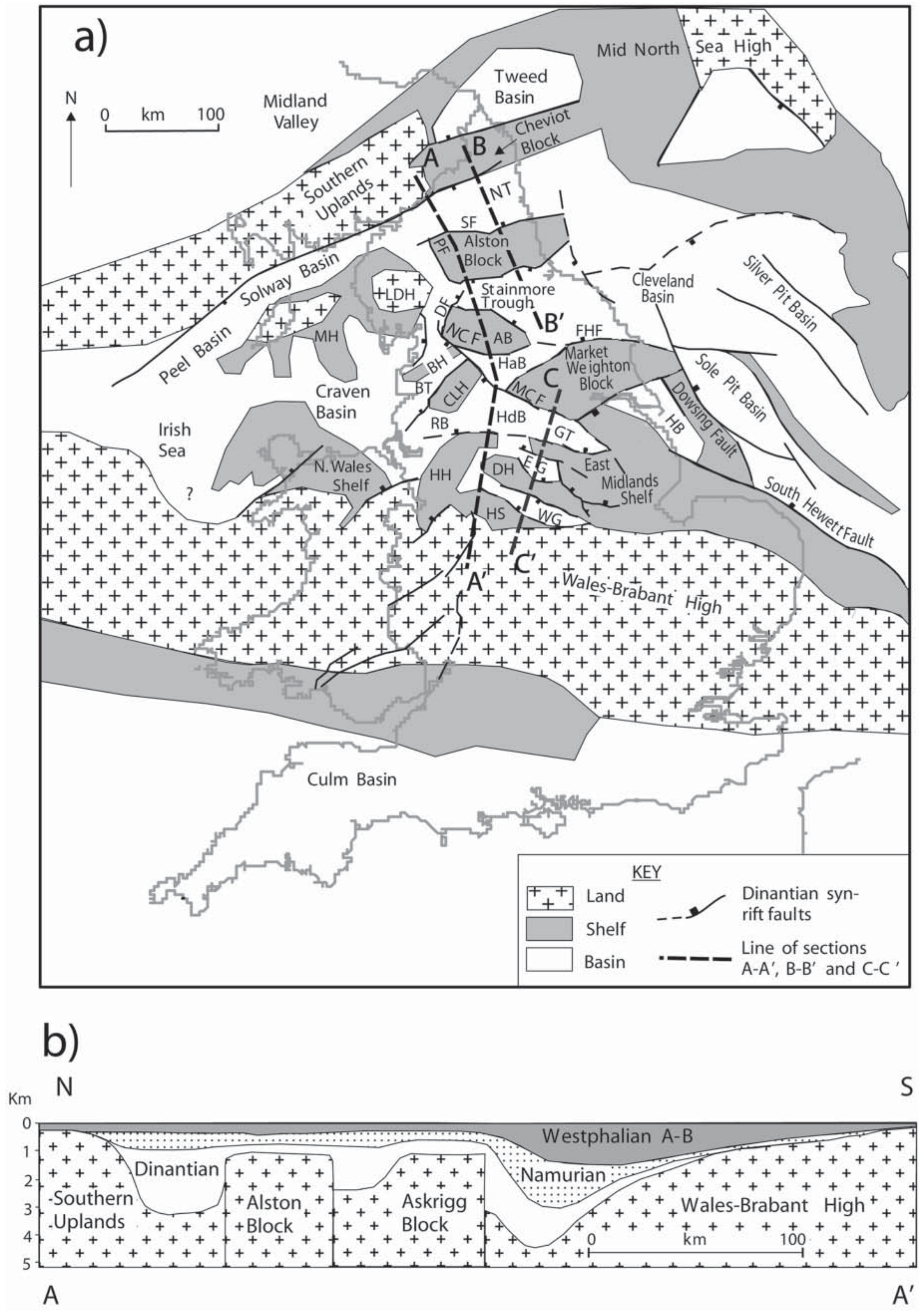

Fig. 9.2. (**a**) Dinantian palaeogeography of England and Wales showing the main tectonic features, including extensional basins and platforms (Waters *et al.* In press). Location of cross-sections: A–A’ (Fig. 9.2b), B–B’ (Fig. 9.3) and C–C’ (Fig. 9.4). AB, Askrigg Block; BH, Bowland High; BT, Bowland Trough; CLH, Central Lancashire High; DF, Dent Fault; DH, Derbyshire High; EG, Edale Gulf; FHF, Flamborough Head Fault; GT, Gainsborough Trough; HaB, Harrogate Basin; HdB, Huddersfield Basin; HB, Humber Basin; HH, Holme High and Heywood High; HS, Hathern Shelf; LDH, Lake District High; MCF, Morley–Campsall Fault; MH, Manx High; NCF, North Craven Fault; NT, Northumberland Trough; PF, Pennine Fault; RB, Rossendale Basin; SF, Stublick Fault; WG, Widmerpool Gulf. (**b**) Schematic cross-section of the Pennine Province showing the change from several Dinantian ‘rift’ basins to a single Westphalian ‘sag’ basin (after Leeder 1982).

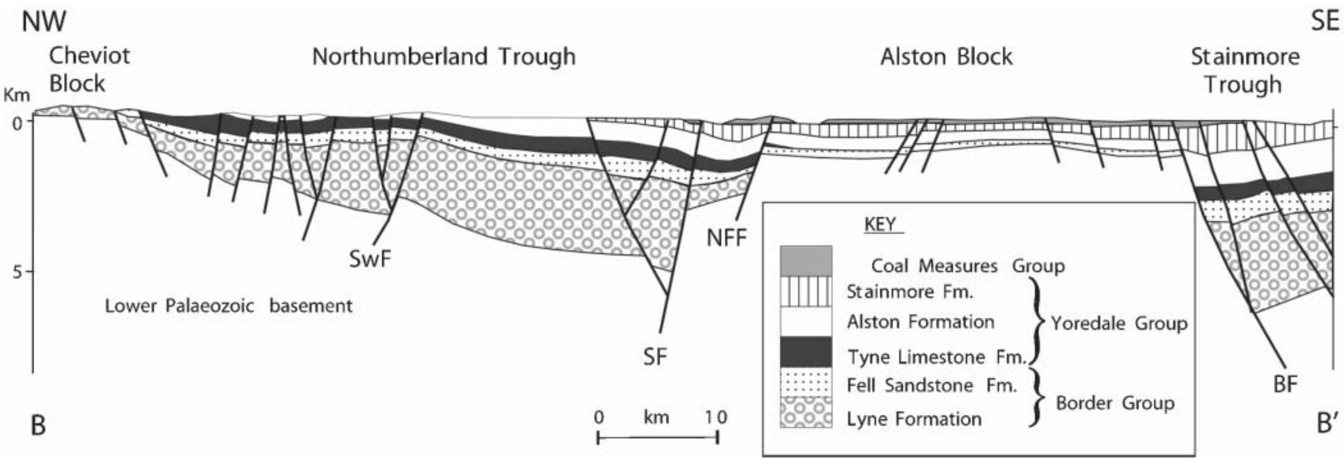

Fig. 9.3. Cross-section showing the Carboniferous infill of the Northumberland and Stainmore troughs, separated by the Alston Block (after Chadwick *et al.* 1995). Line of section is shown in Fig. 9.2a. BF, Butterknowle Fault; NFF, Ninety Fathom Fault; SF, Stublick Fault; SwF, Sweethope Fault.

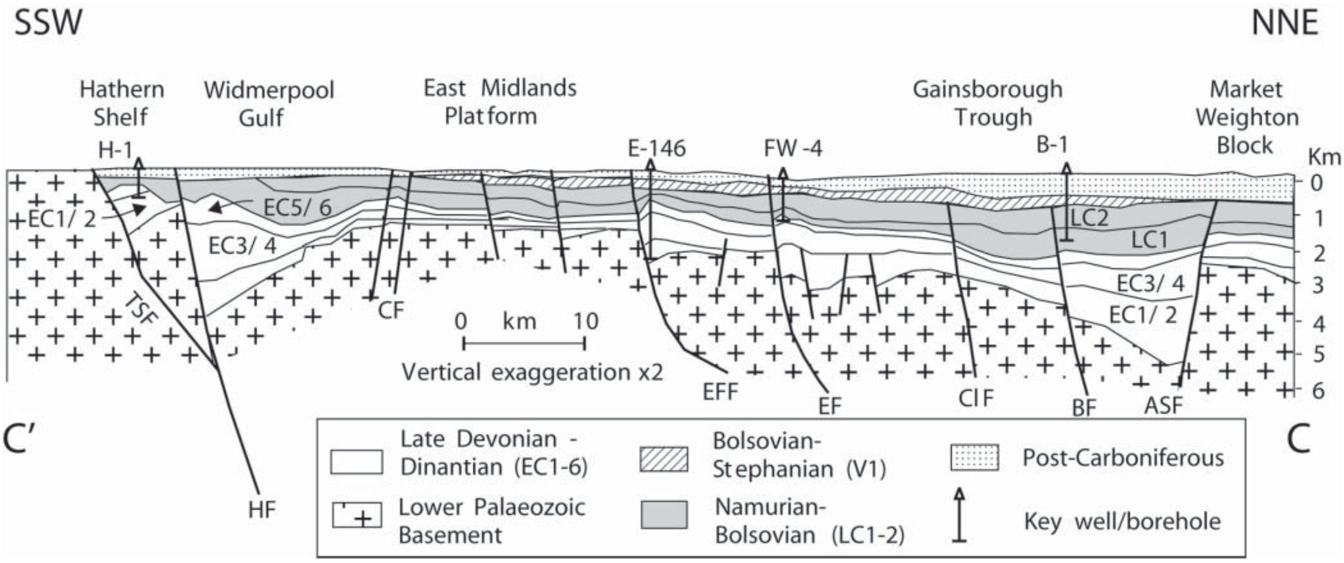

Fig. 9.4. Cross-section of the East Midlands showing the increased thickness of Carboniferous strata within the half-graben of the Widmerpool Gulf and Gainborough Trough (after Fraser *et al.* 1990). Line of section is shown in Figure 9.2a. Seismic sequences from Fraser *et al.* (1990) are summarized in Figure 9.10. ASF, Askern–Spittal Fault; BF, Beckingham Fault; CF, Cinderhill Fault; ClF, Clarborough Fault; EF, Egmanton Fault; EFF, Eakring–Foston Fault; HF, Hoton Fault; TSF, Thringstone–Sileby Fault. Boreholes and wells: B-1, Beckingham No.1; E-146, Eakring No. 146; FW-4, Farleys Wood No. 4; H-1, Hathern No. 1.

Brigantian cycles to estimate sea-level fluctuations in the order of 10–50 m, reaching up to 95 m by late Brigantian times. The magnitude of Silesian sea-level fluctuations has been estimated as 60 ± 15 m (Church & Gawthorpe 1994). Power spectral analysis estimates of marine band periodicities for Kinderscoutian–Duckmantian strata of 120 ka (Maynard & Leeder 1992) are based on a time duration of 8 ± 3.2 Ma. With 60 marine bands recognized from Namurian strata (Holdsworth & Collinson 1988; Martinsen 1990) and the average duration of the Namurian of 6 Ma (Claoué-Long *et al.* 1995), marine band periodicity may have been as short as 65 ka (Riley *et al.* 1995).

Igneous activity

Carboniferous and Permian igneous rocks, north of the Variscan Front, are described fully by Stephenson *et al.* (2003). Carboniferous intrusive and extrusive igneous rocks crop out in a number of relatively small and isolated centres in the Northumberland Trough, Solway Basin and Tweed Basin in northern England, the Derbyshire Peak District, the Black Country of the West Midlands, the Welsh Borderlands and the Bristol/Gloucester areas (Fig. 9.7). Boreholes for oil and coal exploration in the East Midlands (see Fig. 9.4), Oxfordshire and Berkshire have proved additional Carboniferous igneous rocks at depth. All the igneous rocks are basic and interpreted as within-plate activity on the Laurussian continent, produced in response to lithospheric thinning during back-arc extension (Leeder 1982). The nature of the igneous activity evolved in response to changes in tectonic processes and can be broadly subdivided into events of Dinantian and Silesian age (Fig. 9.7). Tournaisian and Viséan lavas in the Solway and Tweed basins and Northumberland Trough and the late Viséan lavas and sills of Derbyshire are tholeiitic. Tournaisian and Viséan lavas in southern England are typically alkaline.

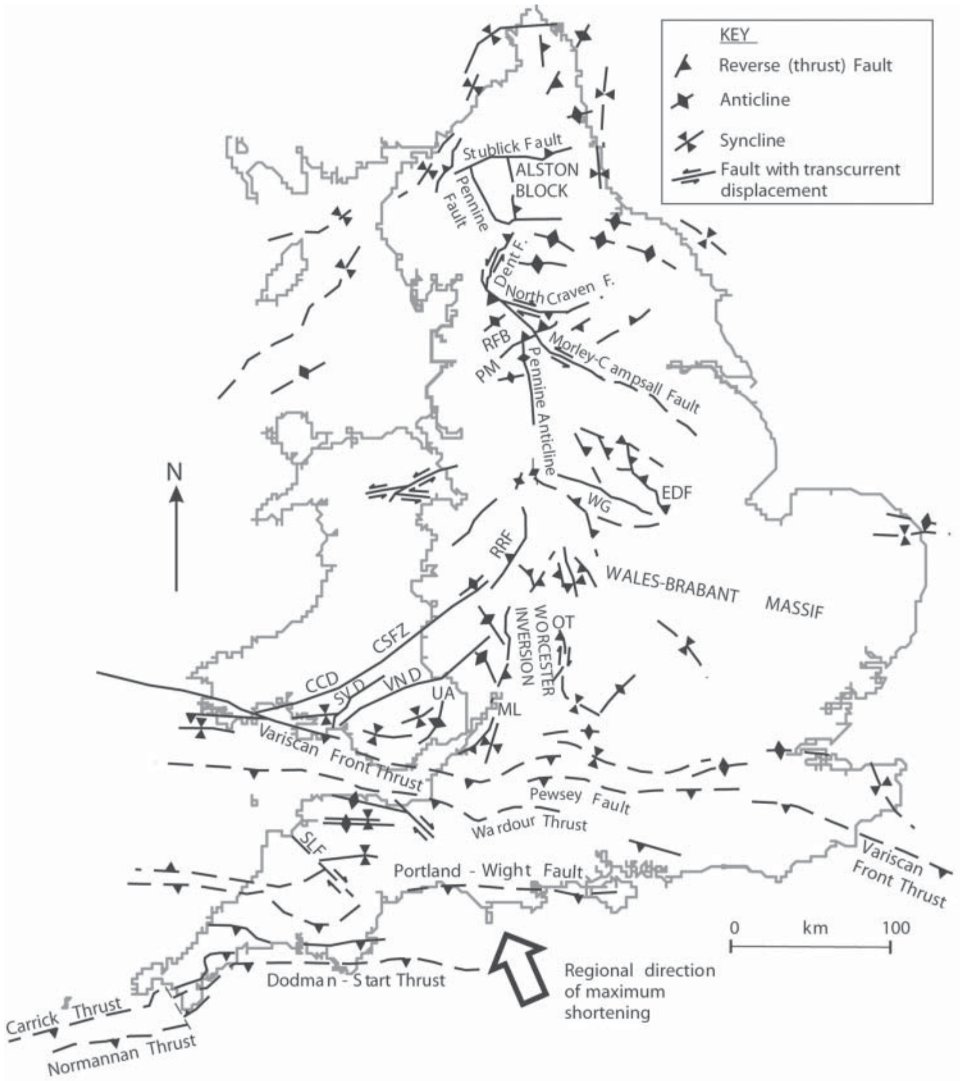

Fig. 9.5. Map showing the main late Carboniferous inversion structures associated with Variscan compression. CCD, Carreg Cennen Disturbance; CSFZ, Church Stretton Fault Zone; EDF, Eakring-Denton Fault; ML, Malvern Lineament; OT, Oxfordshire Thrust; PM, Pendle Monocline; RFB, Ribblesdale Fold Belt; RRF, Red Rock Fault; SLF, Sticklepath–Lustleigh Fault; SVD, Swansea Valley Disturbance; UA, Usk Anticline; VND, Vale of Neath Disturbance; WG, Widmerpool Gulf.

The Namurian appears to be a time of relatively little igneous activity in England and Wales, limited to thin bentonite horizons interpreted as altered vitric tuff deposits sourced from volcanic activity within the Variscan destructive plate margin (Spears *et al.* 1999). A resurgence in activity during the Westphalian and Stephanian is mainly associated with alkaline sills and dykes in central and southern England, although some tholeiitic lavas also occur in the Westphalian of the East Midlands. In NE England, widespread intrusion of tholeiitic magmas as dykes and sills, such as the Whin Sill (Plate 19) occurred during the Stephanian. The products of all these events show a typical lack of differentiation in comparison with their Scottish equivalents, probably because only small volumes of magma were produced and the eruptive activity was short-lived (Francis 1970). Thin tonsteins, kaolinite mudstones formed from the alteration of volcanic ash, are common within the Westphalian strata of England and Wales. Two types of tonstein have been recognized, one formed from basaltic ash of local origin and the other from rhyolite or rhyodacite ash of distant origin, possibly from the Variscan destructive plate margin (Spears & Lyons 1995).

Carboniferous and Permian igneous rocks, south of the Variscan Front, are described fully by Floyd *et al.* (1993*a*). These include Dinantian–Permian alkali-basalt lavas and pyroclastic rocks and the calc-alkaline granite batholith of SW England, which was intruded during late Carboniferous–early Permian times (Chapter 11). These represent magmatism generated in response to the northward subduction of the Rheic oceanic plate (Upton 1982).

Mineral resources

The thick limestones of the Carboniferous Limestone Supergroup are of great importance in the construction industry, being used as building stones and in cement and crushed rock aggregate manufacture. In the iron and steel industry limestone is used as a flux and dolostone as a refractory during smelting. Limestone has a wide range of uses in the chemical industry, glass manufacture and as an agricultural fertilizer. The use of limestone in power station flue gas control has become increasingly important. The main limestones of the Yoredale Group are typically thinner, and their quality is somewhat

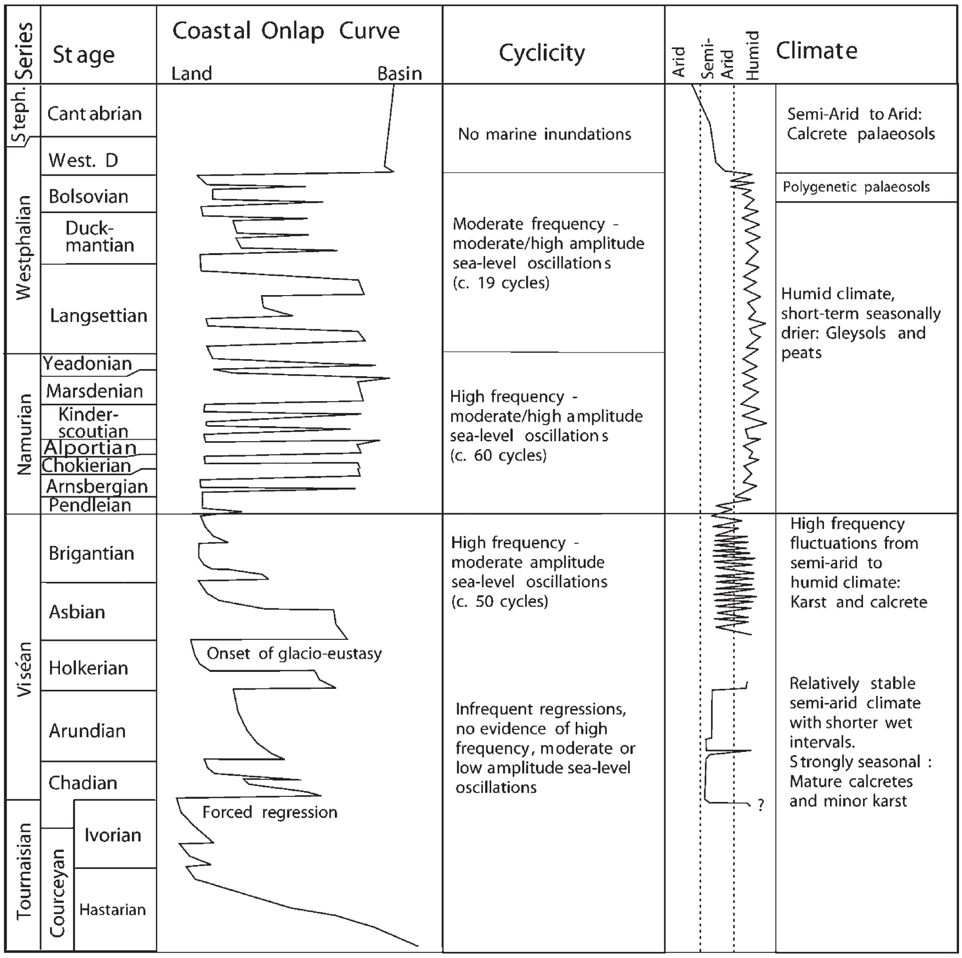

Fig. 9.6. Carboniferous sea-level and climatic record, for the Dinantian, after Wright & Vanstone (2001) and Silesian, after Ramsbottom (1977) and Ramsbottom *et al.* (1978).

reduced by the presence of clay and chert. Within this group the Great Limestone is quarried at numerous sites in County Durham and Northumberland for aggregates and cement.

The main Dinantian platform carbonates also play host to metalliferous veins, particularly lead and zinc, in the Peak District of Derbyshire, and the Askrigg and Alston Blocks of the northern Pennines. Calcite, fluorspar and barytes are commonly associated with this mineralization. Vein calcite and fluorspar are still worked at several sites within the Peak District. In the northern Pennines, barytes was extensively worked in the past and a small number of mines continue extraction in County Durham, Cumbria and Derbyshire. The metalliferous mineralization also occurs at several relatively impermeable intervals within the Yoredale Group and also in the lower part of the Millstone Grit Group of the Craven Basin. There has been a long history of mining these minerals, although current extraction is very limited in scale. In west and south Cumbria hematite is present as replacement mineral flats or cones (‘sops’) within the Great Scar Limestone Group. Formerly, these deposits sourced a significant iron and steel industry, but extraction is now reduced to a single mine.

Mudstones and shales of the Coal Measures and to a lesser extent of the Millstone Grit Group, are worked for bricks, tiles and ceramic building materials, although extraction has decreased over the past century. The Etruria Formation of the Warwickshire Group continues to be worked at numerous clay pits within the West Midlands and North Staffordshire for facing and engineering bricks and roofing and floor tiles.

Sandstones from the Coal Measures and Millstone Grit Group have historically been worked for building stone, although current demand is for specialized items such as monumental stone, paving flags and roof tiles. Within the Elland Flags of West Yorkshire the value of certain sandstone beds was sufficient to justify underground working, although such activities have now ceased. The working of sandstone for crushed aggregate and sand has become increasingly important and now represents the main bulk extraction industry in parts of the Pennines. In South Wales and Gloucestershire, sandstones of the Pennant Sandstone Formation continue to be extensively worked for building stone, roadstone and high specification aggregates.

The Coal Measures are rich in economic minerals and its presence was of utmost importance in the initiation of the industrial revolution in England and Wales. Many large industrial conurbations in northern and central England and South Wales owe their location to the close proximity of these strata. Coal seams have been extensively worked at depth in mines and at the surface as opencasts (Plate 15). Extraction continues, though at a much-reduced scale and relying increasingly on opencast operations. The thinner coal seams present within the Millstone Grit Group and Yoredale Group have also been worked, but on a much smaller scale. Fireclays are kaolinite-rich palaeosols, or seatearths, which were often extracted along with their overlying coal seams. Fireclays are used for production of refractory firebricks, pipes and sanitary ware, but modern extraction is on a much-reduced scale, with workings in Lower Coal Measures of Yorkshire, Leicestershire and Shropshire. Ganisters are

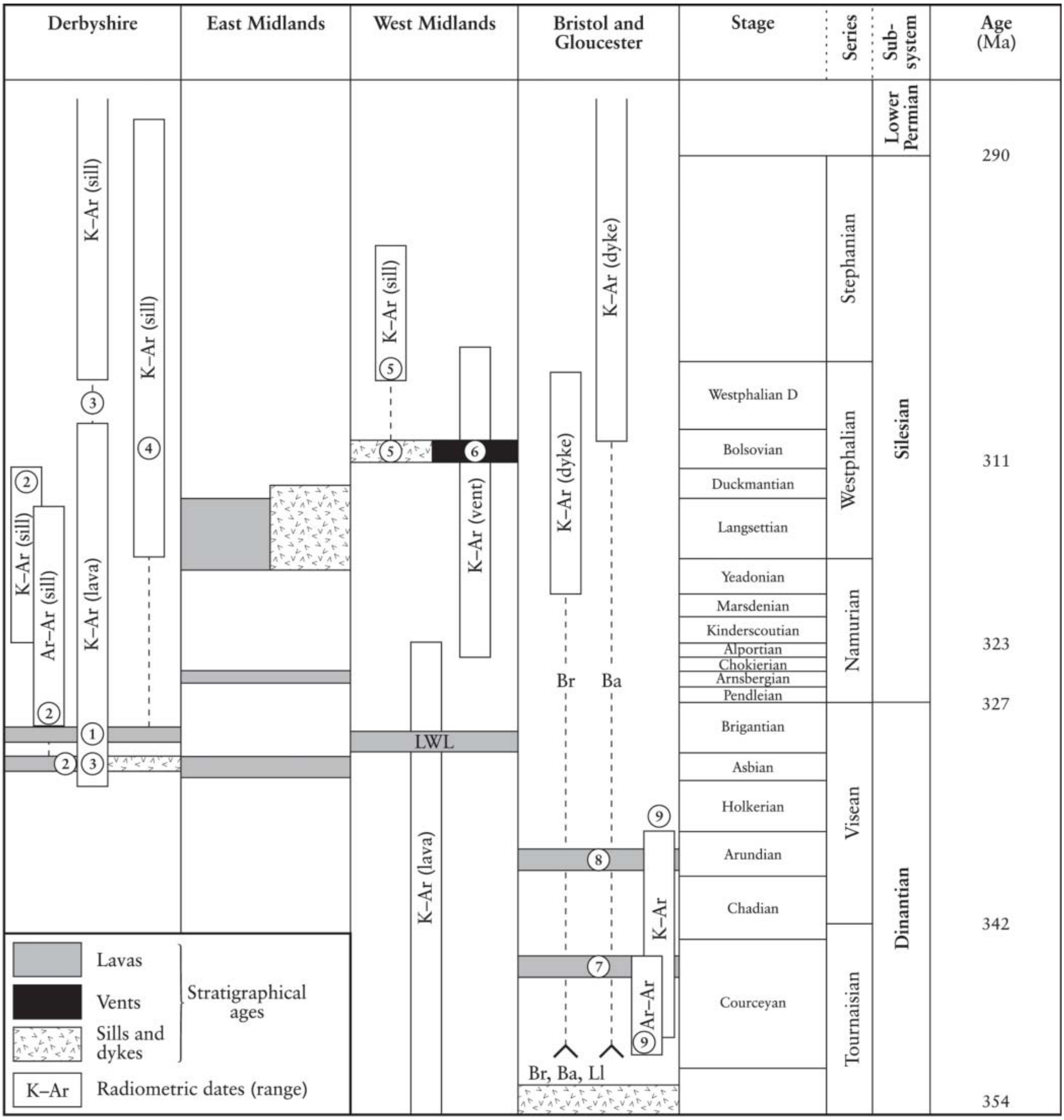

Fig. 9.7. Age and distribution of intrusive and extrusive igneous activity within central and southern England and Wales (excluding Cornwall and Devon) (from Waters 2003*a*, with permission from JNCC 2004). GCR sites: 1 – Litton Mill, 2 – Water Swallows, 3 – Tideswell Dale, 4 – Calton Hill, 5 – Clee Hills, 6 – Barrow Hill, 7 – Middle Hope, 8 – Spring Cove, 9 – Golden Hill. Ba, Bartestree Dyke; Br, Brockhill Dyke; Ll, Llanllywel Monchiquite Dyke; LWL, Little Wenlock Lavas. Timescale is that of Gradstein & Ogg (1996).

leached siliceous palaeosols, principally worked for silica bricks and furnace linings for the iron and steel industry. The main worked ganisters have historically been extracted in the Pennines from the lower part of the Lower Coal Measures, also often in association with fireclays. Ironstones were locally worked and sourced early iron and steel industries, notably in South Wales and Yorkshire. However, Coal Measures ironstones are of no importance today due to their thin and laterally impersistent nature and relatively poor quality, with the ironstones typically containing only 30% metallic iron.

Hydrocarbon production from the Carboniferous of onshore northern England commenced in the 1920s and continues in a number of small fields. Natural gas is extracted in Yorkshire and Lincolnshire from thick Coal Measures and Millstone Grit sandstone reservoirs, including the Oaks Rock, Rough Rock and Chatsworth Grit. Oil is primarily extracted in Lincolnshire and Nottinghamshire, mainly from the Mexborough Rock, Crawshaw Sandstone, Rough Rock and Chatsworth Grit. The main hydrocarbon source is the late Dinantian and early Namurian mudstone of the Bowland Shale Formation,

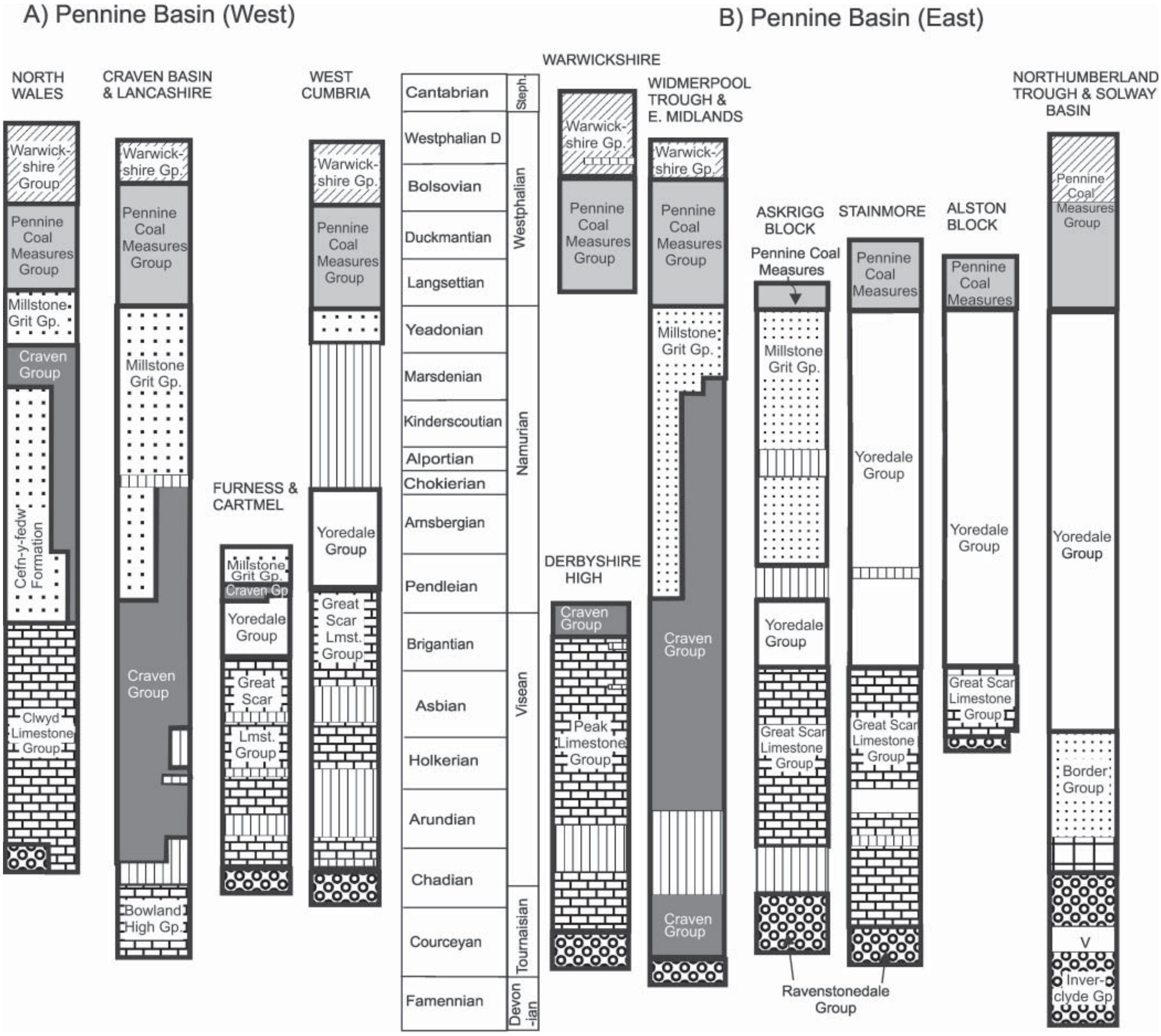

Fig. 9.8. Group lithostratigraphical framework for the Carboniferous of: (**A**) Western part of the Pennine Basin, from west Cumbria to North Wales; (**B**) Eastern part of the Pennine Basin, from Northumberland to the East Midlands; (**C**) South Wales and southern England, with relationships to lithofacies. Adapted from Waters *et al.* (2006*a*).

which has its thickest development in the East Midlands, notably in the Gainsborough Trough (Fig. 9.4). Closer to the Pennine Basin depocentre, the deep burial of source rocks and maturation prior to Variscan structural trap development severely limits oil potential in Lancashire, Yorkshire and North Staffordshire (Fraser *et al.* 1990).

Igneous rocks have been worked locally for roadstone and high specification aggregate, mainly within Dinantian lavas and sills of the Peak District and the Westphalian sills of the West Midlands.

Water resources

Carboniferous rocks are classified as minor aquifers, comprising a heterogeneous multilayered aquifer system (Jones *et al.* 2000). Sandstones and limestones typically form aquifers, whereas argillaceous strata mainly form aquitards or aquicludes. Carboniferous strata typically lack significant intergranular permeability. Groundwater movement occurs mainly through joints and fractures, which tend to be prevalent within sandstone and limestone beds. Dissolution within the thick platform carbonates of the Carboniferous Limestone Supergroup can result in open joints and cave systems along which groundwater flow rates are high. The prevalence of faulting and the lateral impersistence of sandstones, notably in the Coal Measures, affect the interconnectivity of aquifers and can significantly reduce yields, but fracturing associated with mining subsidence has enhanced groundwater flows in some areas of Coal Measures and overlying Warwickshire Group. Groundwater extraction from the Carboniferous aquifers is largely by industrial users, although this is in decline, resulting in the phenomenon of rising water tables in many of the industrial coalfield areas. Coal Measures aquifers tend to have non-potable groundwater, with poor water quality due to acid mine drainage and other anthropogenic contamination.

Stratigraphical framework

The economic importance of strata of Carboniferous age has resulted in over 200 years of research, and in numerous

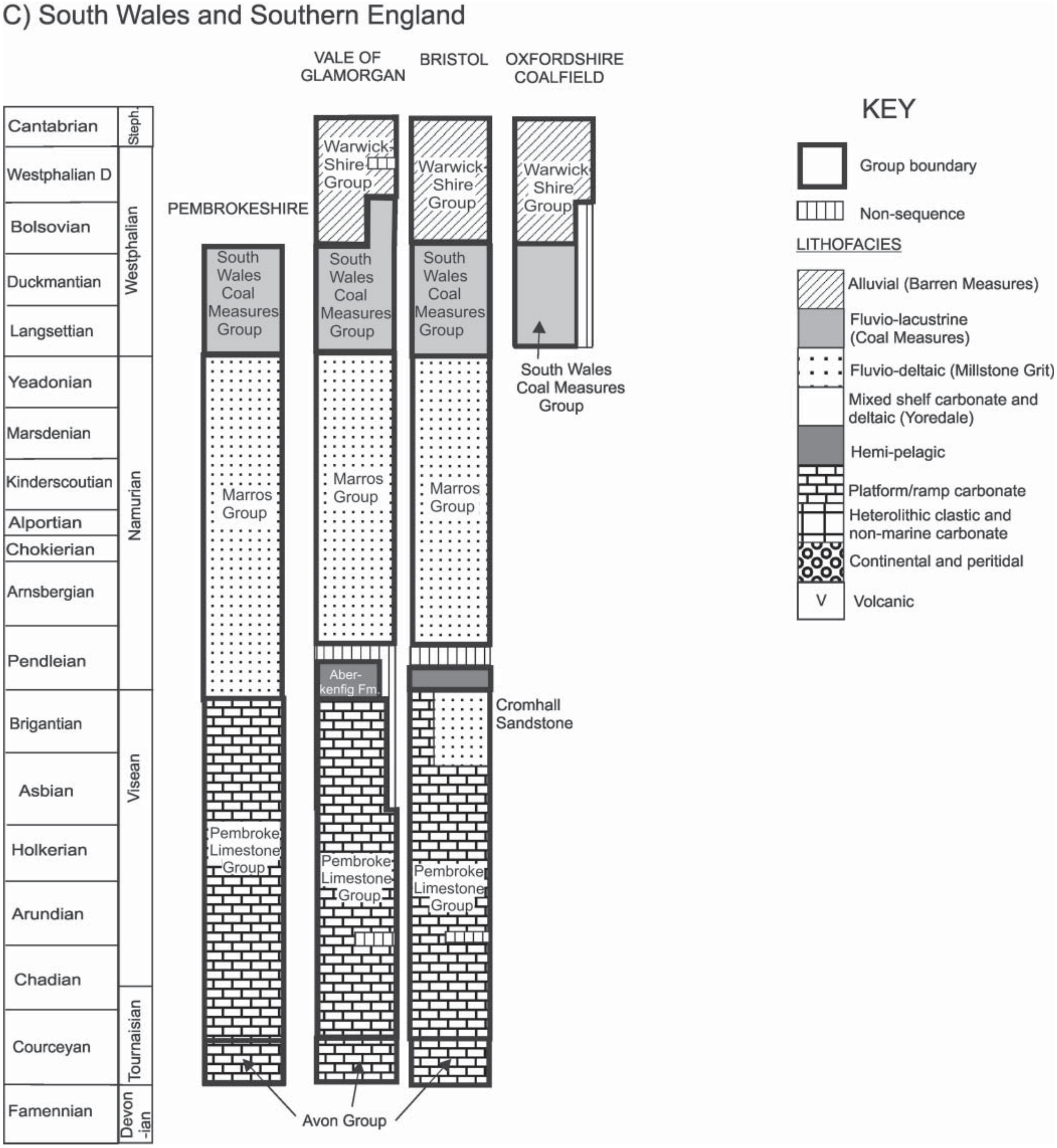

Fig. 9.8. Continued.

attempts to classify them. Much of this work was done long before procedures for naming rock units had been codified, and a haphazard approach to the establishment of the hierarchy of units prevailed. The earliest framework was relatively simple and essentially lithostratigraphical, but advances in the understanding of Carboniferous biostratigraphy, especially in the first half of the 20th century, led to a reappraisal and redefinition of lithostratigraphical terms as if they were chronostratigraphical units. Also, the localized nature of research produced numerous local names for essentially the same unit. The complexity in nomenclature has, to an extent, hindered the regional understanding of the Carboniferous successions of the UK.

The Geological Society Special Reports for the Dinantian and Silesian (George *et al.* 1976; Ramsbottom *et al.* 1978) provide useful stratigraphical correlations between key sections across the United Kingdom and Ireland. The reports aimed to integrate litho-, chrono- and biostratigraphy in a unifying scheme. However, the reports simply indicated how existing lithostratigraphical nomenclature related to a newly defined chronostratigraphical framework.

Lithostratigraphical framework for the Carboniferous

The British Geological Survey recently rationalized the nomenclature of Carboniferous lithostratigraphical units in the UK

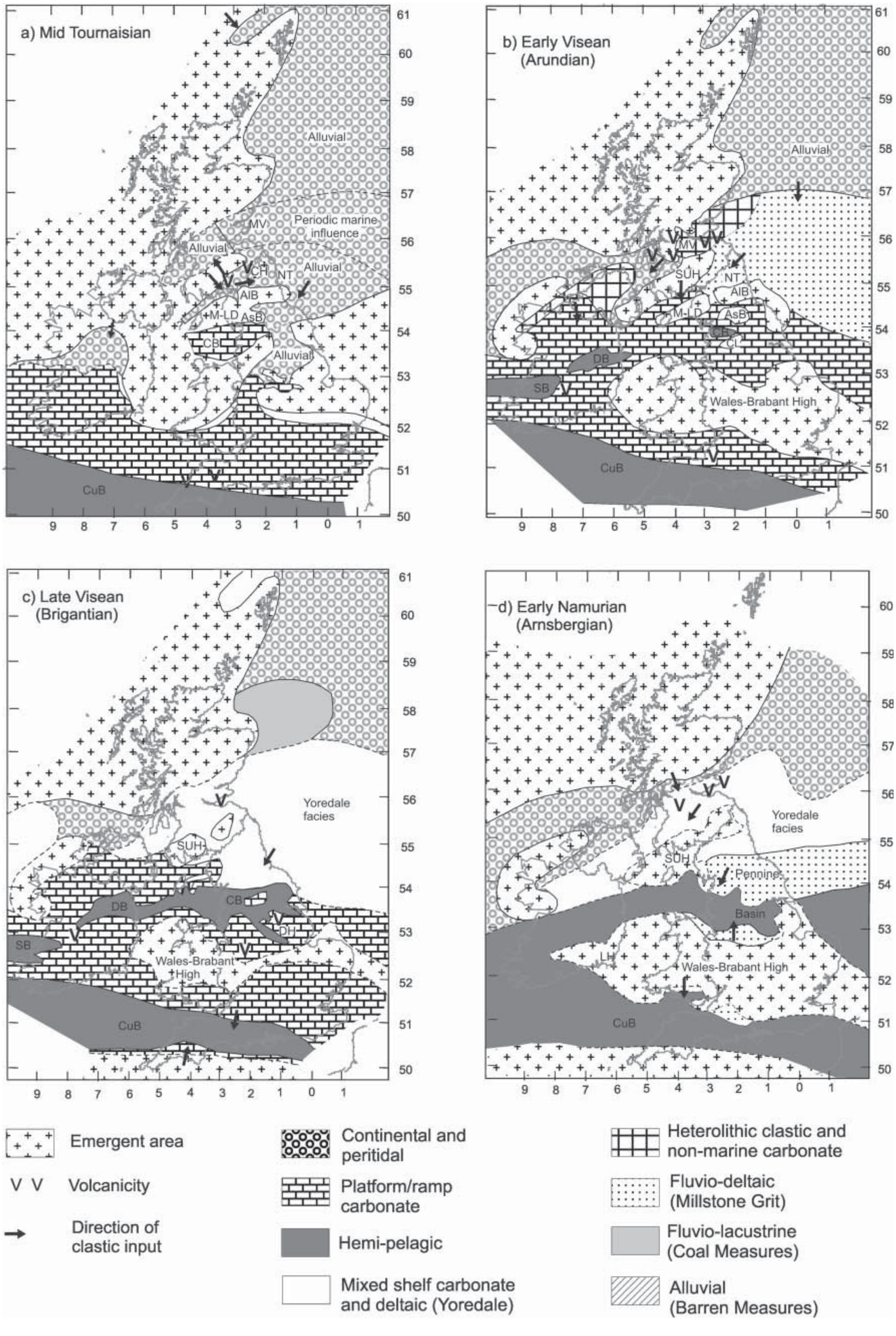

Fig. 9.9. Palaeogeographical reconstructions for England and Wales and adjacent offshore areas, showing disposition of the main lithofacies shown in Figure 9.8. (**a**) Mid Tournaisian; (**b**) Arundian; (**c**) Brigantian; (**d**) Arnsbergian; (**e**) Langsettian; (**f**) Westphalian D. Adapted from Cope *et al.* (1992). AlB, Alston Block; AsB, Askrigg Block; CB, Craven Basin; CH, Cheviot High; CL, Central Lancashire High; CuB, Culm Basin; DB, Dublin Basin; LH, Leinster High; M–LD, Manx–Lake District High; MV, Midland Valley; NT, Northumberland Trough; SB, Shannon Basin; SUH, Southern Uplands High.

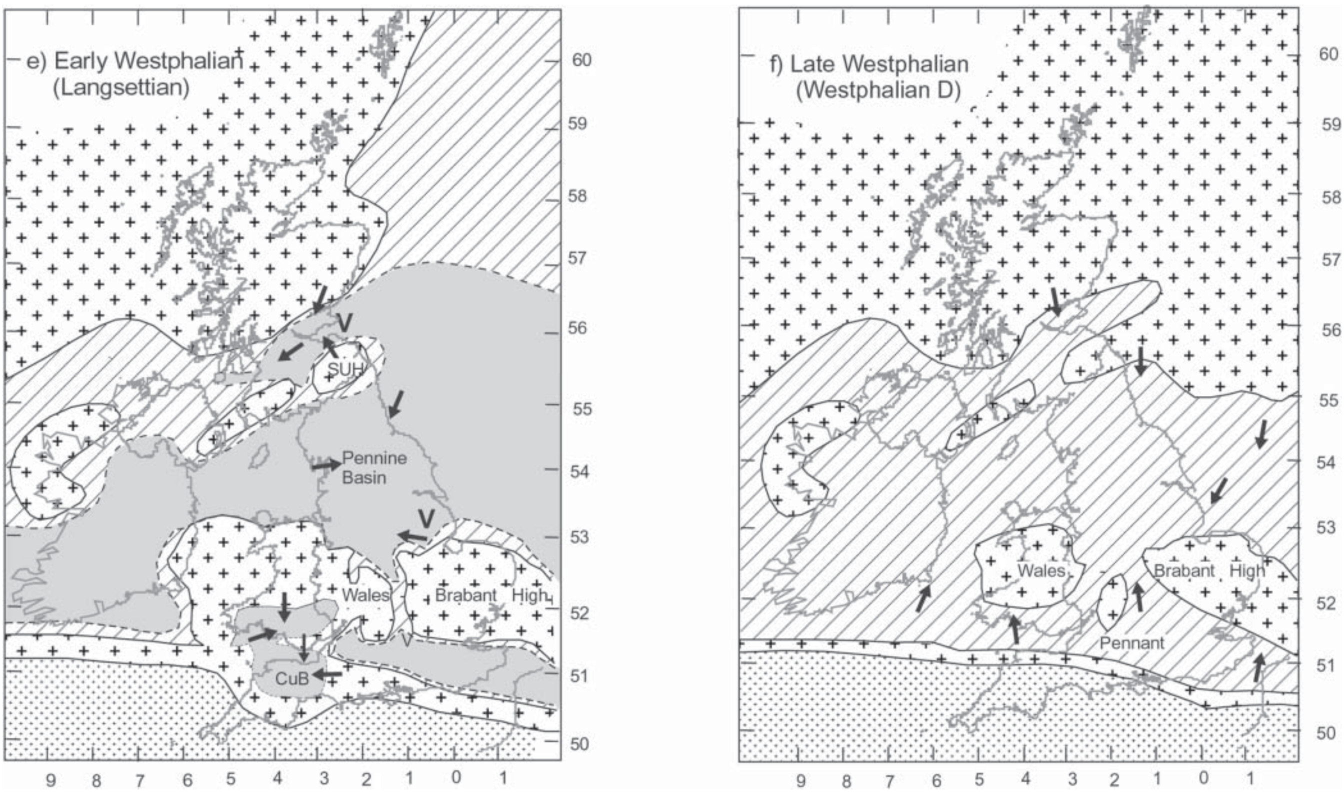

Fig. 9.9. Continued

(Waters *et al.* 2006*a*). The new scheme, presented here, equates lithostratigraphical groups with eight broad types of lithofacies associations. Distinct group names have been identified for each lithofacies grouping, with several names defined where the lithofacies developed in isolated tectonic regions during the Carboniferous (Fig. 9.8 and 9.9). The eight principal lithofacies associations are as follows.

Continental and peritidal lithofacies association
The lithofacies association was impersistently developed from Late Devonian to Viséan times across northern England and North Wales and comprises two facies that are commonly interdigitated in the Northumberland–Solway Basin.

a) *Continental fluvial clastic (‘Cornstone’) facies* comprises combinations of purple-red conglomerate, sandstone and red mudstone. The depositional environments range from alluvial fan, fluvial channel and floodplain overbank, respectively. The calcretes (‘Cornstones’) that characterize the facies are nodules and thin beds of concretionary carbonate. These carbonates represent immature–mature soil profiles developed on floodplains under the influence of a fluctuating water table in a semi-arid climate.
b) *Peritidal marine and evaporite (‘Cementstone’) facies* comprises grey mudstone, siltstone and sandstone, characterized by the presence of beds, and locally nodules, of ferroan dolostone (‘cementstones’) and evaporites (mainly gypsum and anhydrite). These were deposited in alluvial plains and marginal marine flats subject to periodic desiccation and fluctuating salinity, also indicating a semi-arid climate.

The continental fluvial clastic (‘Cornstone’) facies commonly forms the first element of basin infill and may extend onto horst and tilt-block highs, whereas the peritidal marine and evaporite (‘cementstone’) facies is generally limited to basins. The lithofacies association as a whole is represented by the Inverclyde Group within the Northumberland-Solway Basin, the Ravenstonedale Group in the Stainmore Trough and numerous formations representing isolated alluvial fan deposits, notably along the northern margin of the Wales–Brabant High (Figs 9.8 and 9.9a).

Heterolithic clastic and non-marine carbonate lithofacies association
The lithofacies association consists of interbedded grey sandstone, siltstone, mudstone and subordinate thin beds of lacustrine limestone and dolostone, seatearth, coal and sideritic ironstone. The range of depositional environments includes alternating fluviatile, deltaic, lacustrine and relatively rare marine mudstone deposits, often in thin cycles. This facies, more extensively developed in the Midland Valley of Scotland (Fig. 9.9b), is also present in Viséan strata of the Border Group, restricted to the Northumberland Trough (Fig. 9.8b).

Platform carbonate lithofacies association
Platform carbonates were mainly deposited on footwall highs during the Dinantian. There are two facies, resolved by the basic morphology of the platform (Kendall & Schlager 1981):

a) *Carbonate ramp facies* comprises calcareous mudstone with common dark bituminous and bioclastic limestone units, and locally the presence of carbonate breccias. Large carbonate mud-mounds, also referred to as ‘knoll reefs’ or ‘Waulsortian reefs’, also occur in this facies during the early Dinantian (Bridges *et al.* 1995). The facies represents deposition on gently inclined marine slopes, which may range from shallow-water to deeper-water, low-energy environments.
b) *Carbonate shelf facies* includes blanket bioclastic carbonates with crinoid banks, small bioherms, shelly or coral biostromes and algal (*Girvanella*) bands. This facies was deposited during the Viséan in a tropical shallow-marine environment on shelves and footwall highs, with a steep

slope separating platform and basin environments. The facies often includes potholed bedding surfaces overlain by thin bentonite clays ('clay wayboards'), interpreted, respectively, as emergent surfaces and palaeosols in volcanic ash (Walkden 1972, 1974). Marginal shelf 'Cracoean' buildups developed during the late Dinantian (Mundy 1994).

Dinantian carbonate platforms commonly display a predictable sequence of evolutionary changes (Kendall & Schlager 1981). Initially, a ramp-like structure developed with relatively steep gradients and rapid lateral facies transitions. This evolved into a steep-sided, broad flat shelf. The lithofacies association is represented across England and Wales by the Carboniferous Limestone Supergroup, which comprises several geographically separated groups. The Great Scar Limestone Group occurs across the Alston and Askrigg blocks and fringing the Manx–Lake District High (Figure 9.8). The Peak Limestone Group of the East Midlands and Clwyd Limestone Group of North Wales occupy parts of the northern margin of the Wales–Brabant High. These groups are not laterally continuous and, hence have separate group names. Isolated platform carbonates also developed on the Holme High and Central Lancashire High within an otherwise basinal environment. The Pembroke Limestone Group occupies the southern flank of the Wales–Brabant High, from South Wales to Bristol, overlying a mud-dominated Carbonate ramp facies of the Avon Group (Figure 9.8c).

Hemi-pelagic lithofacies association
This lithofacies association comprises dark grey–black mudstones, in part calcareous, with calcareous nodules ('bullions'). Thin sandstone and limestone beds are locally common and breccias may sometimes be present. The facies was deposited in quiet and relatively deep basinal environments and was associated with minor sand-rich turbidites within pro-delta environments, or carbonate-rich turbidites on carbonate slopes. Breccias may represent proximal turbidites, debris flows or slump features. The facies is found in the Viséan and Namurian gulf areas of central England and North Wales as the Craven Group (Figs 9.8 and 9.9) and in most of the Carboniferous of the Culm Basin of SW England.

Mixed shelf carbonate and deltaic ('Yoredale') lithofacies association
This lithofacies association comprises typically upward-coarsening successions of limestone, shale, sandstone, seatearth, ganister and coal. The limestone, shale and some sandstones are marine. The clastic component was derived from the progradation of high-constructive lobate deltas into the marine environment. The delta tops were often colonized by vegetation, resulting in the generation of seatearth palaeosols and coals. This facies, represented by the Yoredale Group, was widespread in the Viséan and early Namurian across northern England, as far south as the Craven Fault System (Figure 9.8 and 9.9c).

Fluvio-deltaic ('Millstone Grit') lithofacies association
The Millstone Grit lithofacies association comprises typically upward-coarsening successions of black shale, grey mudstone, siltstone, fine- to very-coarse-grained sandstone, with seatearths and relatively thin coal seams. Initial black shale deposition as 'marine bands' reflects marine transgression and delta abandonment; subsequent coarsening upwards into sandstones indicates delta progradation.

There are two facies:

The deep-water turbidite-fronted lobate delta facies is more typical of the lower part of the lithofacies association, representing initial basin infill. Coals and seatearths are typically rare.
The shallow-water sheet-like delta facies is more typical of the upper part of the lithofacies association, representing reduced accommodation within the basin. Coals and seatearths are common, but typically thin.
This is represented by the Millstone Grit Group, which extended across northern and central England during the Namurian–early Westphalian (Figs 9.8 and 9.9d). This group includes predominantly northerly-sourced, quartz-feldspathic sandstones. A similar facies, but with predominantly quartzitic sandstones derived from erosion of the Wales–Brabant High, forms the Marros Group south of the high (Figs 9.8c & 9.9d), from South Wales to Bristol. On the northern flank of the High similar protoquartzitic sandstones, identified as the Cefn-y-fedw Sandstone Formation of North Wales and Morridge Formation of the East Midlands, are present (Fig. 9.8).

Fluvio-lacustrine ('Coal Measures') lithofacies association
The lithofacies association comprises both upward-fining and upward-coarsening successions typically of grey–black mudstone, grey siltstone, fine- to medium-grained sandstone, seatearths and relatively thick coal seams. Cyclic successions are thinner and more numerous than in the underlying Fluvio-deltaic ('Millstone Grit') lithofacies association. Environments include wetland forest and soils (coal and seatearth), floodplains (plant-rich or rooted siltstone and mudstone), river and delta distributary channels (thick sandstones), prograding lacustrine deltas (upward-coarsening sequences) and shallow lakes (mudstones with non-marine faunas). Marine bands are generally much less common than in the Fluvio-deltaic ('Millstone Grit') lithofacies association. The Fluvio-lacustrine ('Coal Measures') lithofacies association was mainly deposited during the Westphalian. It occurs as the Pennine Coal Measures Group of northern and central England and North Wales (Figs 9.8a, b & 9.9e) and as the South Wales Coal Measures Group to the south of the Wales–Brabant High (Figs 9.8c and 9.9e), from South Wales to Kent. It recurs as the Grovesend Formation in late Westphalian and Stephanian times, south of the Wales–Brabant High.

Alluvial ('Barren Measures') lithofacies association
This facies association ranges from the late Westphalian to early Permian and occurs as two facies:

a) *The 'Red-bed' facies* consists of predominantly red, brown or purple-grey mudstone, siltstone and sandstone. Pebbly sandstone, conglomerate and breccia are locally developed. Minor components comprise grey mudstone, thin coals, lacustrine limestone ('*Spirorbis* limestone') and pedogenic limestone (calcrete). Environments of deposition include alluvial fans, fluvial channels, overbank areas and lakes. The 'Red-bed' facies has undergone oxidation at, or close to, the time of deposition, indicating a semi-arid climate.
b) '*Pennant' facies* consists of grey sandstone, pebbly sandstone–granulestone, characteristically an immature lithic arenite, commonly thick-, massive- or cross-bedded. Subordinate components comprise grey mudstone and thin coal. The facies represents fluvial channel and fluvial overbank deposits derived from the south.

This lithofacies, as the Warwickshire Group, is present on the northern and southern fringes of the Wales–Brabant High (Fig. 9.8). The 'Red-bed' facies is dominant along the southern margins of the Pennine Basin, but is also present on the southern margin of the Southern Uplands High as the Whitehaven Sandstone Formation. The 'Pennant' facies is mainly found south of the Wales–Brabant High in the South Wales, Bristol and Oxfordshire Coalfield, deposited during Bolsovian–Westphalian D as the Pennant Sandstone Formation. The facies was also deposited locally in the southern parts of the Pennine Basin, during Westphalian D times, as the Halesowen Formation.

Chronostratigraphical Framework

The term Carboniferous was created as a formal stratigraphical term by Conybeare & Phillips (1822) for strata present in England and Wales and was first referred to as a System by Phillips (1835). Broad similarities within the successions of England and Wales with the rest of Western Europe have allowed development of a regionally applicable chronostratigraphy.

In Western Europe the Carboniferous System traditionally comprises two subsystems, an older Dinantian and younger Silesian, corresponding to Lower Carboniferous and Upper Carboniferous, respectively (Fig. 9.10). The Dinantian–Silesian boundary was chosen to represent a regional facies transition from dominantly carbonate to terrigenous clastic strata and does not reflect a global change in flora or fauna. The lower boundary of the Silesian is defined as the base of the ammonoid *Cravenoceras leion* Zone.

The Dinantian is subdivided into the Tournaisian and Viséan Series, whereas the Silesian is subdivided into three series, Namurian, Westphalian and Stephanian. These series were originally chosen to represent prominent facies variations in Western Europe.

The stage nomenclature used in Western Europe is based on basal stratotypes defined by George *et al.* (1976) for the Viséan, Ramsbottom (1981) for the Namurian and Owens *et al.* (1985) for the Westphalian, largely from localities in northern England. The Stephanian Series is poorly represented in England and Wales, with only strata from the oldest Cantabrian Stage recognized. The distribution at outcrop of the main chronostratigraphical units and the location of the stage stratotypes is shown in Fig. 9.11.

The Mississippian and Pennsylvanian of the USA have become recognized internationally as subsystems and strictly represent Lower and Upper Carboniferous, respectively, in international usage. The mid-Carboniferous boundary separating the two subsystems occurs within the Chokierian Stage of the Namurian Series in Western Europe. International stage names have been created (Fig 9.10), though not all have been defined (Heckel 2004). Difficulties in direct comparisons between international and Western European stages have resulted in the UK largely maintaining usage of the regional Western European chronostratigraphical nomenclature (but see Cossey *et al.* 2004).

Biostratigraphical features

Ammonoids (goniatites) are an essential component of Carboniferous biostratigraphy within the late Dinantian, Namurian and early Westphalian Series, where they provide the greatest biostratigraphical resolution. Some ammonoid biozones can be recognized across Western Europe and some biozones are applicable globally. Thick-shelled ammonoids occur within thin hemi-pelagic marine beds ('marine bands') that were deposited during marine transgressions. Marine bands typically contain distinctive ammonoid faunas. Ammonoid biozones are intervals defined by the successive first appearance of ammonoid taxa, with the base of the biozones coinciding with the bases of specific marine bands.

Corals have been of historical importance in the biozonation of Dinantian platform carbonates (Vaughan 1905; Garwood 1913), although they are now considered strongly facies-controlled. Foraminifera are also of biostratigraphical importance in Dinantian carbonates. They are particularly abundant in mid-ramp and platform settings, and also present in basinal deposits in limestone turbidites (Riley 1993). The formal foraminifera zonation for Belgium, established as the standard for NW Europe, has been applied to British and Irish sequences by Conil *et al.* (1980).

Conodonts are present in marine deposits, notably carbonate turbidites and hemi-pelagic shales. Conodont zones are particularly important for Dinantian correlation (Varker & Sevastopulo 1985).

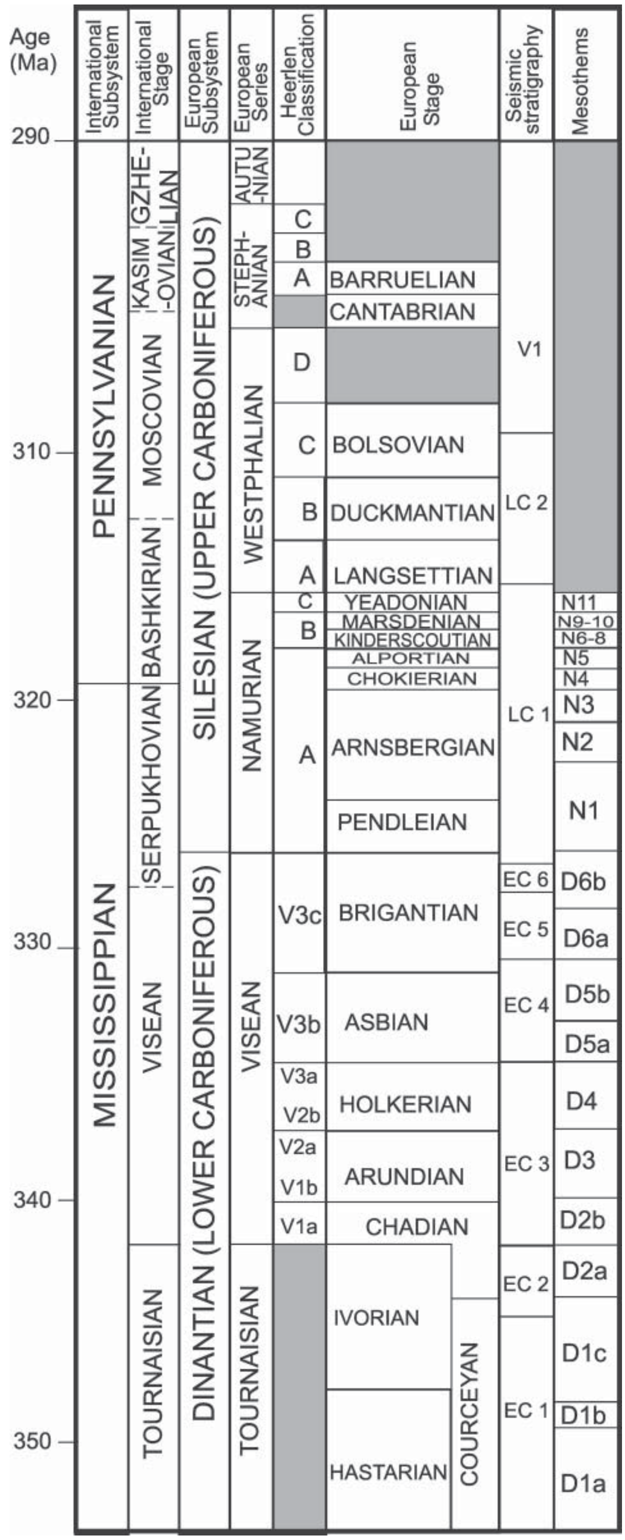

Fig. 9.10. Chronostratigraphical framework for the Carboniferous of England and Wales. Ages derived from Menning *et al.* (2000). Seismic sequences from Fraser *et al.* (1990). Mesothems from Ramsbottom (1973, 1977). International nomenclature that of Heckel (2004).

Palynomorphs (miospores) are present in both marine and terrestrial environments and have been used for biozonation up to and including the Westphalian D. Palynomorphs have proved important zonal indicators in the Northumberland Trough, where ammonoid faunal bands are rare. Palynology has been particularly useful for establishing the stratigraphy

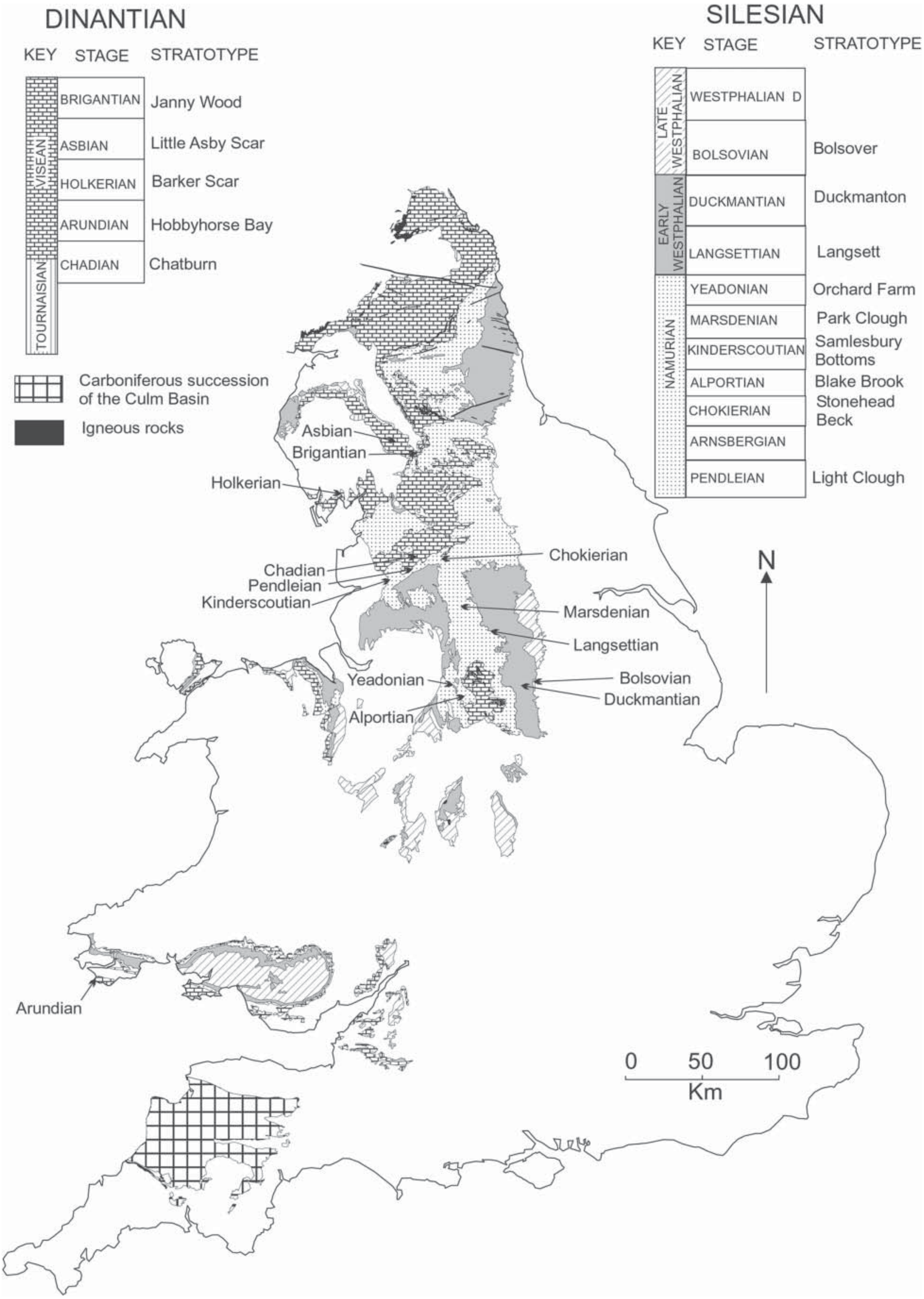

Fig. 9.11. Geological map showing the distribution of Carboniferous strata, subdivided into the main chronostratigraphical units. The map also shows the location of the stage stratotypes.

for the offshore Carboniferous where macrofossils are more difficult to obtain. Macrofloras are becoming increasingly important for the biozonation of Westphalian D and Stephanian strata (Cleal 1991).

In the Dinantian and Namurian, marine bivalves present within hemi-pelagic shales in association with ammonoids are of some stratigraphical importance (Riley 1993). In the Westphalian, the non-marine bivalves assume great importance (Trueman & Weir 1946). They tend to occur in association with fish and ostracodes. Estheriids ('*Estheria*'), small crustaceans that occupied brackish waters, can occur as prominent marker bands.

Sequence stratigraphy

The Carboniferous successions of England and Wales have been a fertile testing ground for the application of sequence stratigraphic methodologies in outcrop and subsurface studies largely for Silesian successions (Read 1991; Maynard 1992; Martinsen 1993; Church & Gawthorpe 1994; Hampson 1995; Hampson *et al.* 1997; Brettle 2001). Ramsbottom (1973, 1977) anticipated the advent of sequence stratigraphy in the 1990s (Van Wagoner *et al.* 1990). He recognized larger scale cycles in Carboniferous sequences ('mesothems') and defined the boundaries of each of these major cycles as widespread disconformities in shelf areas (Fig. 9.10). The mesothem model was criticized (Holdsworth & Collinson 1988; Martinsen 1990), and Namurian stage boundaries were never adjusted to coincide with mesothem boundaries, as proposed by Ramsbottom (1977) and Ramsbottom *et al.* (1978). Marine bands remain the most reliable means of local and regional correlation for Carboniferous successions and many individual marine bands can be traced within and between basins, providing a high-resolution biostratigraphical framework (Ramsbottom *et al.* 1978; Riley *et al.* 1995). However, sequence stratigraphic methodology enhances these established correlation methods and enables the important re-interpretation of critical elements of the sedimentary strata.

Sequence stratigraphic methodology uses a range of key surfaces, not just the marine bands, to examine facies relationships. These key surfaces include regionally widespread surfaces of erosion and emergence, referred to as sequence boundaries (Posmentier & Vail 1988; Van Wagoner *et al.* 1988) and a hierarchy of transgressive surfaces that are considered to reflect changes in relative sea level.

The presence of surfaces of erosion within the strata between marine bands has implications for timing and linkage of depositional environments. The strata between marine bands are referred to as cycles or cyclothems and have been considered to represent genetically-related facies. The facies-pattern variability that dominates the Yoredale, Millstone Grit and Coal Measures groups (see the section on 'Lithostratigraphical framework for the Carboniferous') has been interpreted in terms of differing positions within the depositional systems. In this traditional model, 5–30 m thick, late Viséan–early Namurian cyclothems comprising marine carbonates and non-marine clastic sediments were attributed to autocyclic channel avulsion and lobe switching (Leeder & Strudwick 1987). Erosively based sandstone units within cyclothems have traditionally been interpreted as the deposits of fluvial systems that were an integral part of the depositional system, e.g. distributary channels on delta plains (Elliott 1975). An alternative interpretation is that some thicker sandstones with substantial basal erosional relief could be interpreted as valleys incised during periods of sea-level fall and filled during the early rise.

Thick, sandstone-dominated multistorey fluvial systems are a common feature of Silesian strata and a number of characteristics can be used distinguish those that are valley fills from others of distributary channel origin. The four main characteristics of valley fill sandstones are defined by Hampson *et al*. (1997). (1) The basal surface to the valley fill is a regionally extensive high relief erosion surface that can be correlated laterally to an interfluve surface; the erosion surface should be more extensive than those surfaces associated with individual channels. (2) The facies associations above the erosional unconformity will differ greatly from the underlying associations. (3) The erosional unconformity removes underlying strata, sometimes at a scale that produces an identifiable time gap recognized by the removal of marine bands. (4) Valley fills have a distinctive internal architecture, they are commonly multistorey and record a trend of increasing accommodation evident from, for example, increasing preservation of channel members, that reflects rising sea level during the valley fill phase and which culminates in the initial flooding surface.

The recognition of interfluves is a critical test for the interpretation of erosional unconformities as sequence boundaries. Interfluves generally have well-developed, mature profiles, reflecting a longevity of exposure, that is equivalent to the period of valley incision and fill, and the palaeosol is overlain directly by a flooding surface. Relatively few good interfluve examples have been reported so far (Davies & Elliott 1996; Hampson 1998), possibly because many palaeosols may have been overprinted during the rising relative sea level associated with the transgressive surface.

The identification of erosional unconformities and interfluves within Carboniferous cyclothems indicates that, within a cyclothem, it cannot be assumed that sediments were genetically related and, in fact, the unconformity-bound sequences should be identified as the units of linked strata. The erosion and palaeosol surfaces (sequence boundaries) representing periods of sea-level fall are equally as important as the ammonoid bearing marine bands (maximum flooding surfaces) representing rising sea level. Major palaeogeographical re-organizations generally occurred during the development of the sequence boundaries and the horizons are also associated with potentially significant stratal omission.

The main implication of using sequence stratigraphy alongside more established correlation techniques, is that predictive models can be developed for the timing of depositional facies. Specific stratigraphical intervals containing major sandstone reservoir facies can be predicted by extending a high-resolution sequence stratigraphic framework developed in one area into basins containing time-equivalent strata.

Geochronology

Radiometric ages for the Carboniferous have been principally derived from thin tuffs, tonsteins and bentonites, which can provide ages of eruption in sedimentary successions with good biostratigraphical control. The main sources of internationally recognized ages are U–Pb zircon and Ar/Ar sanidine, although inconsistencies are recognized between sources and laboratory techniques (Menning *et al.* 2000). Much of the published data comes from Central and Western Europe, although as chronostratigraphical correlations with England and Wales are well established, these ages are applicable in the UK. A significant SHRIMP ion microprobe ^{206}Pb–^{238}U zircon date of 314.5 ± 4.6 Ma has been determined for biostratigraphically well-constrained Arnsbergian bentonites from the Pennine Basin (Riley *et al.* 1995). This date is some 5 Ma younger than an Ar/Ar plateau date for Arnsbergian strata in central Europe (Menning *et al.* 2000). Because of questions raised on the accuracy of SHRIMP dating techniques, the age scale presented on Fig. 9.10 is based upon Ar/Ar dates (Menning *et al.* 2000).

In the UK, much reliance has been placed on K–Ar dates determined from intrusive dolerites (Fitch *et al.* 1970). However, many of these dates have been affected by subsequent argon mobility and consequently are of little significance in calibration of the Carboniferous Period and its component series and stages. For example, the Kelso Lavas and

Birrenswark Volcanic formations, which are undoubtedly of Tournaisian age, have been dated by this method as late Devonian, at 360 Ma (de Souza 1975) and 361 ± 7 Ma (de Souza 1982), respectively. However, in SE Wales, a biotite K–Ar date of 336 ± 7 Ma (Fitch *et al.* 1969) from the Golden Hill diatreme pipe is in agreement with Viséan age fossils found in a block of limestone within the pipe (Bevins 2003). In Derbyshire, the Lower Miller's Dale Lava, of Asbian age, has a much younger whole-rock K–Ar age of 315 ± 12 Ma (Fitch *et al.* 1970), interpreted by these authors as a close approximation to the age of hydrothermal alteration, rather than an extrusion date. Derbyshire intrusions have typically yielded whole-rock K–Ar ages of 287 ± 13 Ma (Fitch *et al.* 1970) to an average of 311 ± 6 Ma (Stevenson *et al.* 1970), suggesting an age range of Bolsovian–Autunian. However, in Derbyshire no dolerite intrusions are found in strata of Namurian or Westphalian age (Fig. 9.7), and geochemical similarities between intrusions and the Dinantian lavas suggest the two are genetically linked. This suggests that the dates have been reset to a younger age by argon loss.

A whole-rock K–Ar date of 308 ± 10 Ma has been determined on a dolerite from Barrow Hill, near Dudley (Fitch *et al.* 1970). Extrusive volcaniclastic deposits associated with the vent are interbedded with sedimentary strata of Bolsovian age. This suggests that the radiometric age probably represents a close minimum for the true intrusive age. Fitch *et al.* (1970) also provided K–Ar radiometric dates for the sills intruded nearby within Bolsovian strata in the West Midlands, giving apparent minimum ages for intrusion of 295 ± 5 (Stephanian) to 265 ± 5 Ma (Permian). However, intrusions with this geochemistry are not found in strata younger than Bolsovian age. K–Ar dates for the Great Whin Sill (Plate 19) and the Little Whin Sill, both of which have undergone post-crystallization metasomatism, have been determined as 295 ± 19 Ma (Fitch & Miller 1964).

Dinantian: platform carbonates and clastic/carbonate filled basins

Introduction

The Pennine Basin includes the depositional area between the Southern Uplands and Wales–Brabant High (Fig. 9.2). During the Dinantian, the Pennine Basin was dominated by fault-controlled troughs and highs ('block and basin' topography). Significant troughs include the Northumberland Trough-Solway Basin, Stainmore Trough and Craven Basin. The Craven Basin is used as a generic name for a series of linked embayments, including the Bowland Trough, Harrogate Basin, Edale Gulf, Gainsborough Trough and Widmerpool Gulf and intervening structural highs (Fig. 9.2). In central and northern England these basins contain relatively continuous Dinantian successions ranging from 1.5 to 3 km in thickness (Fraser *et al.* 1990; Leeder 1992). To the south of the Wales–Brabant High, shelf/ramp carbonates accumulated in South Wales and in the Bristol and Mendips areas, in turn passing southwards into the deep-water marine shales and turbidites of the foreland Culm Basin of Cornwall and Devon.

The arid continental environment established during the Devonian continued into the early Tournaisian. Sedimentation was dominated by alluvial fan accumulations along basin margins. Also, there was localized development of fluvial and playa-lake deposits within small internally drained basins, with thick evaporites locally formed (e.g. flanks of the Derbyshire High).

A late Tournaisian–early Chadian marine transgression resulted in the deposition of peritidal marine sabkha deposits within those basins open to marine influence. The reduced topography of the block areas resulted in a diminished influx of finer-grained alluvial sediments. Isolated marine carbonate platforms became established as highs were submerged. Platform carbonates also accumulated on both the northern flank (North Wales and East Midlands) and southern flank (South Wales–Bristol and the Mendips areas) of the Wales–Brabant High.

The early Dinantian basins were gulf-like, initially hypersaline seas, apparently tideless, but with variable influx from freshwater river systems. Thick, open marine platform carbonates thinned onto the footwalls and up the hanging-wall dip slopes (Figs 9.2a & 9.3). Evidence of intermittent subaerial exposure and minor cyclicity occurs within these carbonate successions.

During the Tournaisian, sedimentation in the Northumberland Trough evolved from predominantly alluvial deposition to finer-grained deltaic deposition with subordinate marine influence. An early Tournaisian axial drainage pattern developed, with lateral alluvial fans on the southern margin of the Southern Uplands and in the Vale of Eden (Fig. 9.9a). By late Tournaisian–early Chadian times, mudstone-dominated ferroan dolostone beds ('cementstones') were deposited on alluvial plains and marginal marine flats subject to periodic desiccation and fluctuating salinity. These deposits may also have extended northwards into the Midland Valley of Scotland. In the central Northumberland Trough a deltaic system prograded west at this time, whilst periodic marine incursions flooded eastwards. During the late Tournaisian the diminishing relief of the Southern Uplands High discharged smaller volumes of sediment to the alluvial fans and fluvial systems on the northern margin of the Northumberland Trough/Solway Basin. Further to the south, in the Stainmore Trough, peritidal carbonates, comparable to the cementstones, were deposited and were interbedded with alluvial fan conglomerates.

To the north of the Wales–Brabant High, alluvial deposits accumulated in small, possibly internally drained basins. Local development of anhydrites probably reflects deposition in a sabkha environment. Late Tournaisian–early Chadian marine transgression is evident in North Wales, where red clastic beds are overlain by dolomitized carbonates deposited in a near-shore high-energy environment. Possible Waulsortian mudmounds were present offshore to the north (Somerville *et al.* 1989). In South Wales the Tournaisian is characterized by a fully marine shelf succession.

In England and North Wales, a period of sustained marine transgression marked the Arundian (Fig. 9.9b). The Askrigg block was submerged and about 150 m thickness of Arundian–Holkerian platform carbonates were deposited. Water depths in the Stainmore Trough increased (Higgins & Varker 1982). In the Craven Basin Waulsortian mud-mounds, which had developed during the Late Chadian, were replaced in Arundian times by limestone turbidite deposition. Low relief carbonate ramps dominated late Devonian–Holkerian deposition in South Wales and Bristol regions (Wright 1987). Evaporitic deposition ceased on the flanks of the Derbyshire High and marine conditions were established. In North Wales Arundian limestones overlapped and overstepped earlier Carboniferous strata.

From the early Asbian, carbonate platforms throughout England and Wales show a consistent evolution from gently sloping ramps into steep-margined, flat-topped shelves (Walkden 1987). This is interpreted by Wright & Vanstone (2001) as reflecting a global climate change from relatively stable sea levels to a period of high frequency sea-level oscillation driven by the development of a major ice-sheet in the southern hemisphere (Fig. 9.6). Major Brigantian-aged deltas prograded southwards but were periodically drowned by marine incursions, producing the cyclic *Mixed shelf carbonate and deltaic ('Yoredale') lithofacies association*. In northern England this lithofacies association extends across the region and into the North Sea (Fig. 9.9c).

Basinal sedimentation, characterized by hemi-pelagic shales and carbonate turbidites, extended from the Dublin Basin, across the Bowland Trough to the Gainsborough and Widmerpool gulfs. To the south of this basinal area, extensive platform carbonate deposition continued over the East Midlands Shelf, Derbyshire High and North Wales. The Wales–Brabant High was a subdued feature at this time.

The main control on Dinantian volcanicity throughout England and Wales was the N–S lithospheric stretching and thinning associated with the formation of faulted blocks and basins (Leeder 1982). Much of the activity occurred along lines of pre-existing basement lineaments which commonly bound the main blocks and basins (Francis 1970). The main centre of igneous activity at this time was in Derbyshire, with minor volcanism in the Bristol/Gloucester and Wenlock areas and in the East Midlands (Fig. 9.7).

Chronostratigraphy

The Dinantian, introduced by Munier-Chalmas & de Lapparent (1893), has long been subdivided into the Tournaisian and Viséan series in Europe. However, George *et al.* (1976) were not prepared to use these terms in their review of British chronostratigraphy, indicating inconsistencies in the definition of these series. Instead, they defined six regional stages for the Dinantian (Fig. 9.10), based upon stratotype stage boundaries. The base of each stage is taken at a lithological change below the entry of a diagnostic faunal group.

The Courceyan Stage, defined by George *et al.* (1976), broadly corresponds biostratigraphically with the Tournaisian Series (Ramsbottom & Mitchell 1980). The Hastarian and Ivorian stages of Conil *et al.* (1977), defined in Belgium, have succeeded the Courceyan Stage on the continent and have been applied increasingly in Britain. However, definition of these stages remain problematical and the zonal boundaries used to define the base of the Ivorian Stage are poorly represented in Britain, so the Courceyan has been retained here. The remaining five stages, all with stratotypes defined in England and Wales, are components of the Viséan Series. They are in ascending order: Chadian, Arundian, Holkerian, Asbian and Brigantian stages (George *et al.* 1976). They have no formal international recognition and several need to be redefined (Riley 1993). Each of the stratotype sections is described in detail by Cossey *et al.* (2004).

The basal Chadian Stratotype at Chatburn, near Clitheroe, Lancashire was incorrectly located by George *et al.* (1976) within the Chatburn Limestone Formation, of Tournaisian age. Riley (1993) has indicated that the true entry of the index fossil is some 300 m higher in the succession, within the Hodder Mudstone Formation. He has proposed the terms early and late Chadian, to correspond to the Tournaisian and Viséan components of the stage, respectively. This distinction between a chronostratigraphical and biostratigraphical base for the Chadian Stage has resulted in considerable confusion, which could be avoided by redefining the Chadian stratotype to concur with the base of the Viséan Series.

The Arundian stratotype is at Hobbyhorse Bay, Dyfed, South Wales (Fig. 9.11), defined at the base of the Pen-y-Holt Limestone above the dolomitized Hobbyhorse Bay Limestone. The Holkerian stratotype is at Barker Scar, south Cumbria, defined close to the base of the Park Limestone Formation. The Asbian stratotype, at Little Asby Scar, Ravenstonedale, Cumbria, is taken at the base of the Potts Beck Limestone Formation. The Brigantian stratotype is at Janny Wood, near Dent, Cumbria, the base of the stage defined by George *et al.* (1976) as coinciding with the base of the Peghorn Limestone. However, it has been proposed that the boundary be moved to a lower level at the base of the Birkdale Limestone (Cózar & Somerville 2004).

Biostratigraphy

The ammonoid faunas of the early Dinantian are best known from the deep marine Culm Basin of Devon and Cornwall, and are poorly developed in northern Britain and Ireland. The ranges of ammonoid zones in Britain are shown in Figure 9.12, for the Dinantian after Riley (1993). The base of the *Gattendorfia subinvoluta* Ammonoid Zone equates with the base of the Tournaisian Series.

Fewtrell *et al.* (1981) reported the stratigraphical distribution of British Dinantian foramanifera and recognized problems with the Chadian and Asbian stratotypes of George *et al.* (1976) and indicated discrepancies with the Belgium zonation scheme (Conil *et al.* 1977). A British zonation scheme has yet to emerge. However, Figure 9.12 provides the ranges of Dinantian foraminifera using the zonal scheme for Belgium and applied to the British Isles by Conil *et al.* (1980). The boundary between Hastarian and Ivorian stages of the Tournaisian corresponds with the boundary between *Chernyshinella* (Cf1) and *Paraendothyra* Biozones (Cf2), the position of which remains uncertain in England and Wales. The base of the Chadian Stage was defined by the first change in lithology below the entry of *Eoparastaffella* (George *et al.* 1976), also used to define the base of the international Viséan Series. The base of the Arundian Stage is defined by the first change in lithology below the entry of the family *Archaediscidae* (George *et al.* 1976).

The Dinantian conodont biozones for the Britsh Isles are shown in Figure 9.12, modified from Varker & Sevastopulo (1985). The base of the Tournaisian Series, and hence the Carboniferous System, was redefined by Conil *et al.* (1977) to occur at the base of the *Siphonodella sulcata* Conodont Zone. The boundary between Hastarian and Ivorian stages of the Tournaisian is recognized as corresponding with the boundary between the *Siphonodella* and *Dollymae hassi* Biozones. Important regional studies of conodonts include Armstrong & Purnell (1987) for the Northumberland Trough, Metcalfe (1981) for Dinantian–early Namurian strata of the Craven Basin and Riley in Chisholm *et al.* (1988) for the Tournaisian–Viséan boundary in the Peak District.

A complete miospore zonation for the Dinantian of Britain was proposed by Neves *et al.* (1972, 1973) and developed by Clayton *et al.* (1978). This zonal scheme is summarized in Figure 9.12. The base of the *Vallatisporites vallatus–Retusotriletes incohatus* (VI) Miospore Zone equates with the base of the Tournaisian.

The pioneering work of Vaughan (1905) defined coral assemblage zones for the Bristol area. Garwood (1913) initiated a comparable zonation for northern Britain, defined by faunal marker bands. The index names used for these zones, shown in Figure 9.12, are still widely referred to in modern literature. Courceyan zones were revised as assemblage biozones by Ramsbottom & Mitchell (1980), Mitchell (1981) and Sevastopulo & Nudds (1987). The distribution of Viséan rugose corals and heterocorals are summarized by Mitchell (1989) and Sutherland & Mitchell (1980), respectively. The base of the Holkerian Stage is defined as the lithological change that occurs below the incoming of diagnostic corals *Carcinophyllum vaughani* and *Lithostrotion minus* and brachiopods *Davidsonina carbonaria*, *Composita ficoides* and *Linoprotonia corrugatohemispherica* (George *et al.* 1976) and broadly corresponds with the S2 Zone. The base of the Asbian Stage was defined by George *et al.* (1976) as the lithological change which occurs below the incoming of diagnostic corals *Dibunophyllum bourtonense*, *Siphonodendron (Lithostrotion) pauciradiale*, *S. junceum*, *Palaeosmilia murchisoni* and brachiopods *Linoprotonia hemisphaerica*, *Daviesiella llangollensis*. The base of the Brigantian Stage occurs at the lithological change below the incoming of diagnostic coral fauna *Diphyphyllum lateseptatum*, *Actinocyathus (Lonsdaleia) floriformis*,

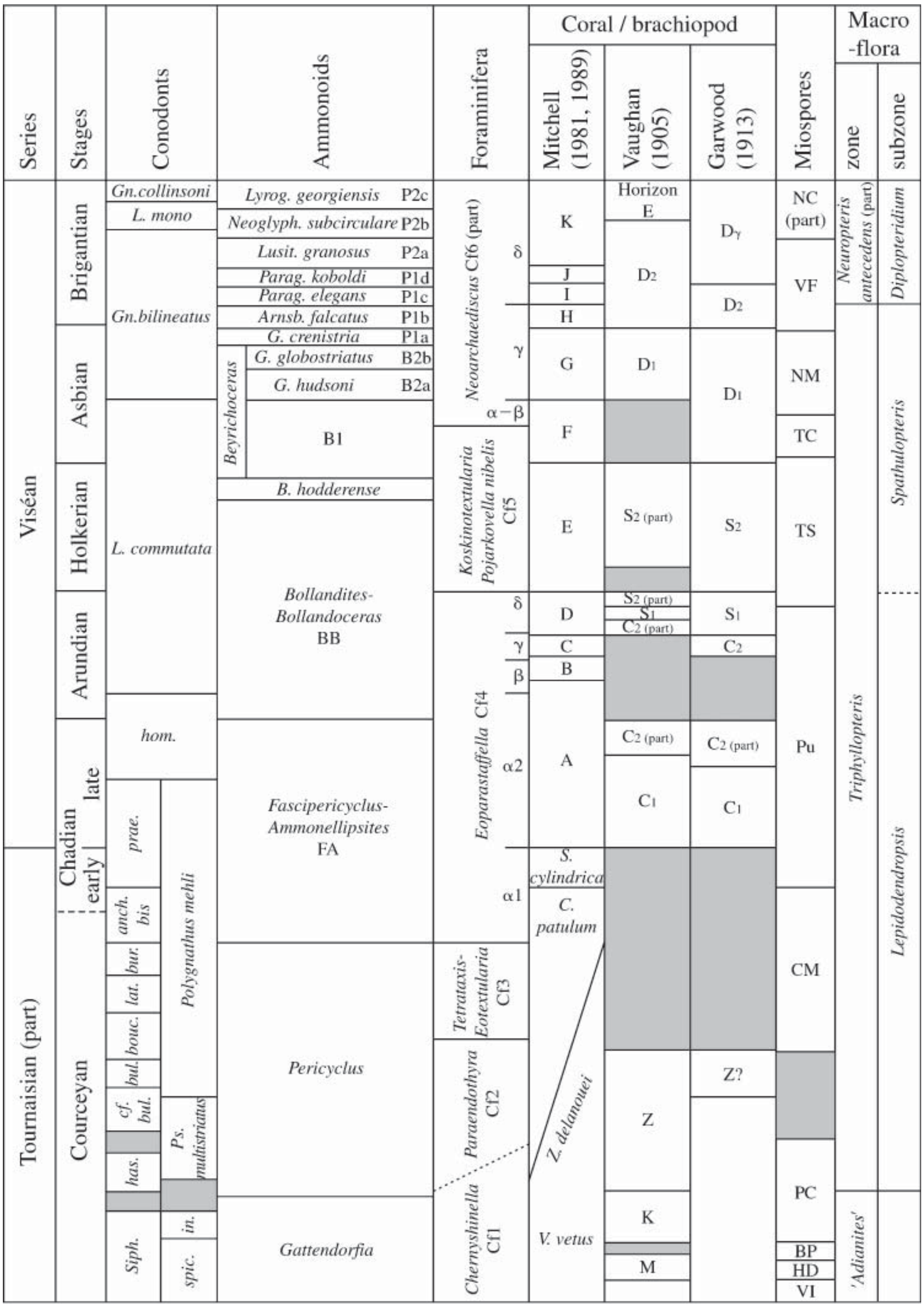

Fig. 9.12. Dinantian biostratigraphal zonations, (derived from Riley 1993, with permission from the Geological Society, London 2004). Stipple ornament shows interzones (conodonts and miospores) or non-sequences (corals and brachiopods). anch. bis., *Scaliognathus anchoralis–Polygnathus bischoffi*; Arnsb., *Arnsbergites*; B., *Bollandoceras*; bouc., *Dollymae bouckaerti*; bul., *Eotaphrus bultyncki*; bur., *Eotaphrus burlingtonensis*; C., *Caninophyllum*; coll., *Gnathodus girtyi collinsoni*; has., *Dollymae hassi*; hom., *Gnathodus homopunctatus*; in., *Polygnathus inornatus/Siphonodella*; L., *Lochriea*; mono., *mononodosa*; lat., *Doliognathus latus*; Lusit., *Lusitanoceras*; Lyrog., *Lyrogoniatites*; Neoglyph., *Neoglyphioceras*; Parag., *Paraglyphioceras*; prae., *Mestognathus praebeckmanni*; S., *Siphonophyllia*; Siph., *Siphonodella*; spic., *Polygnathus spicatus*; V., *Vaughania*; Z., *Zaphrentis*.

Nemistium edmondsi, *Orionastraea* spp., *Palastraea regia* and brachiopods *Productus hispidus*, *Productus productus* and *Pugilis pugilis*.

Sequence stratigraphy

The Dinantian strata of England and Wales display common patterns that suggest an allocyclic control, for example global sea-level change, on deposition (Fig. 9.6). A Tournaisian marine transgression resulted in widespread flooding across the 'Old Red Sandstone' terrestrial environment and subsequent development of ramp carbonates in northern and central England and North Wales. Many Asbian–Brigantian shelf carbonates display repeated shallowing upward cycles, which commonly culminate in palaeokarst surfaces formed during emergence (Walkden 1987; Walkden & Walkden 1990). There is a progressive increase in cycle thickness from 1–5 m in the early Asbian to greater than 10 m in the early Brigantian, and a concomitant trend towards deeper water sedimentation at the cycle bases (Walkden 1987).

The types and distribution of cycles present in British Dinantian successions have been reviewed by Walkden (1987) and computer-modelled by Walkden & Walkden (1990). These authors conclude that small-scale, glacio-eustatic sea-level oscillations were the principal cause of late Dinantian cyclicity but that the incremental accumulation of the cyclic sequences was accommodated by regional subsidence. Late Asbian successions reflect relatively small, but relatively frequent sea-level fluctuations in which rapid transgressions and regressions precluded the formation or preservation of peritidal facies (Walkden & Walkden 1990).

Changes in cycle style at the Asbian–Brigantian boundary (Somerville & Strank 1984*a*; Walkden 1987) also suggest that regional controls were operating. The strongly asymmetric form of Brigantian cycles, dominated by thick sequences of deeper water platform facies, indicates that transgressive inundations were larger, more rapid and protracted than those of Asbian age (Walkden 1987). This suggests that eustatic sea-level rises during the Brigantian were enhanced by regional downwarping (Ramsbottom 1981; Walkden 1987; Walkden & Walkden 1990) possibly marking the onset of thermal subsidence, which later dominated Silesian basin development (Leeder 1982).

The subdivision of British Carboniferous successions using event stratigraphy was initiated by Ramsbottom (1973, 1977, 1979). He identified cyclical facies changes (mesothems), which he argued resulted from eustatic transgressive–regressive pulses (Fig. 9.10). The pronounced thickness and facies variations of Dinantian strata, between individual blocks and basins, implies that the local development of accommodation also influenced sediment distribution (George 1958, George 1978). Leeder (1988), Fraser & Gawthorpe (1990) and Fraser *et al.* (1990) have suggested that many of the cyclical and widespread facies changes reflect discrete periods of rifting and subsidence alternating with episodes of tectonic quiescence, although these cannot explain the small scale but reasonably widespread cycles. Davies *et al.* (2004) suggest that facies changes correlated within separate Dinantian block successions may, in part at least, reflect parallel evolutionary trends operating largely independently of small-scale eustatic and tectonic events.

A seismostratigraphical classification for the Dinantian of the East Midlands (Ebdon *et al.* 1990) and entire Carboniferous of northern England (Fraser *et al.* 1990) recognized six Dinantian (broadly Late Devonian–late Brigantian) sequences, separated by seismic sequence boundaries (Fig. 9.10). These sequences were interpreted as synrift deposits, with eustatic sea-level changes considered insignificant. The resolution is coarse, in comparison with the existing chronostratigraphical subdivision based upon biostratigraphy, as argued by Riley (1993), but is valid for seismic interpretation and demonstrates the importance of a structural control.

Regional developments

Northumberland–Solway Basin

Inverclyde Group

Carboniferous deposition commenced during the Tournaisian with alluvial, lacustrine and evaporite sediments (continental and peritidal lithofacies association) of the Inverclyde Group, deposited along parts of the northern margin of the Northumberland Trough–Solway Basin. The Inverclyde Group was defined in the Midland Valley of Scotland, but is known to extend into the northern part of the Northumberland Trough and Solway Basin (Fig. 9.8) and the term is used to replace former names, such as the Berwick Cementstone Group (Waters *et al.* 2006*a*). The group is up to 900 m thick in the Tweed Valley and up to 640 m in the Solway Firth area, and typically comprises a lower Kinnesswood Formation and an upper Ballagan Formation, locally separated by volcanic rocks (Figs 9.13 & 9.14).

Initially, during the early Tournaisian, alluvial fan deposits of the Kinnesswood Formation were deposited in a series of small, linked basins with internal drainage that formed during the early stages of crustal extension (Chadwick *et al.* 1995). The formation comprises red sandstones, siltstones and conglomerates with calcretes, resting unconformably upon Silurian strata.

A phase of volcanic activity occurred during the initial phase of extensional faulting in Tournaisian times. The Birrenswark and Kelso Volcanic formations locally overlie the Kinnesswood Formation in the northern part of the Solway Basin (Lumsden *et al.* 1967) and Tweed Basin (Greig 1988), respectively (Fig. 9.14). The Cottonshope basalts, located on the SW flank of the Cheviot Block, and Cockermouth Lavas, present along the southern margin of the Solway Basin also belong to this episode. These volcanic formations comprise typically tholeiitic olivine-basalts and subordinate tuffs and sedimentary strata.

Subsequent deposition was characterized by an influx of alluvial fans, fluvial and fluvio-deltaic sediments derived from the Southern Uplands, intercalated with lacustrine and arid coastal plain deposits (Deegan 1973; Leeder 1974). This is the Tournaisian–Chadian Ballagan Formation, comprising interbedded sandstone, shale, limestone and anhydrite. In the central Northumberland Trough a lateral facies change sees the Ballagan Formation pass into the increasingly marine-influenced Lyne Formation of the Border Group (Fig. 9.14).

Border Group

The early Viséan Border Group is limited to the Northumberland Trough–Solway Basin and comprises components of the Heterolithic clastic and non-marine carbonate lithofacies and Fluvio-deltaic ('Millstone Grit') lithofacies associations. This group is a redefinition of the Lower, Middle and Upper Border groups of Day *et al.* (1970), from the Bewcastle area of the Northumberland Trough (Waters *et al.* 2006*a*). The component formations are the Lyne Formation, overlain diachronously by the Fell Sandstone Formation (Fig. 9.13).

Deposition of the Border Group commenced within the axial part of the Northumberland Trough with peritidal, deltaic and fluvial deposits of the Lyne Formation. The late Tournaisian–Chadian formation comprises cyclical sequences of fine-grained subarkosic sandstone, siltstone, mudstone and thin limestone. The peritidal limestones contain common thin oolitic pellet beds, stromatolites and vermetid gastropod bioherms and biostromes, and in the Solway Basin quasi-marine shelly faunas contain abundant brachiopods *Antiquatonia (Dictyoclostus) teres*. The first marine limestones developed later towards the NE of the basin. The Lyne Formation sandstones were deposited from lobate deltas that periodically migrated along the basin axis from NE to SW (Leeder 1974). A second clastic source, represented by the Whita Sandstone, is present in the northern part of the basin (Fig. 9.14) derived from a local northerly source in the Southern Uplands High. The Lyne Formation is at least 890 m thick, the base not proved, in the central part of the trough.

The Fell Sandstone Formation comprises fluvial deposits (Monro 1986, Turner *et al.* 1993), which accumulated initially in the east of the basin (Chadian–Holkerian) and which pass westward diachronously into a succession of fluvio-deltaic and shallow-marine deposits (Arundian–Holkerian). In the NE of the Northumberland Trough, the formation comprises between 130 and 300 m of fine- to medium-grained, mica-poor, subarkosic sandstone with sparse interbeds of red mudstone. Seatearths are common, but only associated with thin coals in the upper part of the formation. There is an unconformity at the base of the formation, with the Lyne Formation absent. Here, the formation is interpreted as deposits of several braided rivers,

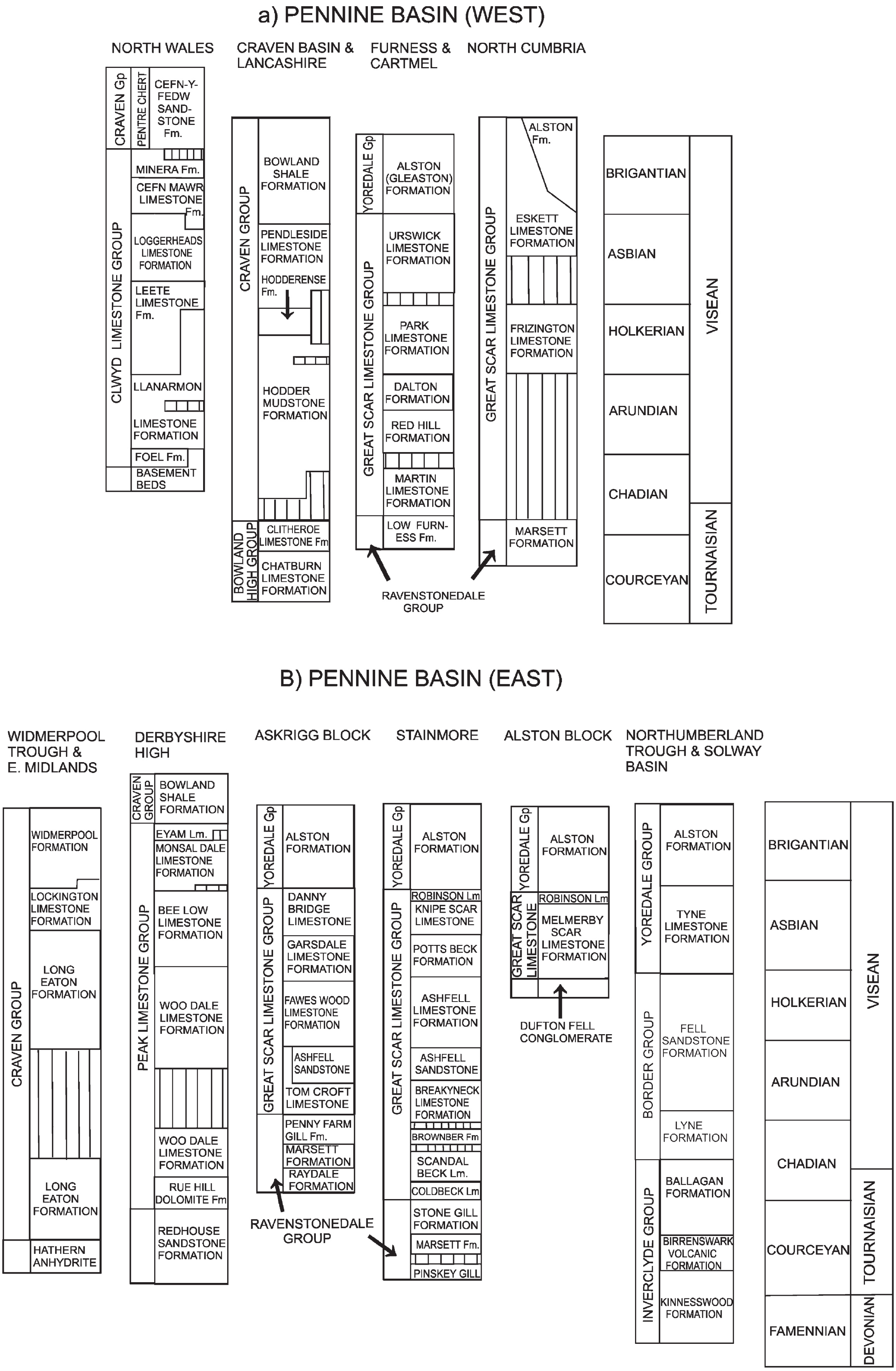

Fig. 9.13. Dinantian lithostratigraphical nomenclature for: (**a**) West Cumbria to North Wales; (**b**) Northumberland to the East Midlands. Adapted from Waters *et al.* (2006*a*).

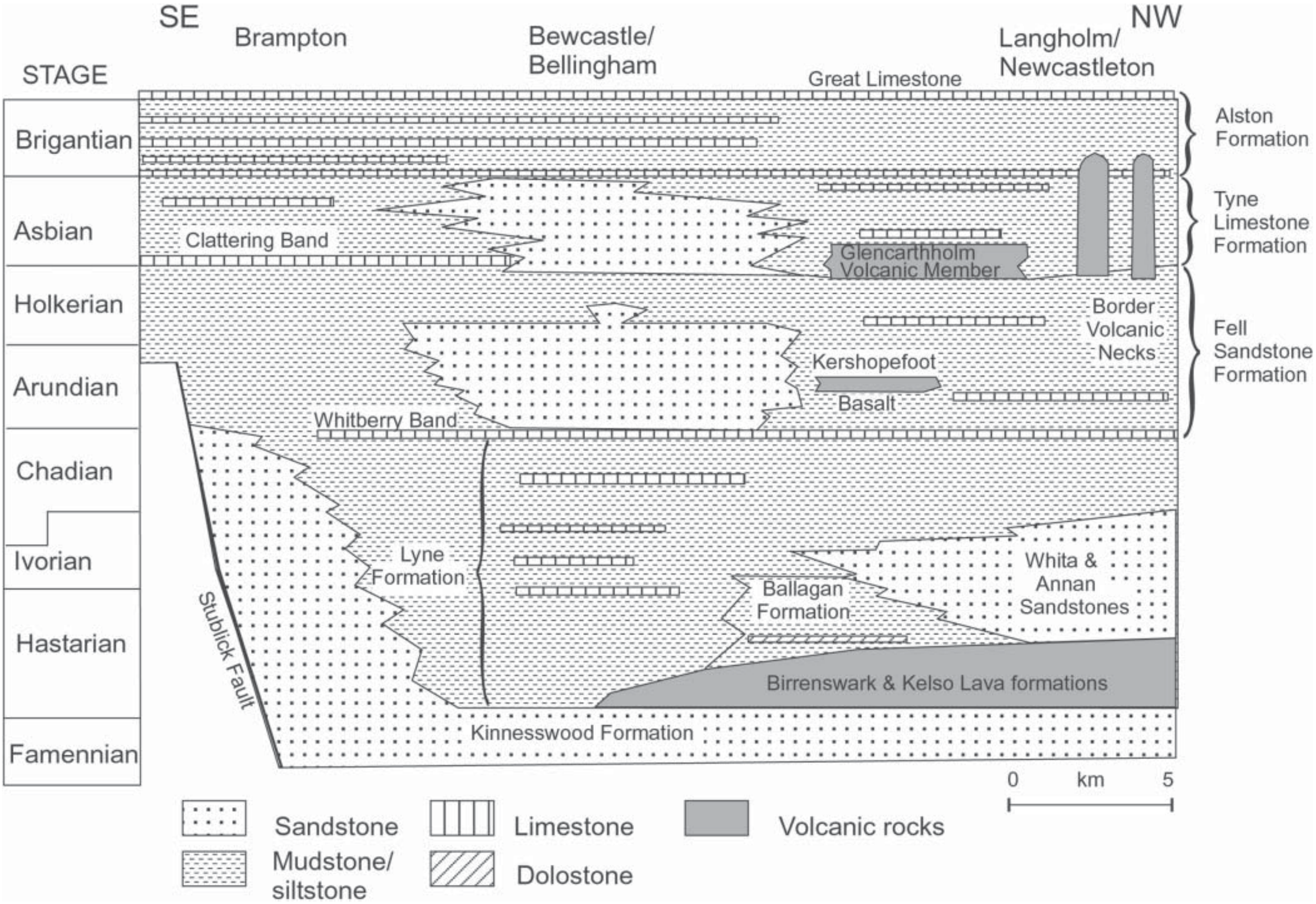

Fig. 9.14. Correlation of Dinantian strata within the Northumberland Trough–Solway Basin. A schematic NW–SE section, adapted from Gawthorpe *et al.* (1989).

occupying belts several kilometres wide, locally confined by intrabasinal syndepositional normal faults along the axial part of (Turner *et al*. 1993). Toward the central part of the trough the formation passes into a 300–450 m-thick succession of cyclical mixed fluvio-deltaic and shallow-marine sediments. This succession is similar to the underlying Lyne Formation, although the sandstones are thicker and limestones thinner in the Fell Sandstone Formation (Day *et al.* 1970). Within the central part of the trough, the base of the Fell Sandstone Formation is conformable and defined at the base of the Whitberry Band (Fig. 9.14).

A phase of volcanic activity within the Fell Sandstone Formation, known only from the northern margin of the Solway Basin, is evident as the Kershopefoot Basalt (Fig. 9.14).

Yoredale Group

The Yoredale Group is dominated by Mixed shelf carbonate and deltaic ('Yoredale') lithofacies association deposits and comprises three formations, namely the Tyne Limestone, Alston and Stainmore formations (the latter is Namurian in age). The group is the first lithostratigraphical unit within the Northumberland Trough–Solway Basin to extend beyond the confines of the graben. The group covered northern England during late Viséan–late Namurian times (Fig. 9.3). This distribution reflects a diminution in the topographical effects of the block and basin topography. However, tectonic controls on sedimentation persisted, with marked thickness variations across the Stublick–Ninety Fathom Fault, separating the Northumberland Trough from the Alston Block (Chadwick *et al.* 1995).

During the Asbian a heterogeneous succession, referred to as the Tyne Limestone Formation (Waters *et al.* 2006*a*), includes elements of a *Mixed shelf carbonate and deltaic 'Yoredale' lithofacies association*, which became established for the first time within the central basin. Localized lacustrine and deltaic deposits were deposited in the eastern part of the trough. The formation comprises typically upward-coarsening cycles of basal thin, laterally extensive marine limestone, marine shale often bioturbated, thin sandstone occasionally topped with seatearth and ganister, and an overlying coal. The base of the formation is the Clattering Band (Fig. 9.14), or its correlative Kingbridge Limestone, with distinctive fauna of *Siphonodendron (Lithostrotion) martini, Lithostrotion portlocki* and *Semiplanus*, marking the basal Asbian transgression (Day *et al.* 1970). In the NE Northumberland Trough there is a distinctive facies variation in the lower part of the formation, comprising up to 300 m of lacustrine shales and limestones, deltaic sandstones and coals.

A phase of volcanic activity restricted to the northern margin of the Solway Basin comprises the Glencartholm Volcanic Member (Fig. 9.14). Present at the base of the Tyne Limestone Formation, the succession of interbedded basaltic and trachytic pyroclastic rocks occur along with other volcaniclastic and sedimentary units and are up to 180 m thick (Lumsden *et al.* 1967). Numerous intrusive bodies, commonly referred to as 'volcanic necks', link the outcrops of the Kelso and Birrenswark Volcanic formations, and are probably associated with both the Holkerian–Asbian and earlier Tournaisian volcanic episodes.

The Alston Formation is described in detail for the area to the south of the Northumberland Trough, which includes its

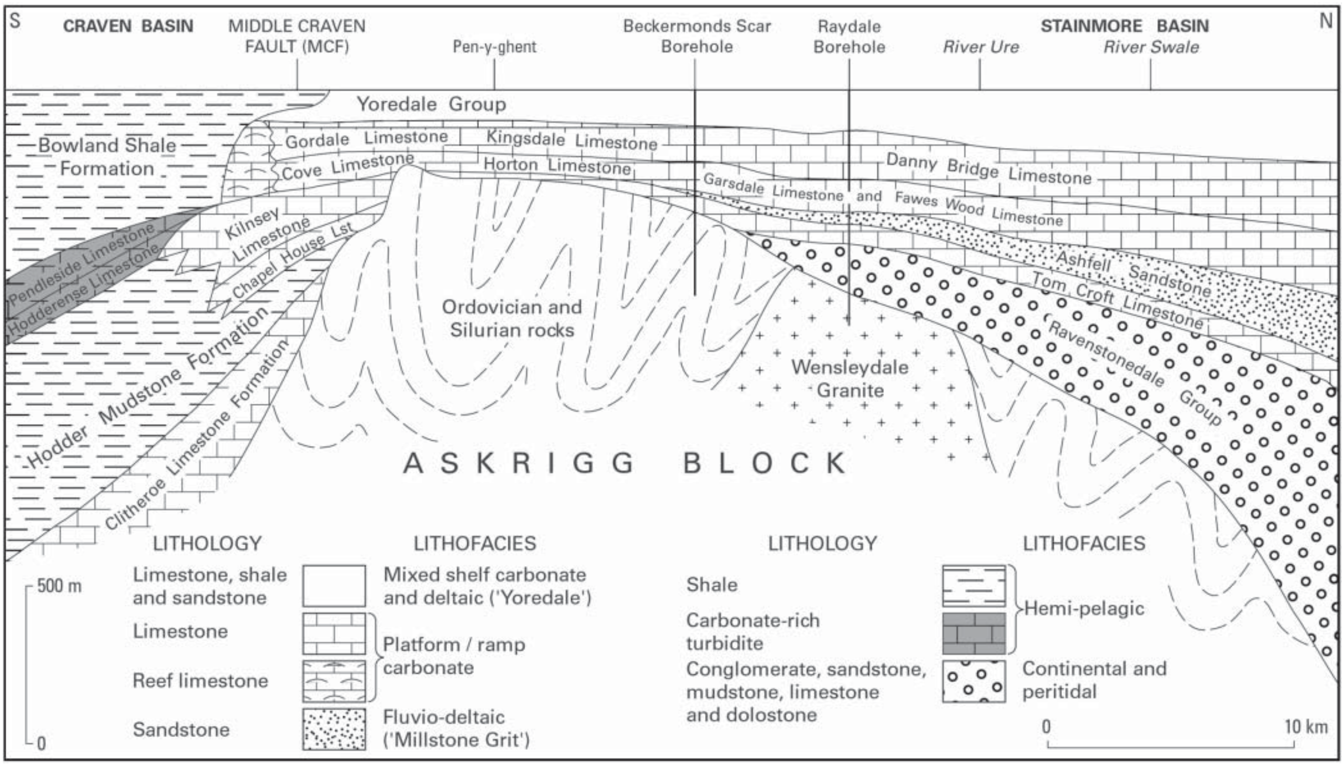

Fig. 9.15. Correlation of Dinantian strata within the northern part of the Craven Basin, Askrigg Block and Stainmore Trough. A schematic N–S section, adapted from Aitkenhead *et al.* (2002).

type area on the Askrigg Block. The base of the formation is taken at marker limestones used to define the base of the Brigantian Stage. These include the Callant Limestone of the Solway Basin, the Low Tipalt Limestone of the central part of the Northumberland Trough and a Spirifer Band a few metres below the Watchlaw Limestone of the NE part of the Northumberland Trough (Cossey *et al.* 2004).

Stainmore Trough, Askrigg–Alston blocks and Lake District High

Ravenstonedale Group

Carboniferous deposition commenced in this region during the Tournaisian with the *Continental and peritidal lithofacies* deposits of the Ravenstonedale Group (Fig. 9.8). The group is thickest, approximately 380 m, within the Stainmore Trough, thinning as the group onlaps onto the Askrigg Block (Fig. 9.15). The base of the group is everywhere marked by an unconformity upon Ordovician–Devonian strata. The onset of sedimentation within the Stainmore Trough is locally represented by a peritidal marine succession of grey, dolomitic limestone and dolostone, interbedded with calcareous mudstone and silty sandstone of the Pinskey Gill Formation. The formation lithologies yield a miospore assemblage broadly characteristic of the CM Zone (Holliday *et al.* 1979; Johnson & Marshall 1971) and a conodont assemblage also suggesting a Tournaisian age (Varker & Higgins 1979). However, the alluvial fan deposits of the Marsett Formation form the basal unit over much of the trough. The overlying Stone Gill Formation comprises grey, porcellanous limestone and thin dolostone, with beds of argillaceous limestone, sandstone and mudstone, representing a return to peritidal deposition.

Elsewhere, the Continental fluvial clastic ('Cornstone') facies is preserved in local basins, whose distribution adjacent to the Pennine/Dent and Lake District High boundary faults suggests that they were preserved in half-grabens formed during the initial, Late Devonian–Early Carbonifereous, stages of extension. The Low Furness Formation of south Cumbria (Rose & Dunham 1977) comprises a succession of conglomerate, sandstone and shale with subordinate limestone and gypsum, up to 240 m thick, and contains miospores characteristic of the Tournaisian CM Zone (Holliday *et al.* 1979), comparable in age to the alluvial fan deposits of the Stainmore Trough. However, the Mell Fell Conglomerate Formation (and equivalent Sedbergh Conglomerates and Shap Wells Conglomerates) were deposited on the margins of the Lake District High prior to Tournaisian volcanism and were tilted and eroded before the phase of Tournaisian marine transgression (Waters *et al.* 2006). These conglomerates are attributed to the Devonian Old Red Sandstone Group and are older than the alluvial fan deposits assigned to the Ravenstonedale Group. Tournaisian volcanism included the Cockermouth Lavas Formation of north Cumbria.

Deposition of the Ravenstonedale Group on the Askrigg Block followed an early Viséan sea-level rise. The Chadian–early Holkerian succession (Burgess 1986) was deposited in marginal marine conditions in comparison to the more open marine setting of the Stainmore Trough. Similar depositional environments of peritidal marine and fluvial environment with intervening periods of alluvial fan deposition are present on both the Askrigg Block and Stainmore Trough, although the succession is younger on the block. Initial deposition of hypersaline deposits of the Raydale Dolomite Formation comprises thinly bedded and nodular dolostones interbedded with siltstone and sandstone. The overlying Marsett Formation comprises reddish brown and greenish grey sandstone and conglomerate with rare dolostone beds, deposited within an alluvial environment. The uppermost Penny Farm Gill Formation consists of interbedded limestone, dolostone, sandstone and siltstone, often rhythmically bedded, representing a return to peritidal deposition. Locally, a nodular dolostone bed with rhizoliths, indicative of emergence, marks the top of the Ravenstonedale Group on the Askrigg Block (Burgess 1986).

Great Scar Limestone Group

During the Viséan a combination of marine inundation of block areas and reduced influx of siliciclastic material permitted establishment of a series of thick limestones, forming the Platform carbonate lithofacies association strata of the Great Scar Limestone Group. The group has a widespread distribution extending from south Cumbria, Askrigg Block (the type area), Stainmore Trough, Alston Block and Lake District High (Figs 9.8 & 9.13). The group name was formalized on the Askrigg Block by George *et al.* (1976) and is now used to define the facies development across northern England (Waters *et al.* 2006*a*). It replaces the Orton Group and part of the Alston Group in Stainmore and the Chief Limestone Group in west Cumbria.

Deposition of the Great Scar Limestone Group in the Stainmore Trough commenced during the Tournaisian with the Coldbeck Limestone Formation (Dunham & Wilson 1985). Here, the base of the group, taken at the top of the Algal Nodular Beds, is conformable upon the Ravenstonedale Group. The Great Scar Limestone Group is thickest in the Stainmore Trough, at about 800 m and also has the longest age-range for the group, from Tournaisian to Asbian. The Martin Limestone Formation comprises the earliest deposits in south Cumbria (Rose & Dunham 1977; Johnson *et al.* 2001). Both the Coldbeck and Martin Limestone formations are carbonate-dominated, deposited within a nearshore–peritidal, restricted marine environment with common stromatolites and oncolites.

A basal Arundian sea-level lowstand produced an unconformity at the base of the Breakyneck Limestone Formation, within the Stainmore Trough, the base of the Red Hill Formation in south Cumbria and base of the Frizington Limestone Formation in north and west Cumbria (Fig. 9.13). The subsequent sea-level rise established an open, shallow-marine environment and thick bioclastic limestones were deposited. During the Arundian–Holkerian these carbonates extended across the Stainmore Trough (Breakyneck Limestone and Ashfell Limestone formations), onto the flanks of the Lake District High (Red Hill, Dalton and Park Limestone formations in south Cumbria and Frizington Limestone Formation in north and west Cumbria) and onlapped the Askrigg Block (Tom Croft Limestone and Fawes Wood Limestone formations). The succession comprises typically dark grey bioclastic and highly bioturbated limestone, with crinoid banks, shelly or coral biostromes and algal (*Girvanella*) bands. Within the Stainmore Trough, there are brief incursions of siliciclastic deposits. The Brownber Formation represents alluvial deposits and the Ashfell Sandstone Formation comprises fluvio-deltaic strata,which encroached into the Stainmore Trough from the north, possibly as the distal extension of the Fell Sandstone Formation.

The Great Scar Limestone Group shows an evolution from thick, dark grey Arundian–Holkerian carbonates to pale grey Asbian–Brigantian cyclic limestones with eight major potholed bedding surfaces overlain by thin mudstones (Waltham 1971). The palaeokarst surfaces indicate periodic emergence. This succession is represented on the Askrigg Block by the Garsdale Limestone and Danny Bridge Limestone formations, and in south Cumbria and north and west Cumbria by the Urswick Limestone and Eskett Limestone formations, respectively. From late Holkerian to early Brigantian times, ‘Cracoean’ buildups of knoll reefs and shelf-edge tracts formed a marginal facies along the southern margin of the Askrigg Block carbonate shelf (Arthurton *et al.* 1988, Mundy 1994). The Alston Block was the final horst to be inundated, and deposition of the Melmerby Scar Limestone Formation both commenced and terminated during the Asbian Stage. Consequently, the group only reaches a maximum thickness of 107 m across the Alston Block (Dunham 1990).

Yoredale Group

Deposition of platform carbonates ceased over most of northern England during the late Viséan in response to the southward encroachment of the Mixed shelf carbonate and deltaic (‘Yoredale’) lithofacies association of the Yoredale Group. In west Cumbria, platform carbonate deposition persisted into early Namurian (Pendleian) times.

The Yoredale Group extends across northern England and ranges from late Viséan to late Namurian age (Fig. 9.8). The group is named following the long-established usage of the term Yoredale facies, based upon the description of Yoredale cycles as early as Phillips (1836). This term replaces the essentially chronostratigraphical Wensleydale Group of the Askrigg Block, Alston Group of the Alston Block and Lower and Upper Liddesdale groups of the Northumberland Trough (Waters *et al.* 2006*a*).

The Yoredale Group comprises typically upward-coarsening cycles of basal thin, laterally extensive marine limestone, marine shale, thin sandstone frequently topped with seatearth and ganister, and an overlying coal. The limestones are typically dark blue-grey, thin bedded and biomicritic, with a benthonic fauna and rare ammonoids. The sandstones are typically pale grey, fine–medium grained and quartzitic–subarkosic. The cycles, which range from 15 to 90 m thick, are named after the limestone present at the base of the cyclothem. Details of limestone nomenclature and correlations, and cyclothem thicknesses, are provided by Dunham & Wilson (1985) for the Askrigg Block and Stainmore Trough, and by Dunham (1990) for the Alston Block. The progradation of high-constructive lobate deltas deposited the clastic sediments, with extensive shallow-marine reworking following delta abandonment (Elliott 1975). The marine limestones were deposited as a consequence of sea-level rise and switching or abandonment of the delta lobes.

The conformable base of the Yoredale Group is typically drawn at the base of marine limestone marker bands. On the Alston Block the base of the group is taken at the base of the Peghorn (Lower Smiddy) Limestone, defined as the Brigantian Stage Basal Stratotype (George *et al.* 1976). The base of the group on the Askrigg Block and Stainmore Trough occurs at the base of the Lower Hawes Limestone. The greatest thickness for the Dinantian component of the group is 1219 m, and was proved in the eastern part of the Stainmore Trough (Dunham & Wilson 1985). The group, formations and individual sandstones tend to thicken into troughs and half-grabens.

The Brigantian Alston Formation is distinguished from the Namurian components of the group (see Namurian: advancing deltas) by the common presence of thick, bioclastic limestones. In the absence of the *Cravenoceras leion* Marine Band, the base of the Namurian is taken near to the base of the Great Limestone of the Alston Block–Stainmore Trough and equivalent Main Limestone of the Askrigg Block.

Craven Basin

Within the overall basinal environment of the Craven Basin, isolated areas of platform carbonates developed on small footwall highs. Some of these platforms were short-lived, becoming submerged and buried beneath Dinantian basinal shales of the Craven Group in response to both active rifting (Gawthorpe 1987) and periodic eustatic sea-level rises.

Bowland High Group

At least 2300 m of Tournaisian carbonates, including the Chatburn Limestone and Clitheroe Limestone formations, accumulated on the Bowland High. The Chatburn Limestone Formation comprises mostly medium-dark grey, bioclastic and peloidal packstone and wackestone limestone, locally with abundant algal oncolites, with thin subordinate beds of calcareous mudstone (Arthurton *et al.* 1988, Facies associations 1 and 2 of Gawthorpe 1986). The formation was deposited on a

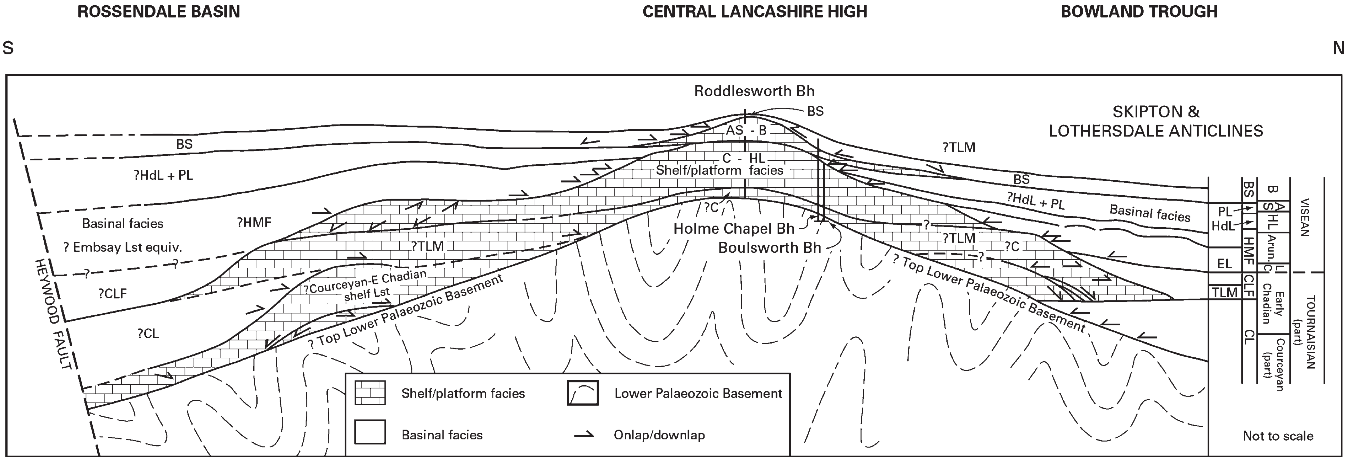

Fig. 9.16. Correlation of Dinantian strata within the western part of the Craven Basin. A N–S composite seismic reflection profile, adapted from Kirby *et al.* (2000). Lithostratigraphy: BS, Bowland Shale Formation; CL, Chatburn Limestone Formation; CLF, Clitheroe Limestone Formation; EL, Embsay Limestone Formation; HdL, Hodderense Limestone Formation; HMF, Hodder Mudstone Formation; PL, Pendleside Limestone Formation; TLM, Thornton Limestone Member. Chronostratigraphy: Arun., Arundian; AS, Asbian; B, Brigantian; C, Courceyan; HL, Holkerian; LC, Late Chadian.

shallow carbonate shelf (Riley 1990) or gently sloping seafloor ranging from 75–100 m depth, with a significant contribution of extra-basinal, fine terrigenous material at greater depths (Gawthorpe 1986). The overlying Clitheroe Limestone Formation comprises pale grey packstone, wackestone and floatstone with subordinate mudstone, with rapid lateral changes in thickness and facies (Facies association 7 of Gawthorpe 1986). Waulsortian limestones (knoll reefs or mud mounds) are a distinctive component of the formation. The Clitheroe Limestone is associated with the development of a carbonate ramp and northward retreat of shelf carbonates to be replaced by Waulsortian limestones (Riley 1990). The buildup of Waulsortian limestones was briefly interrupted by a phase of shallowing and development of storm-generated carbonates.

Seismic and geophysical logs have been used to identify further small accumulations of platform carbonates in the subsurface (Fig. 9.16). Successions of Chadian–Asbian age for the Central Lancashire High and Holme High have been recognized (Evans & Kirby 1999).

Craven Group
During the Viséan, Hemi-pelagic lithofacies association deposits of the Craven Group dominated within the Craven Basin. The Craven Group replaces numerous geographically localized group names for a Dinantian and Namurian succession of this facies, located between the platform carbonates of northern England and the northern flank of the Wales–Brabant High (Waters *et al.* 2006*a*). Sediments accumulated predominantly from suspension in moderately deep water, largely below the storm wave-base. Thin sandstone and limestone beds were introduced, possibly by storms and/or as turbidites.

The lower part of the Craven Group comprises calcareous mudstone and siltstone, interbedded with wackestone limestone and subordinate limestone breccias, conglomerates and sandstones (Gawthorpe 1986; Arthurton *et al.* 1988; Riley 1990). The formations are broadly defined by the relative abundance of limestone and mudstone. The limestone beds (e.g. within the Hodder Mudstone and Pendleside Limestone formations) represent slope carbonate turbidites developed as aprons basinward to the ‘Cracoean reef’ facies of the Askrigg Block (Fig. 9.15) or adjacent to the Central Lancashire High (Fig. 9.16). The presence of slumps, debris flows and gravity slides in the Craven Group (Gawthorpe & Clemmey 1985; Riley 1990) are evidence for relatively steep slopes and have been considered the product of slope instability induced by late Chadian–early Arundian and late Asbian–early Brigantian tectonic activity (Gawthorpe 1987). The upper part of the Craven Group is the Bowland Shale Formation (Fig. 9.13), of late Brigantian and Namurian age. The formation comprises dark grey and black organic-rich mudstone, with subordinate beds of siltstone, sandstone and dolomitic limestone. The formation shows an increase in siliciclastic sandstone turbidites derived from deltas accumulating on the margins of the basin.

The Craven Group typically rests unconformably upon submerged platform carbonates, including the Clitheroe Limestone Formation of the Craven Basin (Fig. 9.15) and Courceyan–Asbian carbonates upon the Central Lancashire High (Fig. 9.16). Unconformities occur internally within the group at the base of the Pendleside Limestone Formation in Lancashire and Pentre Chert Formation in North Wales. The absence of proven late Chadian and Arundian strata within the Long Eaton Formation of the Widmerpool half-graben (Fig. 9.17) may also indicate the presence of an unconformity. This unconformity may relate to a late Holkerian phase of basin inversion, also seen on the margin of the Wales–Brabant High (Fraser & Gawthorpe 1990).

Derbyshire

During the Tournaisian, strata of the Continental and peritidal lithofacies association were deposited adjacent to the Derbyshire High (Figs 9.9a, 9.13 and 9.17). Alluvial fan gravels, the Redhouse Sandstone Formation, have been proved in the subsurface (Aitkenhead & Chisholm 1982) and comprise at least 170 m of reddish brown pebbly sandstone with beds siltstone and mudstone and nodular dolomite recording calcrete development. Evaporites proved in the subsurface at Eyam (the Middleton Dale Anhydrite Formation) also belong to this phase.

Peak Limestone Group
A late Tournaisian marine transgression established the platform carbonates of the Peak Limestone Group, which generally rest unconformably upon deformed Lower Palaeozoic strata, or conformably upon strata of the Continental and peritidal lithofacies association. Internally, the group includes several local disconformities (Fig. 9.17). Subaerial palaeokarstic dissolution surfaces are also common, as in North Wales, in the Asbian and Brigantian limestones (Walkden 1974). The lithostratigraphical nomenclature for the Peak District

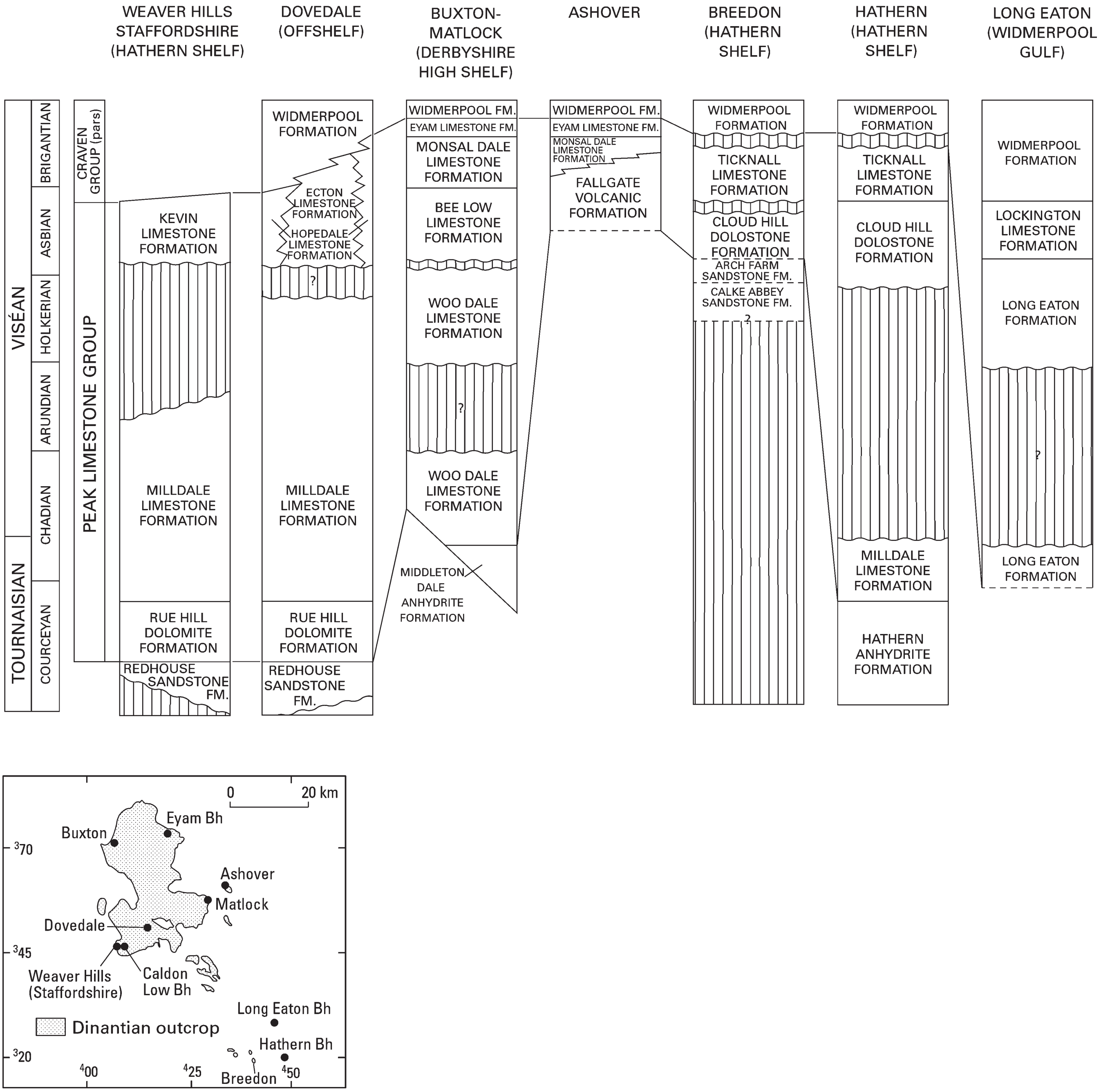

Fig. 9.17. Correlation of Dinantian strata in the Peak District of Derbyshire and Staffordshire. Adapted from Aitkenhead & Chisholm (1982).

(Fig. 9.17) is adapted by Waters *et al.* (2006*a*) from Aitkenhead & Chisholm (1982).

The Milldale Limestone Formation comprises limestone of both Waulsortian reef and inter-reef facies. The single or compound mud-mounds are composed of fossiliferous, massive micrite with common spar-filled cavities, whereas the inter-reef facies consists of well-bedded crinoidal biosparite and subordinate dark grey, cherty, micritic limestone. This deeper water succession, deposited at water depths of 220–280 m (Bridges & Chapman 1988), passes laterally and gradationally into the shallower water Woo Dale Limestone Formation (Fig. 9.17). The lower Woo Dale Limestone Formation, which comprises a grey-brown–dark grey dolomitic limestone, passes up into medium and pale grey, thick-bedded biosparites. The presence of 'birdseye' structures and rare coals within the top part of the formation suggests a regressive event associated with development of peritidal and restricted lagoonal environments during Holkerian times (Schofield & Adams 1985).

By Asbian times there was a clear differentiation between a shelf area, fringed by apron-reefs, and an off-shelf area where ramp carbonates are overlain by basinal deposits of the Craven Group. The shelf area includes the Asbian Bee Low Limestone Formation and the Brigantian Monsal Dale Limestone and Eyam Limestone formations (Fig. 9.17). The Bee Low Limestone Formation consists of very thick beds of pale grey biosparite and biopelsparite calcarenites, with pedogenic crusts and palaeokarstic surfaces, commonly overlain by thin, red-brown and grey-green bentonites. The Monsal Dale Limestone Formation comprises a heterogeneous succession of pale–medium grey, thin- to thick-bedded limestones with sporadic cherts, and dark grey, thin-bedded, cherty limestones with argillaceous partings. The basal limestone often includes abundant *Girvanella* or *Saccaminopsis*. The Eyam Limestone Formation typically comprises dark grey, thin-bedded, cherty bioclastic limestone with dark grey mudstone intercalations. A reef facies comprises pale grey limestone in small knolls, typically of massive biomicrite, with a distinctive brachiopod fauna. These reefs were deposited in comparatively shallow water with evidence of periodic emergence, in contrast to the deeper water Waulsortian mud-mounds of the Milldale Limestone Formation. In the off-shelf area, there is an Asbian–Brigantian succession of carbonate turbidites, which show an upward transition from limestone-dominated (Ecton Limestone Formation) passing up into deeper water mudstones with limestone and sandstone turbidites (Widmerpool Formation). The Hopedale Limestone Formation comprises Cracoean reef and inter-reef facies developed between the shelf and off-shelf areas.

In Derbyshire basaltic lavas, sills and pyroclastic rocks are common. There are several centres of igneous activity, including Matlock and Miller's Dale. The eruptions from the different centres are not contemporaneous and flows cannot be correlated from one centre to another (Aitkenhead *et al.* 1985). Walters & Ineson (1981) recognized 30 distinct lavas and beds of pyroclastic rock and Francis (1970) identified at least 14 agglomerate vents. In the subsurface to the east (Fig. 9.17), the proportion of volcanic rocks to limestone increases, and the name Fallgate Volcanic Formation has been given to the succession there (Aitkenhead & Chisholm 1982). The thickest section (293 m, not bottomed) was proved in a borehole near Ashover, where tuffs and basalts were interbedded with thin limestones. Much of the lava near Ashover was erupted subaqueously (Ramsbottom *et al.* 1962). Locally, the upper part of the Widmerpool Formation in the adjacent Widmerpool Gulf includes Brigantian subaqueous basaltic lavas, tuffs, agglomerates and hyaloclastites.

The majority of igneous activity is of tholeiitic affinity (Macdonald *et al.* 1984) and occurred during early Brigantian times (Fig. 9.7), although extrusive igneous rocks are also associated with carbonates of late Holkerian–late Brigantian age (Walters & Ineson 1981). The lavas are thin, typically a few tens of metres, but with some discrete flows up to 42 m thick (Francis 1970) and multiple flows in places (Walters & Ineson 1981; Macdonald *et al.* 1984). They are usually highly altered, fine-grained, vesicular, olivine-phyric and aphyric basalt. Many lavas are thought to have been subaerial flows, although some lavas may have flowed across wet sediments and terminated locally in shallow water (Walkden 1977; Macdonald *et al.* 1984). Other lavas are subaqueously erupted hyaloclastites, as suggested by Elliott (in Ramsbottom *et al.* 1962) and illustrated by Aitkenhead *et al.* (1985, plate 9). The Calton Hill Complex, located about 6 km east of Buxton, comprises Brigantian tuffs, agglomerates and lavas of the Upper Miller's Dale Lava, intruded by alkaline basanite sills, which host spinel lherzolite and harzburgite nodules. These nodules, brought to the surface during the volcanic activity, represent the only English examples of mantle-derived material (Donaldson 1978).

Tuffs are typically subordinate to lavas and sills. K-bentonites are widespread, most notably in the Bee Low Limestones of Asbian age. Between 30 and 40 beds, generally less than 3 cm thick, although locally reaching up to 1.25 m are present within this formation (Aitkenhead *et al.* 1985; Walkden 1972, 1977). These are thought to represent fine volcanic ash of distant origin, possibly not related to the Derbyshire volcanism.

The sills are dominantly medium- to coarse-grained olivine–dolerites, distinguished by the presence of altered olivine phenocrysts, ophitic intergrowths of clinopyroxene and plagioclase, and the absence or rarity of vesicles and amygdales (Macdonald *et al.* 1984). The majority of these dolerite intrusions were emplaced along planes of weakness between lavas and limestones. The sills appear to be genetically related to the extrusive rocks and are probably also of Dinantian age, although whole-rock K–Ar dates on the sills provides dates that are considerably younger than the lavas (Fig. 9.7). The discrepancy is probably a function of argon loss during hydrothermal alteration.

North Wales

Along the northern flank of the Wales–Brabant High 'Basement Beds' of North Wales (Fig. 9.18) represent a number

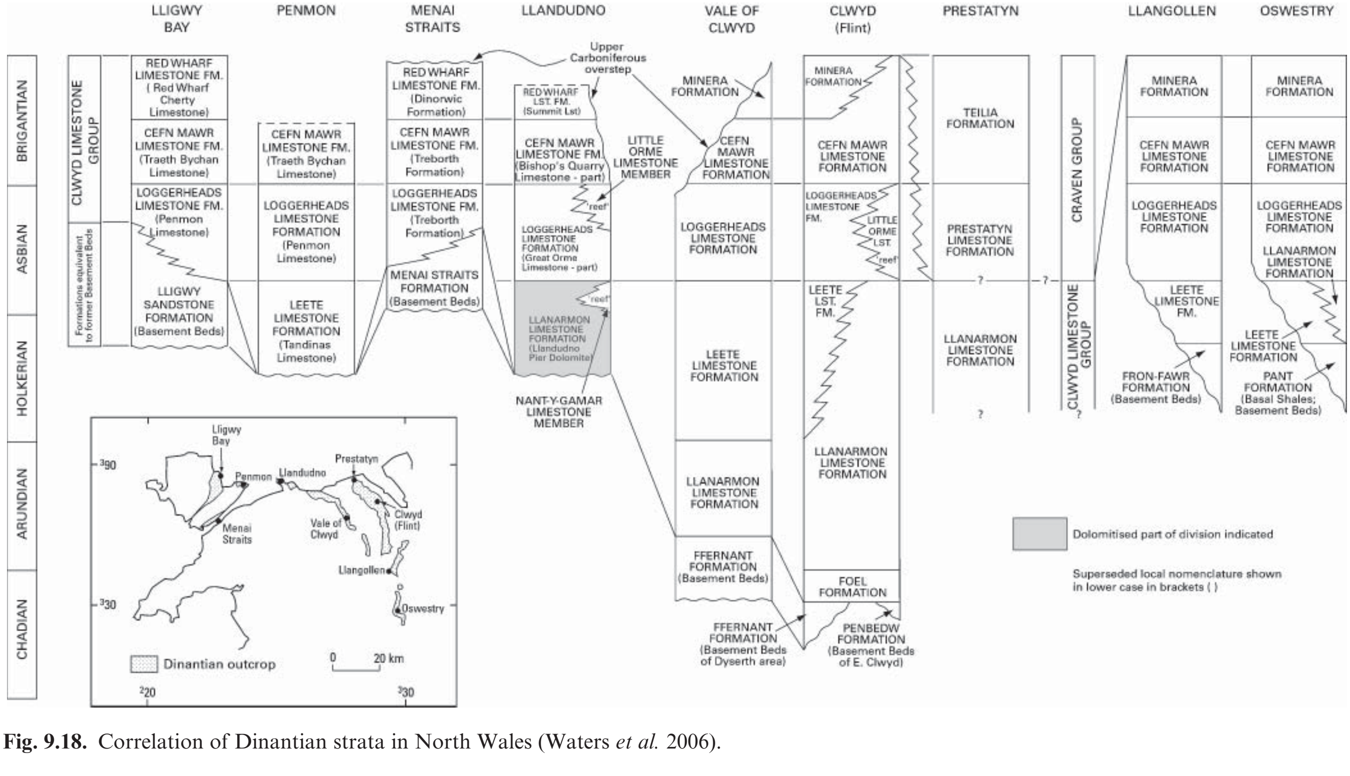

Fig. 9.18. Correlation of Dinantian strata in North Wales (Waters *et al.* 2006).

of isolated alluvial deposits infilling an incised, possibly fault-influenced, topography at different times (Davies *et al.* 2004). Clasts were derived from local upland areas and composition varies between these isolated deposits. Locally, principally in the Vale of Clwyd, the succession comprises up to 75 m of reddened alluvial breccias, conglomerates, sandstones, siltstones and mudstones. Calcareous nodules and thin beds of variegated, red and green, argillaceous, nodular limestone or dolomite record varying stages in calcrete development. The 'Basement Beds' of North Wales are unfossiliferous, as old as Tournaisian in age.

Clwyd Limestone Group

The Clwyd Limestone Group comprises up to 900 m of dominantly shallow-marine ramp and platform carbonates, which rest locally upon 'Basement Beds', or elsewhere with marked unconformity on Silurian rocks. Strata now included within the Clwyd Limestone Group were thought to comprise only Asbian and Brigantian strata (George *et al.* 1976). However, earlier Chadian, Arundian and Holkerian strata have subsequently been discovered (Davies *et al.* 1989; Somerville & Strank 1984*a*, *b*). The lithostratigraphical nomenclature for North Wales (Fig. 9.18) described below is that of Davies *et al.* (2004).

In North Wales, carbonate sedimentation commenced during late Chadian times with deposition of the Foel Formation in a lagoon or intertidal and supratidal carbonate mud flat. These deposits alternate with facies interpreted as high-energy and open marine deposits that record invasion of sediment derived from sheltering shoals or barriers (Davies *et al.* 1989). The formation comprises porcellaneous calcite mudstone and wackestone, argillaceous packstone, peloidal and locally ooidal grainstone, cryptalgal laminites and oncolitic floatstone, with intercalated red and green variegated mudstone, siltstone and calcareous sandstone.

The major early Arundian marine transgression deposited the Llanarmon Limestone Formation lithologies under relatively high-energy, shallow-marine conditions. The lower part of the formation developed as an eastward facing carbonate ramp (Somerville *et al.* 1989), which by the late Arundian had evolved into a carbonate platform. The formation comprises pale, thick-bedded, peloidal and skeletal grainstones, with subordinate dark, thinner bedded packstones. The upper part of the formation intertongues with, and is progressively replaced by, the Leete Limestone towards the south.

During the Holkerian–early Asbian, the Leete Limestone Formation records a return to deposition in a restricted, probably hypersaline, lagoonal and peritidal setting along the margin of the Wales–Brabant High (Somerville & Gray 1984). The formation comprises rhythmic units of dark, argillaceous skeletal packstone and paler grainstone, overlain by porcellaneous limestone (Davies *et al.* 1989; Somerville & Strank 1984*b*).

During the late Asbian–early Brigantian, the cyclic sequences of the Loggerheads Limestone and overlying Cefn Mawr Limestone represent shoaling-upwards rhythms developed as the product of consecutive marine inundations. The Loggerheads Limestone Formation consists mainly of pale, thick-bedded, commonly pseudo-brecciated, skeletal and peloidal packstone, present in cycles typically topped by palaeokarstic surfaces, and overlain by mudstone palaeosols. Coral and brachiopod assemblages are consistent with the late Asbian D_1 Subzone (George *et al.* 1976). The overlying Cefn Mawr Limestone Formation consists of wackestone, packstone and grainstone arranged in cyclic sequences, the boundaries of which are defined by correlatable calcrete and palaeokarstic features locally overlain by bentonitic clay palaeosols. Black, replacive chert nodules are common. The formation includes a rich coral assemblage, detailed by Somerville (1979), typical of the D_2 Subzone of the *Dibunophyllum* Biozone and the Brigantian Stage. The presence of karstic surfaces, bentonitic soils and well-developed calcrete profiles demonstrate long emergent intervals in response to marine regressions (Walkden 1974, 1977).

The cyclic shoaling upwards successions continue into late Brigantian times, with deposition of Minera Formation limestones and sandstones. The limestone beds are arranged in wackestone, packstone and grainstone cycles, which range from storm wave-base to fair-weather wave-base deposits. Thick, calcareous sandstones commonly developed at the top of the cycles, were deposited within upper shoreface and beach environments (Davies *et al*. 2004).

Late Dinantian igneous activity, equivalent to that seen in Derbyshire, is largely absent in North Wales. The only exception is the Little Wenlock Lava of the Welsh Borders, a Brigantian vesicular microporphyritic olivine-basalt, up to 30 m thick (Francis 1970).

South Wales and Bristol

Avon Group

A major phase of northward-directed marine transgression during the Tournaisian resulted in deposition within a shelf setting of the mudstone-dominated Avon Group, with strata onlapping the southern flank of the Wales–Brabant High. The group mainly comprises dark grey or black mudstone with interbedded crinoidal bioclastic or oolitic limestone. The Avon Group (former Lower Limestone Shale and Cefn Bryn Shales) is named from the type area of the Avon Gorge, south of Bristol, where it is up to 150 m thick, but it also extends across South Wales (Waters *et al.* 2006*a*). The Avon Group is entirely Tournaisian in age (Davies *et al.* 1991).

In the Vale of Glamorgan, South Wales, the Avon Group has been subdivided into three formations (Fig. 9.19a). Initial marine transgression is associated with deposition of interbedded thin skeletal packstone limestone and grey mudstone, with subordinate calcareous sandstone, oolite and hematitic skeletal grainstones (Gayer *et al.* 1973; Waters & Lawrence 1987) of the Tongwynlais Formation. The formation is absent in the North Crop of South Wales, where the middle unit, the Castell Coch Limestone, rests disconformably upon Devonian Upper Old Red Sandstone. The Castell Coch Limestone Formation represents a regional shallowing event, with progradation of high-energy oolite shoals across the Dinantian shelf. The formation comprises thick to well-bedded, commonly cross-bedded, skeletal and oolitic grainstones, rich in crinoidal debris and shows secondary reddening, commonly associated with dolomitization (Waters & Lawrence 1987; Wilson *et al.* 1990). The highest unit, the Cwmyniscoy Mudstone Formation, represents a further marine transgressive deposit (Waters & Lawrence 1987; Barclay *et al.* 1989; Wilson *et al.* 1990). The formation comprises dark grey silty mudstone, sparsely fossiliferous, with subordinate thin bioclastic limestone and calcareous siltstone beds. The mudstone beds are thinner toward the gradational boundary with the overlying Pembroke Limestone Group.

In the Bristol area the Avon Group includes a lower Shirehampton Formation (Fig. 9.19b), which comprises coarse bioclastic and ooidal limestone with subordinate calcareous sandstone and mudstone that has a brackish water fauna with *Lingula* (Kellaway & Welch 1993), mainly deposited in a marine influenced lagoonal environment. Some interbeds of sandstone and red and green mudstone occur locally. A reddened crinoidal limestone, the 'Bryozoa Bed' occurs at the top of the formation. A non-sequence is overlain by greenish grey mudstone with interbedded black crinoidal limestone with a rich shelly fauna of the undivided Avon Group (Kellaway & Welch 1993).

Pembroke Limestone Group

During the Tournaisian the mudstone-dominated shelf deposits of the Avon Group pass upwards into the shallow-marine carbonate-dominated deposits of the Pembroke Limestone Group (Waters *et al.* 2006*a*). This group is characterized by

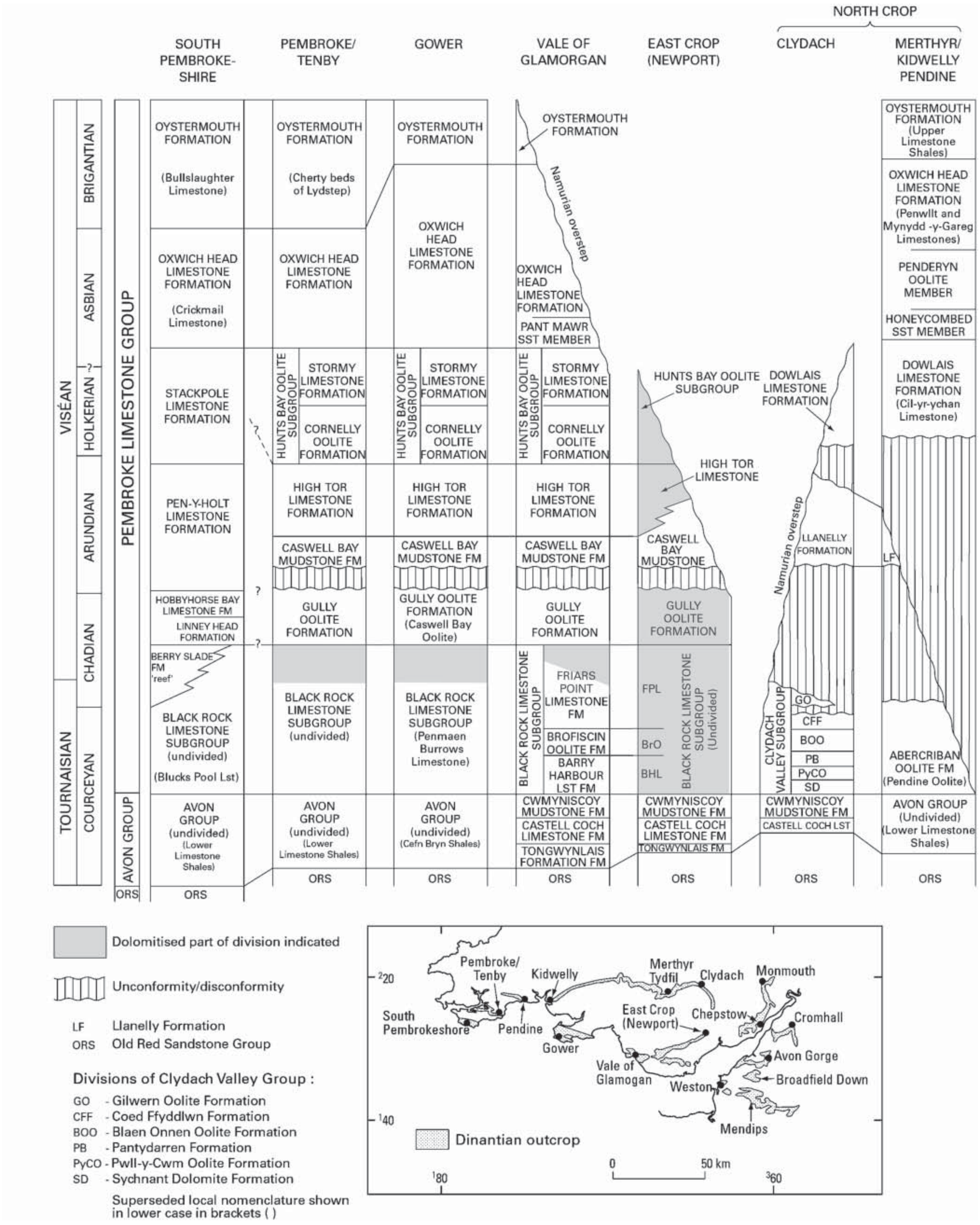

Fig. 9.19. Dinantian lithostratigraphical nomenclature for (**a**) South Wales and (**b**) southern England (Waters *et al.* in press); (**c**) N–S sections showing Dinantian facies variations for South Wales (after Wright 1987).

the Platform carbonate lithofacies association and shows an evolution from Carbonate ramp facies during the Courceyan–Arundian to Carbonate shelf facies during the Holkerian and Asbian (Fig. 9.19c). The lowermost part of the group is identified as the Black Rock Limestone Subgroup. First named in the Bristol region, the subgroup comprises predominantly

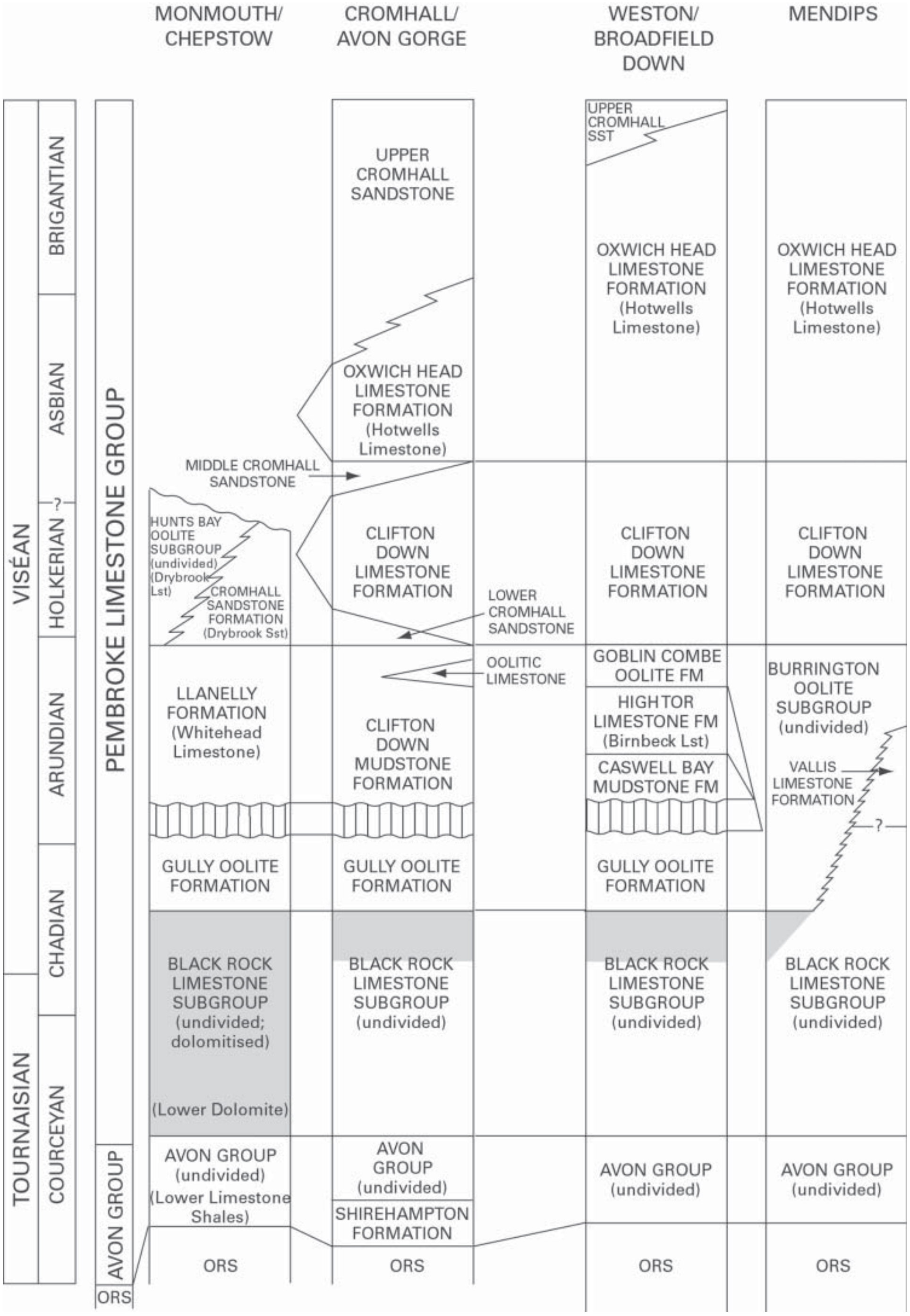

Fig. 9.19b. Continued.

bioclastic limestones, deposited in a ramp setting, that also extend across the South Crop of South Wales (Fig. 9.9a, b). This subgroup passes northward into the Clydach Valley Subgroup of the North Crop of the South Wales Coalfield, dominated by oolitic shoals and peritidal deposits, with abundant palaeosols (Barclay *et al.* 1989). Towards the east of Abergavenny the succession becomes entirely dolomitic.

The Black Rock Limestone Subgroup contains a rich fauna of conodonts, corals and foraminifera and ranges from Tournaisian to Chadian age. The subgroup shows a prominent southwards thickening, to a maximum of 500 m in the Vale of Glamorgan (Waters & Lawrence 1987; Wilson *et al.* 1990) (Fig. 9.19c), and more than 250 m in the Mendips. This contrasts with the condensed, approximately 45 m thick succession of the Clydach Valley Subgroup (Barclay *et al.* 1989). The Black Rock Limestone Subgroup comprises dark grey–black, poorly sorted crinoidal limestone, locally with chert bands and nodules. The limestone is commonly dolomitized, with dolostone generally present in the upper part of the subgroup over the Bristol–Mendips areas and South Crop of South Wales and throughout the succession in the East Crop of South Wales and the Forest of Dean. In the Vale of Glamorgan, where dolomitization is less pervasive, component formations are recognized (Waters & Lawrence 1987; Wilson *et al.* 1990). The lowest, the Barry Harbour Limestone Formation, is a high-energy storm deposit comprising thin-bedded, dark grey,

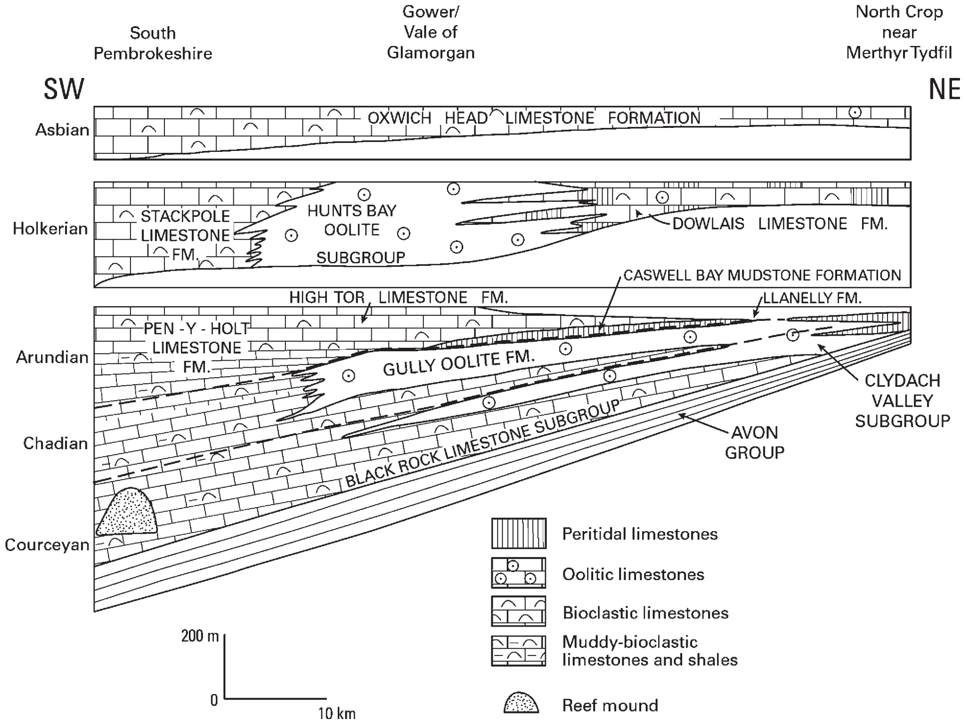

Fig. 9.19c. Continued.

fine- to coarse-grained, crinoidal, skeletal packstone with thin beds of shaly, calcareous mudstone and common replacive chert lenses. The overlying oolite shoals of Brofiscin Oolite Formation were deposited in relatively shallow-marine waters. The formation comprises pale–dark grey, massive to thick-bedded, well-sorted, predominantly ooidal and in part skeletal grainstone. Renewed transgression and re-establishment of deeper-water shelf conditions is associated with deposition of richly fossiliferous, mainly crinoidal, and strongly bioturbated limestones of the Friars Point Limestone Formation. The formation comprises thickly bedded, dark grey–black, fine-grained, skeletal packstones with subordinate thin interbeds of shaly, argillaceous, skeletal packstone.

A late Chadian marine regression is associated with deposition of high-energy carbonates of the Gully Oolite Formation. The regression culminated in a prominent non-sequence at the top of the formation, evident as an irregular and pitted palaeokarst surface sometimes referred to as the mid-Avonian unconformity. The formation, first defined in the Bristol area, is also found across South Wales and the Forest of Dean (Fig. 9.19a). It consists of a distinctive pale grey, massive, medium- to fine-grained, cross-bedded ooid, peloid and skeletal grainstone, locally in coarsening-upward cycles (Waters & Lawrence 1987). The formation shows a southward thickening (Fig. 9.19c), with a maximum thickness of 83 m recorded in the Cardiff area, passing southward into bioclastic limestone of the Linney Head Limestone and Hobbyhorse Bay Limestone formations in south Pembrokeshire.

A basal Arundian marine transgression deposited a mudstone-dominated succession within a lagoonal/peritidal setting. In South Wales and the Weston-super-Mare district this succession is seen as the Caswell Bay Mudstone Formation, which appears to be laterally equivalent to the Clifton Down Mudstone of Bristol, though the latter formation is thicker and has a greater chronostratigraphical range (late Chadian–Arundian). These formations are pale grey–green, porcellaneous limestone, interbedded with dark grey and brown shale and argillaceous skeletal wackestone and packstone. Cryptalgal lamination and birdseye structures are common. The Caswell Bay Mudstone Formation, up to 15 m thick in the Vale of Glamorgan, thins southward and is absent from the Mendips and the southern parts of the Cardiff and Bridgend areas (Fig. 9.19a, b & c).

During the Arundian marine transgression a barrier complex developed, which limited the peritidal deposits of the Caswell Bay Mudstone to the north (Fig. 9.19c). During continued transgression the barrier complex migrated northwards over the peritidal facies (Wilson *et al.* 1990). The barrier complex is defined by the lower part of the High Tor Limestone Formation in South Wales. The High Tor Limestone in South Wales consists of thin- to thick-bedded, bioclastic limestone with a few thin beds of shaly dolomite mudstone and siltstone, whereas in the Weston-super-Mare district the formation (formerly the Birnbeck Limestone) comprises grey–dark grey, thick- to very-thick-bedded bioclastic limestone where the lower part is commonly oolitic (Whittaker & Green 1983).

A late Arundian marine regression resulted in the return of high-energy shoreface deposits of the upper part of the High Tor Limestone Formation in South Wales and Goblin Combe Oolite Formation in the Weston-super-Mare area. The Goblin Combe Oolite comprises pale grey–black, massive, medium- to coarse-grained, ooidal and crinoidal limestone. The High Tor Limestone and Goblin Combe Oolite formations are absent north of Bristol, where they pass laterally into the Clifton Down Mudstone (Fig. 9.19b).

The Llanelly Formation of the North Crop of South Wales shows a comparable history of Arundian marine transgression, with basal fluvial deposits overlain by a shallow-marine peritidal complex, with subsequent regression indicated by re-establishment of fluvial floodplain deposition. The formation rests upon a prominent palaeokarstic surface, above a pedified horizon at the top of the Clydach Valley Subgroup (Wright 1981).

Late Arundian–Holkerian oolitic limestone, with subordinate skeletal, peloidal, oncolitic and micritic limestone present in South Wales are recognized as the Hunts Bay Oolite Subgroup (Fig. 9.19a), comprising two formations in the Vale of Glamorgan; the Cornelly Oolite and Stormy Limestone formations (Wilson *et al.* 1990), with the latter deposited in a lagoonal/peritidal back-barrier environment, which developed behind the Cornelly Oolite shoal. In the Bristol region the strata of equivalent age are identified as the Clifton Down Limestone Formation (Fig. 9.19b). The predominantly bioclastic Stackpole Limestone Formation of south Pembrokeshire, deposited in a front barrier, barrier and back barrier setting and the Dowlais Limestone Formation of the North Crop, a succession of foetid and bituminous peloidal grainstone, packstone and wackestone with dark grey shale interbeds representing lagoonal and peritidal deposits (Barclay *et al.* 1988, 1989), are also the same age as the Hunts Bay Oolite Subgroup. The thickest development of the subgroup is 245 m in the Bridgend area, thinning to the east and removed in the East Crop by the Namurian overstep (Fig. 9.19a). The base of the subgroup is typically conformable. However, the Dowlais Limestone Formation of the North Crop rests upon an unconformity, overstepping older strata toward the west, ranging from Llanelly Formation to the Avon Group.

Continued late Arundian shoaling is associated with deposition of the lower part of the Cornelly Oolite Formation, which comprises a thickly bedded, cross-bedded, ooid grainstone. The marine regression locally culminated in emergence and palaeokarst development. The succeeding strata record a basal Holkerian marine transgression and re-establishment of oolite shoals. The Stormy Limestone and Dowlais Limestone formations are interpreted as deposits within a lagoonal/peritidal back-barrier environment, which developed behind the Cornelly Oolite shoal (Barclay *et al.* 1988, 1989; Wilson *et al.* 1990). The Stormy Limestone Formation comprises a heterolithic succession of interbedded porcellaneous limestone with common stromatolitic lamination and birdseye structures, bioclastic limestone, and packstone-grainstone with skeletal grains, ooids, peloids and intraclasts. Locally, thrombolitic algal bioherms up to 2 m high are present. The Dowlais Limestone is dominated by dark grey, bituminous, bioclastic packstone-grainstone.

The lower part of the Clifton Down Limestone Formation is a relatively unfossiliferous, lagoonal, porcellaneous limestone succession. These limestones are overlain by shelly limestone, algal beds and cross-bedded oolites ('*Seminula* Oolite'), interpreted as tidal channel or bar deposits. In the Bristol region the base of the Holkerian Stage is taken at the sharp base of the '*Seminula* Oolite' (George *et al.* 1976). The succession represents a progressive change to a more open sea environment during the basal Holkerian marine transgression. The uppermost part of the formation comprises a thick calcareous algal limestone sequence.

The Asbian succession is dominated by high-energy marine limestones of the Oxwich Head Limestone Formation in South Wales and Bristol district (former Hotwells Limestone). The limestones accumulated on a mature carbonate platform during a period of overall marine transgression, in which periodic sea-level falls resulted in emergence. The Oxwich Head Limestone Formation in South Wales thickens southward (Fig. 9.19c) and comprises mainly thickly bedded, fine- to coarse-grained, recrystallized skeletal packstone, with distinctive pale–dark grey pseudobrecciation. The limestone contains conspicuous hummocky and pitted palaeokarstic surfaces overlain by thin, red and grey mottled clay beds, interpreted as palaeosols. In the Bristol region, the formation comprises hard, massive, grey–dark grey, ooidal and crinoidal limestone with an abundant coral and brachiopod fauna. The formation is about 225 m thick on Broadfield Down, but thins northward and is absent north of Bristol, where the formation passes laterally northward into the Upper Cromhall Sandstone (Fig. 9.19b). A non-sequence at the base of the formation in the Bristol region may be indicated by the absence of diagnostic early Asbian fauna (Kellaway & Welch 1993).

During the Brigantian there was a significant increase in the introduction of terrigenous material onto the carbonate shelf. In South Wales the mud-dominated succession of the Oystermouth Formation (formerly Upper Limestone Shales) comprises interbedded thin limestone and mudstone beds, silicified limestone and chert. The sand-dominated succession of the Cromhall Sandstone Formation consists of up to three leaves south of Bristol, ranging from Holkerian to Brigantian age. The leaves merge together to the north of Bristol, towards the southern flank of the Wales–Brabant High. This formation comprises grey, red weathering, coarse-grained quartzitic and calcareous sandstone, sandy crinoidal and ooidal limestone, dark grey mudstone and grey, rootlet-bearing fireclay. The sequence is markedly cyclic, a typical cycle comprising limestone passing up into mudstone, siltstone and sandstone and overlain by a seatearth (Kellaway & Welch 1993). The formation represents deposition in marginal marine and estuarine deltaic conditions. These sandstones probably represent terrigenous sands introduced onto an emergent carbonate shelf during marine regression at the end of the Holkerian, and subsequently marine-reworked during base Asbian transgression (Wilson *et al.* 1990).

Olivine-basalt lavas and tuffs are associated with the limestones of the Pembroke Limestone Group and some represent submarine eruptions. These late Tournaisian–early Viséan igneous rocks are largely restricted to the Bristol and Gloucester districts (Fig. 9.7). The Middle Hope Volcanic Member, within the Tournaisian Black Rock Limestone Subgroup, is a succession of up to 37 m of ash-tuffs, lapilli-tuffs and pillow basalts present in the Weston-super-Mare area (Whittaker & Green 1983; Wright & Cossey 2003). Basal tuffs record the onset of volcanic activity on the outer part of a sloping, shallow-marine shelf below storm wave-base (Faulkner 1989). Overlying pillow basalts also indicate subaqueous igneous activity. The volcanic centre developed in progressively shallower water as a result of volcanic updoming and/or development of the volcanic cone, approaching the sea surface before finally subsiding. Lavas and tuffs of Arundian age from the Bristol district at Spring Cove, Goblin Combe, Broadfield Down, Cadbury Camp and Tickenham indicate that volcanic activity occurred over a relatively wide area and included several small vents (Whittaker & Green 1983).

There is relatively little evidence for Carboniferous volcanism in South Wales. The Mathry quartz–dolerite dyke (Cave *et al.* 1989), of probable Carboniferous age, can be traced for some 40 km across SW Wales. Three minor dykes in the Welsh Borders cut strata of Devonian age and are considered to have been intruded during the Carboniferous (Francis 1970). These are the analcime gabbro Brockhill Dyke, the olivine–dolerite Bartestree Dyke and the monchiquitic Llanllywel Dyke (Fig. 9.7). The latter dyke is associated lithologically and geographically with the monchiquite intrusion and volcanic pipe at Golden Hill Quarry, Monmouthshire. The supposed Viséan volcanic diatreme pipe at Golden Hill contains an agglomeratic facies and a NW-orientated dyke-like facies, cutting through Devonian sandstones (Bevins 2003). The pipe and a nearby associated dyke include ultramafic mantle and lower crustal xenoliths (Upton *et al.* 1983).

Namurian: advancing deltas

Introduction

The onset and evolution of broad thermally subsiding basins dominated Namurian sedimentation in England and Wales. The 'block and basin' topography developed during the Dinantian, which resulted in isolated deposition within small sub-basins or as distinct carbonate platforms, was gradually infilled by predominantly fluvio-deltaic deposits. Depositional systems became established over broad areas. Three distinct provinces can be recognized: northern England, the Central

Pennine Basin of central England and North Wales, and the South Wales Basin of South Wales and southern England.

Namurian sedimentation in northern England was dominated by comparatively shallow-water, predominantly non-marine, stacked fluvio-deltaic successions with near-coastal marine intervals. A particularly condensed succession was deposited during Chokierian–Marsdenian times, probably reflecting a period of low subsidence rates and low sediment influx, possibly due to bypass into the Central Pennine Basin to the south. Basinal marine shales are rare and, more typically, marine transgressions are represented by brachiopod-crinoid-mollusc communities developed close to the coast.

The Central Pennine Basin was a broad depositional area extending from the Craven Fault System to the northern flank of the Wales–Brabant High. Eustatically controlled sea-level rises resulted in the deposition of marine shales with acme ammonoid faunas. Fluvio-deltaic sediments, sourced mainly from the north, infilled the remnant basin topography and new accommodation generated during sea-level highstands. In these relatively deep basins (up to a few hundred metres) of the early Namurian, the deltaic systems prograded only a short distance southward, and argillaceous sediments were deposited widely (Fig. 9.9d). The initial phase of coarse clastic basin sedimentation was dominated by accumulation of thick deposits (up to 550 m) from turbidity flows, a notable contrast to deposition within northern England. By late Kinderscoutian times sedimentation had reduced basinal topography and deltas prograded rapidly across the Central Pennine Basin, and commonly formed a sheet-like geometry. During phases of regression, rivers incised into their deltas and palaeosols developed on interfluves. Rivers probably directly fed pro-delta turbidite lobes in the basins; a model particularly invoked for deposition of the Kinderscoutian part of the Millstone Grit Group (Hampson 1997). By Marsdenian times the deltas had reached the northern margin of the Wales–Brabant High and by the Yeadonian, the first influx of westerly sourced fluviodeltaic sediments became apparent in the western part of the basin.

In addition to the northern-sourced sediments, the emergent Wales–Brabant High shed quartzitic sands, deposited as small fluviodeltaic systems, northwards into the Central Pennine Basin (Fig. 9.9d). Much of the sediment may have been derived from about 200 m of uplift associated with a Variscan foreland basin forebulge (Burgess & Gayer 2000). The small deltas fringing the southern part of the Pennine Basin were progressively onlapped by larger delta systems that spread across the basin from the north (Collinson 1988).

The South Wales Basin was a small, partly enclosed basin that was probably linked with the evolving Variscan Foreland Basin, and the Culm Basin in Devon and Cornwall (see Chapter 10). Quartz-rich sediments were shed southwards from the Wales–Brabant High into the basin. Namurian deposition in South Wales was influenced by tectonically-driven differential subsidence, induced by northward propagation of the Variscan Front and reactivation of Caledonian (NE–SW) lineaments, such as the Carreg Cennen, Swansea Valley and Neath disturbances (Fig 9.5). The Pembrokeshire sub-basin was isolated from the main South Wales area of deposition by the Penlan Axis, a growth anticline, which developed in response to movement on the Carreg Cennen Disturbance. Similarly, deposition in South Wales and Bristol was separated by the development of the Usk Anticline. The growth anticlines appear to have acted as local sources of sand, derived from uplifted and eroded Devonian Old Red Sandstone (George 2000). Braid deltas transported sands into a high-energy coastal zone, subject to wave- and storm-generated currents, which passed southward into the deep marine environment of the Culm Basin. In contrast with the Pennine Basin, the South Wales Basin was located at the margins of an open marine connection (Fig. 9.9d) and consequently wave and storm influences were enhanced.

Chronostratigraphy

The Namurian Series comprises seven stages coincident with groups of ammonoid zones: Pendleian (E_1), Arnsbergian (E_2), Chokierian (H_1), Alportian (H_2), Kinderscoutian (R_1), Marsdenian (R_2) and Yeadonian (G_1). Boundary stratotypes for all but the Arnsbergian have been defined by Ramsbottom (1981) in central and northern England (Fig. 9.11). The bases of the stages are taken at the bases of marine bands that display the earliest occurrence of certain diagnostic ammonoid faunas (Fig. 9.20). These are the *Cravenoceras leion* (Pendleian), *Cravenoceras cowlingense* (Arnsbergian), *Isohomoceras subglobosum* (formerly *Homoceras subglobosum*) (Chokierian), *Hudsonoceras proteum* (formerly *Hudsonoceras proteus*) (Alportian), *Hodsonites magistrorum* (Kinderscoutian), *Bilinguites gracilis* (formerly *Reticuloceras gracile*) (Marsdenian) and *Cancelloceras cancellatum* (formerly *Gastrioceras cancellatum*) (Yeadonian).

The earliest occurrence of *Cravenoceras leion* is taken as the base of the Namurian Series. The global Mid-Carboniferous Boundary between the Mississippian and Pennsylvanian subsystems, marked by the first appearance of the conodont *Declinognathodus noduliferus*, occurs within the Chokierian Stage.

Biostratigraphy

Thick-shelled ammonoids occur within thin hemi-pelagic shale beds, commonly referred to as 'marine bands'. In the Central Pennine Basin there are about 60 marine bands (Holdsworth & Collinson 1988). Ammonoid evolution rates were so great during the Namurian that typically each marine band comprises a distinct ammonoid fauna (Fig. 9.20). The nekto-pelagic habit of ammonoids allows the biozones to be recognized across Western Europe and some are applicable globally. The extensive distribution of the marine bands makes them of primary stratigraphical importance. Namurian ammonoid biostratigraphy was developed by Bisat (1924, 1928) and Bisat & Hudson (1943), and was later refined by Ramsbottom (1969, 1971). In northern England, by contrast, ammonoid-bearing marine shales are comparatively rare.

Owens *et al.* (1977) produced a palynostratigraphy for the Namurian of northern England and Scotland, with five miospore biozones encompassing the series (Fig. 9.20). Within the Central Pennine Basin the palynomorph zones have been closely related to ammonoid zones. Palynomorphs have proved particularly important zonal indicators in the Northumberland Trough, where ammonoid-bearing marine bands are rare. The base of the NC Biozone is located in the late Brigantian P_2 ammonoid Biozone, and extends throughout the Pendleian. The base of the TK Biozone occurs near to the base of the Arnsbergian Stage. The base of the overlying SO Biozone has been recognized at the High Wood Marine Band of the Stainmore area, and is considered to be located within the Arnsbergian E_{2b} ammonoid subzone. The base of the KV Biozone occurs at the base of the Kinderscoutian Stage, extending into early Marsdenian strata (Clayton *et al.* 1977). The base of the FR Biozone, in the absence of constraining marine bands, has been taken to approximate to the mid-Marsdenian and extends to the base of the Westphalian Series (base of the *Gastrioceras subcrenatum* Marine Band).

Five conodont biozones are recognized for the Namurian Series (Fig. 9.20). Conodonts have much longer stratigraphical ranges than ammonoids during the Namurian and therefore are of less stratigraphical importance. However, the exact position of the mid-Carboniferous boundary has been defined as the appearance of the conodont *Declinognathodus noduliferus* (Lane *et al.* 1985). This places the mid-Carboniferous boundary close to the base of the Chokierian Stage.

STAGE	ZONE		WESTERN EUROPEAN MARINE BANDS		MIOSPORES	MACROFLORA		CONODONTS
	Index	Ammonoid	Ammonoid	Index		Zone	Subzone	
YEADONIAN	G_{1b}	*Cancelloceras cumbriense*	*Ca. cumbriense*	$G_{1b}1$	*Raistrickia fulva – Reticulatisporites reticulatus* (FR)	*Pecopteris aspera*	*Neuralethopteris larischii*	*Idiognathoides sinuatus – Idiognathoides primulus*
	G_{1a}	*Cancelloceras cancellatum*	*Ca. cancellatum*	$G_{1a}1$				
MARSDENIAN	R_{2c}	*Bilinguites superbilinguis*	*Verneulites sigma*	$R_{2c}2$				
			B. superbilinguis	$R_{2c}1$				
	R_{2b}	*Bilinguites bilinguis*	*B. metabilinguis*	$R_{2b}5$	*Crassispora kosankei – Grumosisporites varioreticulatus* (KV)		*Sigillaria elegans*	
			B. eometabilinguis	$R_{2b}4$				
			B. bilinguis	$R_{2b}3$				
			B. bilinguis	$R_{2b}2$				
			B. bilinguis	$R_{2b}1$				
	R_{2a}	*Bilinguites gracilis*	*B. gracilis*	$R_{2a}1$				
KINDERSCOUTIAN	R_{1c}	*Reticuloceras reticulatum*	*R. coreticulatum*	$R_{1c}4$				*Idiognathoides corrugatus – Idiognathoides sulcatus*
			R. reticulatum	$R_{1c}3$				
			R. reticulatum	$R_{1c}2$				
			R. reticulatum	$R_{1c}1$				
	R_{1b}	*Reticuloceras eoreticulatum*	*R. stubblefieldi*	$R_{1b}3$				
			R. nodosum	$R_{1b}2$				
			R. eoreticulatum	$R_{1b}1$				
	R_{1a}	*Hodsonites magistrorum*	*R. dubium*	$R_{1a}5$				
			R. todmordenense	$R_{1a}4$				
			R. subreticulatum	$R_{1a}3$				
			R. circumplicatile	$R_{1a}2$				
			Ho. magistrorum	$R_{1a}1$				
ALPORTIAN	H_{2c}	*Vallites eostriolatus*	*Homoceratoides prereticulatus*	$H_{2c}2$	*Lycospora subtriquetra – Kraeuselisporites ornatus* (SO)			*Declinognathus noduliferus*
			V. eostriolatus	$H_{2c}1$				
	H_{2b}	*Homoceras undulatum*	*H. undulatum*	$H_{2b}1$				
	H_{2a}	*Hudsonoceras proteum*	*Hd. proteum*	$H_{2a}1$				
CHOKIERIAN	H_{1b}	*Homoceras beyrichianum*	*I. sp. nov.*	$H_{1b}2$				
			H. beyrichianum	$H_{1b}1$				
	H_{1a}	*Isohomoceras subglobosum*	*I. subglobosum*	$H_{1a}3$				
			I. subglobosum	$H_{1a}2$				
			I. subglobosum	$H_{1a}1$				
ARNSBERGIAN	E_{2c}	*Nuculoceras stellarum*	*N. nuculum*	$E_{2c}4$		*Lyginopteris larischii*		*Gnathodus bilineatus bollandensis*
			N. nuculum	$E_{2c}3$				
			N. nuculum	$E_{2c}2$				
			N. stellarum	$E_{2c}1$				
	E_{2b}	*Cravenoceratoides edalensis*	*Ct. nititoides*	$E_{2b}3$		*Lyginopteris stangeri*		
			Ct. nitidus	$E_{2b}2$	*Stenozonotriletes triangulus – Rotaspora knoxi* (TK)			
			Ct. edalensis	$E_{2b}1$				
	E_{2a}	*Cravenoceras cowlingense*	*Eumorphoceras yatesae*	$E_{2a}3$				
			C. gressinghamense	$E_{2a}2a$				
			Eumorphoceras ferrimontanum	$E_{2a}2$				
			C. cowlingense	$E_{2a}1$				
PENDLEIAN	E_{1c}	*Cravenoceras malhamense*	*C. malhamense*	$E_{1c}1$	*Bellispores nitidus – Reticulatisporites carnosus* (NC) part	*Neuropteris antecedens* (part)	*Lyginopteris fragilis*	*Kladognathus – Gnathodus girtyi simplex*
	E_{1b}	*Cravenoceras brandoni*	*Tumulites pseudobilinguis*	$E_{1b}2$				
			C. brandoni	$E_{1b}1$				
	E_{1a}	*Cravenoceras leion*	*C. leion*	$E_{1a}1$				

Fig. 9.20. Summary of the chronostratigraphical units of the Namurian and the main biozones for the most important fossil groups, derived from authors referred to within text. The macrofloral zonations are derived from Cleal (1991).

Sequence stratigraphy

A number of Namurian sandstone bodies that satisfy two or more of the key characteristics for sediments deposited in valleys generated by incision during sea-level fall are recognized. Most Namurian-aged multistorey sandstone bodies are 10–30 km wide and the preserved thickness is 25–35 m (Davies *et al.* 1999).

In northern England, north of the Craven Fault zone, major fluvial sandstone bodies occurred in the uppermost Pendleian; up to 30–40 m of erosional relief over several kilometres can be documented where correlative interfluves are identified. Sandstones in the Kinderscoutian, Marsdenian and Yeadonian of the Central Pennine Basin have been subject to the most scrutiny. Hampson (1997) documents two potential valley sandstones in the Lower Kinderscout Grit. The recognition of major erosional unconformities (sequence boundaries) produced by fluvial incision suggests that, during falling sea-level, sediment bypassed the shelf and was transported directly into the deep basin (Hampson 1997). Therefore the Kinderscoutian succession does not represent a simple southward progradation of a turbidite-fronted delta (Walker 1966*a*).

Those valley fills associated with turbidite-fronted deltas, for example in the Lower Kinderscout Grit (Hampson 1997) and in the Marsdenian Roaches Grit (Jones & Chisholm 1997) thicken to 50–80 m around the area 2–5 km adjacent to their mouths (Hampson *et al.* 1999). Other Marsdenian sandstones, for example the Midgley Grit, are interpreted as fluvial systems deposited following a major sea-level fall but deposited in a platform location and are much more laterally extensive, reaching widths of up to 90 km (Brettle 2001).

Maynard (1992) and Hampson *et al*. (1996) have interpreted the erosional base of the late Yeadonian Rough Rock as a sequence boundary that can be correlated to an interfluve palaeosol. However, Bristow (1988, 1993) does not regard the sheet-like braided river deposit, represented by the Rough Rock, as the product of a fall in sea level. The Farewell Rock of South Wales, which is the same age as the Rough Rock of the Pennine Basin, has also been interpreted in terms of deposition within a valley (Hampson 1998). The base of the Farewell Rock has major erosional relief, associated with an identifiable time gap and an angular discordance in bedding (Hampson 1998). The Farewell Rock can be correlated with the Cumbriense Quartzite of the North Crop, east of Pembrokeshire, which contains several mature palaeosols, interpreted as a well-developed interfluve (Hampson 1998).

Ramsbottom (1977) proposed eleven mesothemic cycles for the British Namurian linked to the appearance of new ammonoid genera, and controlled by eustatic sea-level fluctuations (Fig. 9.10). The boundaries of the mesothems are marked by widespread disconformities in shelf areas. Although the mesothem model for the British Namurian has been criticized (Holdsworth & Collinson 1988; Martinsen 1990), the underlying concept of eustasy as an influence on sedimentation, particularly with respect to widespread marine transgressions, is now widely accepted.

Regional Developments

Northern England

Yoredale Group

In northern England deposition of the Mixed shelf carbonate and deltaic ('Yoredale') lithofacies association of the Yoredale Group continued into the Namurian and extended across the entire region. The Namurian part of the Yoredale Group is referred to as the Stainmore Formation and is distinguished from the underlying Dinantian Alston Formation by a decrease in both the number and thickness of limestones (Waters *et al.* 2006*a*). Limestones in the Stainmore Formation also tend to be darker grey than the Alston Formation limestones. The base of the Namurian Series is taken at the base of the prominent and laterally extensive Great Limestone (Main Limestone).

On the Askrigg Block there are up to four main levels of chert of Pendleian age, typically developed above the limestone component of the cyclothem. Details of limestone nomenclature and correlations, and cyclothem thicknesses, are provided by Dunham & Wilson (1985) for the Askrigg Block and Stainmore Trough, and by Dunham (1990) for the Alston Block (Fig. 9.21).

Millstone Grit Group

The Millstone Grit Group is characterized by cyclic successions of quartz-feldspathic sandstone, grey mudstone, thin coals and prominent seatearths of Fluvio-deltaic ('Millstone Grit') lithofacies association. The Millstone Grit Group is Pendleian–Yeadonian in age on the Askrigg Block. Fluvial sandstones, with palaeocurrents from channelized sandstones suggest a north or NE source. Some seatearths may result from prolonged periods of emergence, e.g. the Mirk Fell Ganister, a lateral correlative of the Pendleian Lower Howgate Edge Grit, and a potential interfluve sequence boundary. The group is about 500 m thick and significantly thinner than the equivalent strata present within the Central Pennine Basin to the south (Figs 9.21 & 9.22). The base of the Millstone Grit Group is marked by a slightly angular intra-Pendleian (E_{1c}) unconformity above the Yoredale Group (Brandon *et al.* 1995). The presence of a Mid-Carboniferous unconformity is indicated by the absence of Alportian strata across the Askrigg Block (Ramsbottom 1977). In west Cumbria there is a large non-sequence in which strata of Chokierian–Marsdenian age are absent (Akhurst *et al.* 1997). The equivalent of the Millstone Grit Group is represented by less than 10 m thickness of dark grey carbonaceous mudstone grading up into siltstone and seatearth.

To the north of the Askrigg Block, the Millstone Grit Group is less well constrained, typically comprising sandy incised valley fills within the Mixed shelf carbonate and deltaic ('Yoredale') lithofacies association. The probable equivalent of the Millstone Grit Group is recognized in the upper part of the Stainmore Formation (Waters *et al.* 2006*a*). Limestones are either very thin or absent and thick, coarse-grained; often pebbly sandstones with ribbon-like geometries are characteristic. These fluvial sandstones have historically been mapped as First and Second Grit (Ramsbottom *et al.* 1978), although the use of such a simple nomenclature for a channel sandstone complex is now questioned.

Central Pennine Basin

Craven Group

Hemi-pelagic lithofacies-association-sedimentation of the Craven Group continued from the Dinantian into the Namurian in the Central Pennine Basin. The Namurian component of this association has historically been named Upper Bowland Shale in the Craven Basin, Edale Shale in Derbyshire (Plate 16) and Holywell Shales in North Wales. These mudstones are laterally contiguous in the subsurface and the use of a single formation name, Bowland Shale Formation, is now preferred (Waters *et al.* 2006*a*). These deposits accumulated predominantly from suspension in moderately deep water, possibly a few hundred metres deep and certainly below storm wave-base. The formation comprises dark grey and black, organic-rich mudstone, with subordinate beds of siltstone, sandstone, ironstone and dolomitic limestone. Thin sandstone and limestone beds were possibly introduced by storms and/or as turbidites. During the late Brigantian–early Pendleian the Bowland Shale Formation shows a decrease in carbonate turbidites and concomitant increase in siliciclastic sandstone turbidites derived from encroaching Millstone Grit Group deltas accumulating on the margins of the Central Pennine Basin. In North Wales impersistent coal seams and seatearths

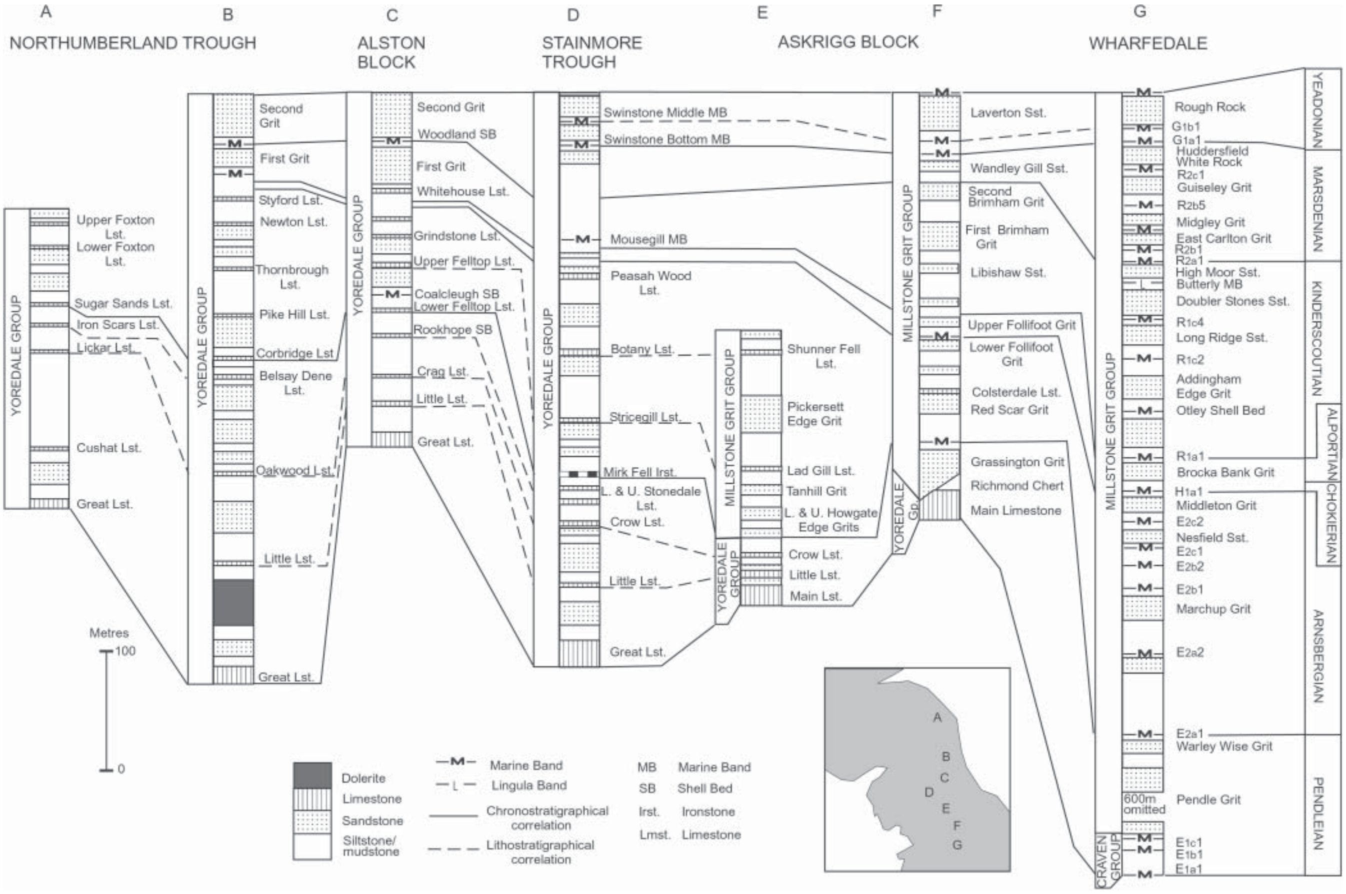

Fig. 9.21. Correlation of Namurian strata across northern England, adapted from Ramsbottom *et al.* (1978).

are present, which suggests a nearshore and/or lacustrine setting for the fine-grained sediments in this region. The newly defined Bowland Shale Formation ranges from late Brigantian to Yeadonian age, with the youngest strata present in the southern part of the Central Pennine Basin.

Millstone Grit Group

The Craven Group is overlain conformably and diachronously by the Millstone Grit Group of the Fluvio-deltaic ('Millstone Grit') lithofacies association. The Millstone Grit Series was until recently defined as a chronostratigraphical unit, equating with strata of Namurian age. The name Millstone Grit Group is now used for a lithostratigraphical unit (Waters *et al.* 2006*a*). The group has been traditionally described as locally named sandstone 'beds', with the intervening argillaceous succession commonly unnamed. Attempts to subdivide the thick cyclic succession have concentrated on the recognition of essentially chronostratigraphical divisions bounded by widespread marine marker bands. This has led to a proposal for component formations, in ascending order, of Pendleton (Pendleian), Silsden (Arnsbergian), Samlesbury (Chokierian and Alportian), Hebden (Kinderscoutian), Marsden (Marsdenian) and Rossendale (Yeadonian) formations (Fig. 9.22).

The Millstone Grit Group extends across most of the Central Pennine Basin. The base of the group is taken at the base of the first thick quartz-feldspathic sandstone, of Namurian age, typically present above the Bowland Shale Formation. The base of the group is markedly diachronous, ranging from Pendleian along the northern margin of the Central Pennine Basin to Yeadonian in North Wales (Fig. 9.22). The thickest development, 1225 m, is recorded in Wharfedale (Ramsbottom *et al.* 1978), in the northern part of the Central Pennine Basin (Fig. 9.21), where deposition commenced first and continued throughout the Namurian.

The fluvial channels recognized on the Askrigg Block supplied sediment to the northern margin of the Central Pennine Basin during Pendleian times. Thick fluvio-deltaic sequences of the Millstone Grit Group were deposited during repeated phases of delta progradation. Deep-water turbidite-fronted lobate delta facies, commonly several hundred metres thick, e.g. Pendle Grit (550 m), Mam Tor Sandstone (Plate 16) to Grindslow Shales (300 m), Roaches and Ashover grits (360 m), characterize early basin sedimentation (Fig. 9.22). These represent systems fed by large distributaries transporting coarse sands directly to submarine feeder channels, by-passing the delta slope to be deposited in a delta-front apron of coalescing turbidite lobes (Walker 1966*b*; Collinson 1969; McCabe 1978; Jones 1980). Following initial basin infill, sedimentation rates began to broadly match subsidence rates and shallow-water sheet-like delta facies were deposited, commonly in cycles tens of metres thick. Significant transport of sediment by turbidity currents was largely absent. Mouth-bar deposits dominate the lower part of each cycle and are overlain by generally sheet-like and laterally extensive sandstones deposited by braided fluvial systems, e.g. Guiseley Grit, Chatsworth Grit, Rough Rock. However, elongate deltas are locally developed, e.g. East Carlton Grit, Haslingden Flags (Collinson 1988). Along the northern margin of the Central Pennine Basin there was complex interdigitation of the deep-water and delta platform deposits during the early Namurian (Fig. 9.22), probably reflecting high-magnitude sea-level rises and falls.

The Namurian deltas were river-dominated with subordinate wave influence. The apparent absence of tidal influence has

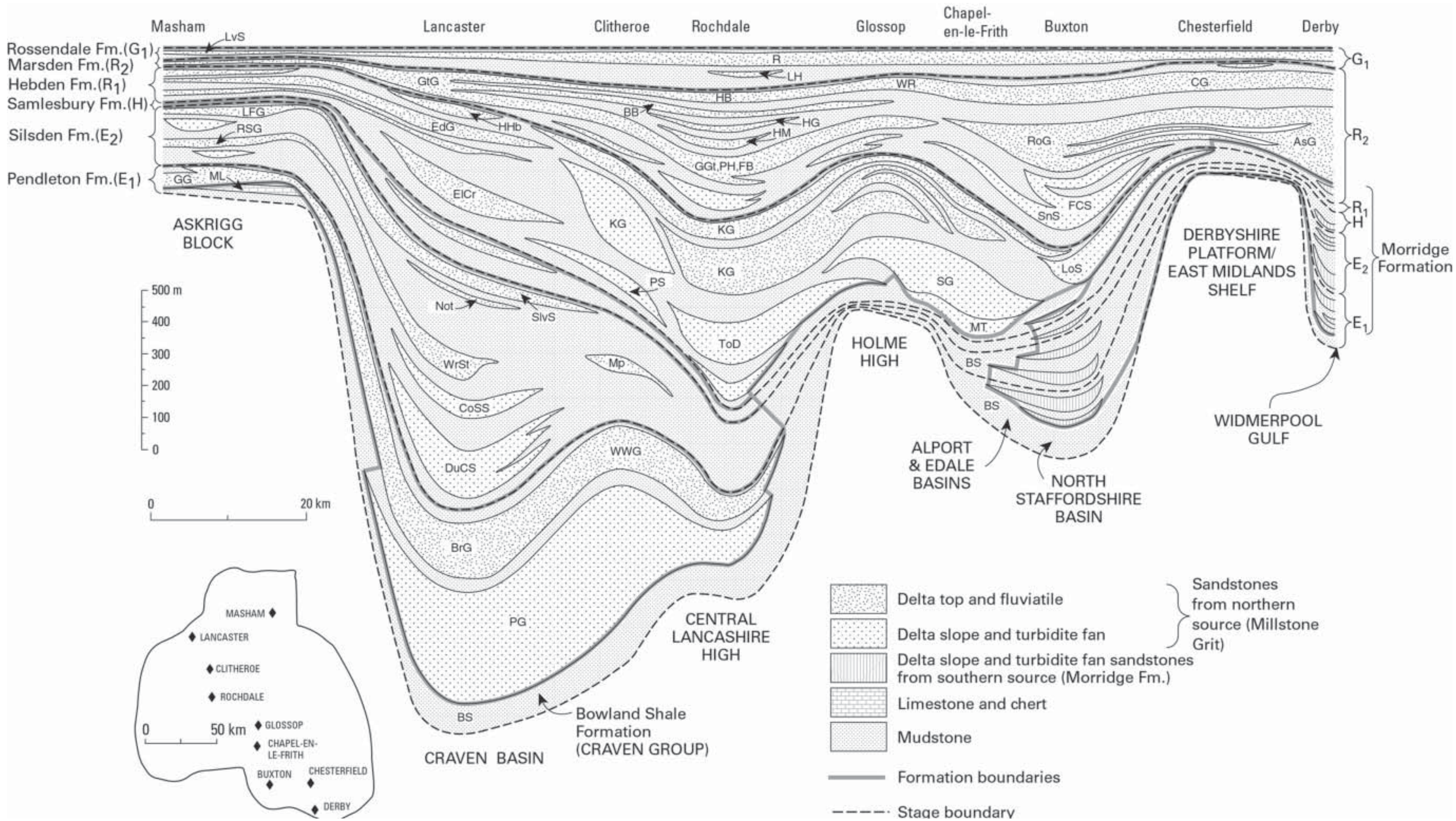

Fig. 9.22. Distribution and lithofacies of the main sandstones of the Millstone Grit Group of the Central Pennine Basin (from Aitkenhead *et al.* 2002). AsG, Ashover Grit; BB, Brooksbottoms Grit; BrG, Brennand Grit; BS, Bowland Shale Formation; CG, Chatsworth Grit; CoSS, Cocklett Scar Sandstones; DuCS- Dure Clough Sandstones; EdG, Eldroth Grit; ElCr, Ellel Crag Sandstone; FB, Fletcher Bank Grit; FCS, Five Clouds Sandstones; GG, Grassington Grit; GGt, Gorpley Grit; GtG, Greta Grits; HB, Holcombe Brook Grit; HG, Hazel Greave Grit; HHb, Heysham Harbour Sandstone; HM, Helmshore Grit; KG, Kinderscout Grit; LFG, Lower Follifoot Grit; LH, Lower Haslingden Flags; LoS, Longnor Sandstones; LvS, Laverton Sandstone; ML, Main Limestone; Mp, Marchup Grit; MT, Mam Tor Sandstones; Not, Nottage Crag Grit; PG, Pendle Grit; PS, Parsonage Sandstone; PH, Pule Hill Grit; R, Rough Rock; RoG, Roaches Grit; RSG, Red Scar Grit; SG, Shale Grit; SlvS, Silver Hills Sandstone; SnS, Sheen Sandstones; ToD, Todmorden Grit; WR, Huddersfield White Rock; WrSt, Ward's Stone Sandstone; WWG, Warley Wise Grit.

been attributed to the location of the Central Pennine Basin within a basin largely isolated from the oceans (Collinson 1988). However, possible tidal features have been recognized within mouth bar sediments deposited by buoyant effluent flumes within Marsdenian and Kinderscoutian deltas in Yorkshire (Aitkenhead & Riley 1996; Brettle *et al.* 2002).

The Millstone Grit Group fluvio-deltaic successions typically show broadly southward flow and a northern provenance. Heavy mineral studies (Drewery 1987; Hallsworth & Chisholm 2000), whole-rock Sm–Nd isotopic ages (Glover *et al.* 1996; Leng *et al.* 1999) and U–Pb radiometric age determinations from zircons and monazites (Drewery 1987; Cliff *et al.* 1991; Hallsworth *et al.* 2000; Evans *et al.* 2001) have recognized sediment contributions from a range of sources. The main sources recognized are Archaean granulite-facies basement, mid–late Proterozoic metasediments and granites of Silurian age associated with the Scandian orogen. Sediment was most probably derived from the margins of the Laurentia and Baltica plates in Greenland and Norway. Locally, deltas appear to infill the Widmerpool Gulf, flowing along the axis of the trough, giving palaeocurrents towards the NW, but have typical northerly-sourced petrography (Jones & Chisholm 1997). The Upper and Lower Haslingden Flags are interpreted as deposits within a birdsfoot delta (Collinson & Banks 1975), with a westerly provenance, shown by McLean & Chisholm (1996).

The earliest Millstone Grit Group succession represents a sudden influx of coarse siliciclastic sediment during the late Pendleian (E_{1c} ammonoid zone), and deposition was restricted to the northern margin of the Central Pennine Basin (Figs 9.21 & 9.22). The initial deposition is represented by the Pendle Grit, which comprises thinly interbedded silty mudstone, siltstone and fine-grained sandstone, cut by massive, laterally impersistent, coarse-grained, pebbly sandstones. These deposits are interpreted as turbidite aprons cut by submarine turbidite channels. The northern part of the basin was rapidly infilled by sediment and the overlying Warley Wise Grit is a shallow-water coarse-grained, cross-bedded sandstone, with periodic emergence indicated by the development of thin coals. Hemi-pelagic mudstones of the Bowland Shale Formation were deposited to the south of the deltas at this time.

During the Arnsbergian there was a return to deposition predominantly from turbidity currents. The succession is dominated by a great thickness of comparatively deep-water siltstone and thin sandstone with some development of laterally impersistent shallow-water cross-bedded sandstones present along the northern margin of the Central Pennine Basin. Thick hemi-pelagic mudstones, including the Caton Shales and Sabden Shales of Lancashire, developed to the south of the turbidite aprons.

During the Chokierian and Alportian comparatively small volumes of sand were introduced into the basin from the north. In Lancashire and Derbyshire a complete succession of hemi-pelagic, dark grey shaly mudstone with numerous marine bands was deposited. In Yorkshire the Brocka Bank Grit, interpreted as a fluvial system, is present in the northern part of the Harrogate Basin, and part of the Alportian succession appears to be absent, possibly representing the mid-Carboniferous unconformity.

During the Kinderscoutian a broadly upwards-coarsening succession reflects a return to a high influx of coarse sands, which extend across most of the Central Pennine Basin (Fig. 9.22). In Derbyshire the lowermost distal turbidite apron is evident as the thin-bedded siltstone and sandstone of the Mam Tor Sandstone (Plate 16). The overlying proximal turbidite lobes of the Shale Grit comprise thick-bedded, coarse-grained sandstone. Overlying thin-bedded siltstones of the Grindslow Shales represent the delta slope, with feeder channels. In turn, the overlying very thick-bedded, cross-bedded and very coarse-grained sandstones of the Kinderscout Grit were deposited within major fluvial distributaries. The strata show a marked southward thickening up to about 600 m in north Derbyshire, infilling available accommodation space south of the Pendleian and Arnsbergian deltas. The Kinderscoutian succession has been envisaged to represent a simple southward progradation of a turbidite-fronted delta (Walker 1966*a*). However, recent studies suggest that major erosional unconformities (sequence boundaries) were produced by fluvial incision during falling relative sea levels and that sediments bypassed the delta through channels directly into the deep basin (Hampson 1997).

The Marsdenian succession includes laterally extensive sandstones and typically thinner cycles than within the underlying strata (Fig. 9.22). The Marsdenian strata thicken up to 600 m to the west of the Pennines, infilling the accommodation to the south and west of the thick Kinderscoutian succession (Collinson *et al.* 1977). Mouth bar-dominated deltas predominate during the early Marsdenian. There is evidence for incised valley formation and development of forced regressive mouth bars during lowstands (Brettle *et al.* 2002). During rising relative sea level, flooding of the incised valleys results in the formation of a shallow coastline embayment infilled with tidally influenced mouth bar deposits.

The Yeadonian succession typically comprises a lower thick succession of dark shale including the *Cancelloceras cancellatum* and *Cancelloceras cumbriense* marine bands. Small contributions of sediment from the west are recognized in the birdsfoot, fluvially dominated deltas of the Lower and Upper Haslingden Flags of Lancashire. The very coarse-grained sheet sandstone of the Rough Rock dominates the upper part of the formation and is present almost basin-wide. The Rough Rock has been interpreted as the fluvial infill of a lowstand incision surface (Maynard 1992) or lateral migration of a widespread sheet sandstone over an alluvial plain, with low gradients and little incision (Bristow 1988). In North Wales the typical northerly-sourced Millstone Grit Group is represented by the lower part of the Gwespyr Sandstone, which comprises fine-grained sandstone beds with subordinate thinly interbedded sequences of sandstone and mudstone and locally thick units of grey mudstone. Thin coals and seatearths are intermittently developed.

Along the southern margin of the Central Pennine Basin, quartzitic sandstones of the Cefn-y-fedw Sandstone Formation of North Wales and Morridge Formation of Staffordshire, were derived from the Wales–Brabant High to the south. Similarities in age and sedimentary architecture resulted in them being traditionally referred to as Millstone Grit. However, these strata are petrographically and provincially quite distinct.

These formations were deposited coevally and record the northward progradation of fluvio-deltaic sediments during Pendleian–late Marsdenian times. The formations are thickest toward the southern margins of the basin where shallow-water sheet-like delta facies predominate, with a thinner succession of predominantly deep-water turbidite-fronted lobate delta facies deposited to the north (Fig. 9.22). In the Widmerpool Gulf intermixing obscures the distinction between sandstones of southern and northern provenance. The formations comprise up to 600 m thickness of quartzose sandstone, locally pebbly, and thin beds of quartz conglomerate, interbedded with mudstone, siltstone and subordinate chert, commonly arranged in upwards-coarsening cycles up to 20 m thick. The quartzose sands appear to have been derived by reworking Old Red Sandstone deposits present on the Wales–Brabant High to the south.

The Cefn-y-fedw Sandstone is thickest north of the Bala Lineament, where it occurs as three separate sandstone units. The Cefn-y-fedw Sandstone intertongues with and onlaps the Pentre Chert Formation, and both intertdigitate with, and are conformably succeeded by, the Bowland Shale Formation. The three sandstone leaves merge into a single, thick sandstone succession to the south. The Morridge Formation conformably overlies, and intertongues with, the Bowland Shale Formation.

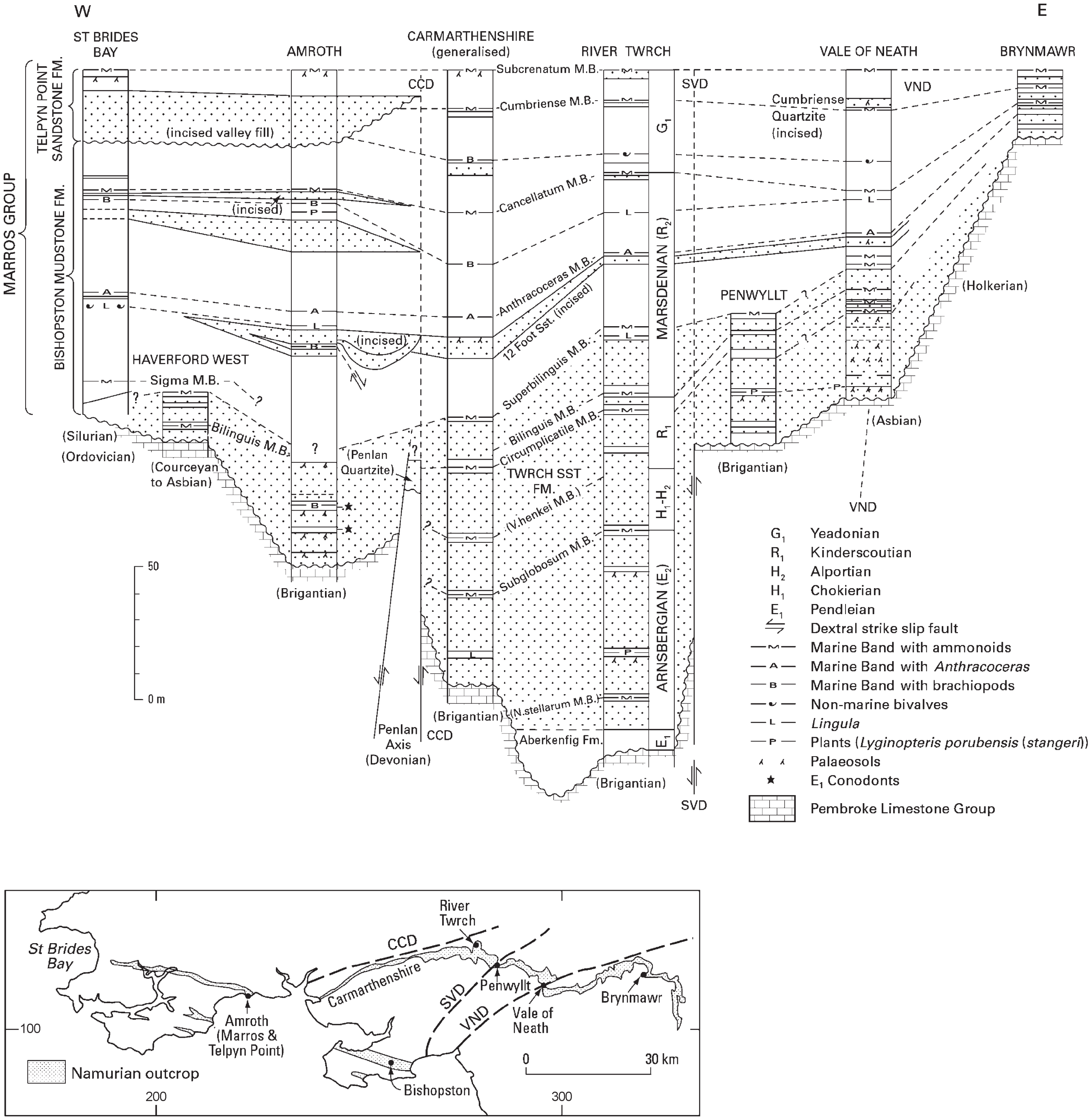

Fig. 9.23. Stratigraphy and correlation of Namurian strata along the North Crop of South Wales, adapted from George (2000). CCD, Carreg Cennan Disturbance; SVD, Swansea Valley Disturbance; VND, Vale of Neath Disturbance.

The youngest sandstone of the Morridge Formation, the Brockholes Sandstones, is of mid-Marsdenian (R_{2b}) age and interdigitates with the Roaches Grit, the local basal sandstone of the Marsden Formation.

South Wales–Southern England

Marros Group

The Namurian succession of South Wales and the Bristol area has traditionally been named Millstone Grit and has been treated as a chronostratigraphical unit equating with the entire Namurian Series. The newly defined Marros Group (Waters *et al.* 2006*a*) represents a lithostratigraphical unit comprising a cyclic lithofacies, similar to the Millstone Grit Group of the Pennines, but dominated by quartzose sandstones derived from the Wales–Brabant High to the north. The source for the Marros Group sediments is likely to be the same as for the Cefn-y-fedw and Morridge formations of the Central Pennine Basin.

Namurian deposition in South Wales commenced with the deposition of up to 35 m of dark grey shales with thin cherts and coarse-grained sandstones (Wilson *et al.* 1990) of the Aberkenfig Formation (the Plastic Clays of Ramsbottom *et al.* 1978) (Fig. 9.23). The formation is probably late Brigantian–early Pendleian in age and is equivalent in facies to the Craven Group developed on the northern flank of the Wales–Brabant High in North Wales. Similar deposits have been recognized in the Bristol area (Kellaway & Welch 1993).

The Marros Group is thickest, about 700 m, in the Gower of South Wales. The group thins and shows several depositional breaks both northwards, approaching the Wales–Brabant High, and eastward, approaching the Usk Anticline (George 1970, Figure 25).

Initial deposition of the Marros Group is characterized by fluvio-deltaic distributary channels, delta front and shoreface–foreshore deposits of the Twrch Sandstone Formation (former Basal Grits). In the North Crop the Twrch Sandstone overlies a prominent unconformity, which has removed the underlying Aberkenfig Formation in the East Crop (Fig. 9.23). In the type area near Ammanford, North Crop, the Twrch Sandstone Formation is dominated by lenticular–tabular quartzose sandstones with thin dark grey mudstone interbeds, some containing ammonoids and *Lingula*, plus minor seatearths and rare thin coals. The sandstones are medium- to coarse-grained, commonly pebbly and conglomeratic, trough cross-bedded and parallel laminated and may occur in upward-coarsening or upward-fining cycles. The fine-grained, well-sorted quartz arenites display hummocky and swaley cross-stratification and parallel to low-angle lamination, with complex palaeocurrent vectors. These deposits are interpreted as storm-dominated delta front and shoreface-foreshore deposits (George 2000). The coarse-grained, poorly sorted sandstones display channelized bases and sharp tops with mature palaeosols, and unimodal southerly-directed palaeocurrents suggesting deposition within braided fluvio-deltaic distributary channels (George 2000). In the type area, the formation ranges from Pendleian to Marsdenian in age, occurring below the *Bilinguites superbilinguis* Marine Band and has a maximum thickness of 190 m. Further to the east, successive overstep in the formation toward the Usk Anticline results in thinning, and progressive eastward younging of the base of the formation from Arnsbergian to Yeadonian age. The formation thins westwards over the Penlan Axis, into the Pembrokeshire sub-basin (Fig. 9.23). The Twrch Sandstone passes laterally westward and southward into the Bishopston Mudstone Formation and is absent in the basin depocentre, around the Gower.

The Bishopston Mudstone Formation (former Middle Shales) comprises three major coarsening-upward deltaic sequences, with interbedded basinal mudstones. In the North Crop, where this formation is comparatively thin and resting conformably upon the Twrch Sandstone, the eroded tops of cycles are overlain by brackish water interdistributary bay muds or marine bands containing benthic brachiopods, crinoids and bivalves indicative of a shallow, near-shore marine environment (Ramsbottom 1969). To the south and SW, where the formation is in excess of 700 m in Pembrokeshire (Ramsbottom *et al.* 1978), the marine bands are characterized by an open marine assemblage of ammonoids and pectinoids. In the East Crop and South Crop, quartzitic sands were entering the basin from the east and south, respectively, continuing through the Marsdenian and Yeadonian (Oguike 1969). The 9 m-thick transgressive systems tract developed beneath the *Cancelloceras cancellatum* Marine Band in Pembrokeshire records the northward migration of lagoonal and accompanying beach deposits and outer barrier bar sands associated with development of a lag-pavement (George 1970). This sea-level rise resulted in widespread deposition of muds, with thin beds of silt and sand attributed to density flows or turbidity flows at the base of pro-delta slopes. In the North Crop input of sands was almost entirely confined to distributary channels, which fed southward and southwestward advancing deltas. Locally, sand-filled channels incised into sheet-like bodies of littoral sand and silt.

During the late Namurian there is a localized return to fluvial sand-dominated deposition within the SW part of the basin (Fig. 9.23). The Telpyn Point Sandstone Formation (formerly one of several 'Farewell Rocks') comprises massive, cross-bedded, upward-fining sandstones, interpreted as fluvial infills of incised valleys (Hampson 1998). Palaeoflows within the incised valleys show a downflow change from southward to eastward, possibly reflecting a diversion around a growth fold evolving within the hanging-wall of the Ritec Fault (George 2001). The channel sandstone is overlain abruptly by argillaceous floodplain and/or estuarine bay sediments. The formation, of Yeadonian age, is limited to the Pembrokeshire sub-basin, where it is up to 30 m thick (Kelling 1974). To the east of Pembrokeshire, the Cumbriense Quartzite of the North Crop is of comparable age to the Telpyn Point Sandstone (Fig. 9.23). The Cumbriense Quartzite is interpreted as a storm-influenced, forced regressive barrier developed on the northern margin of a shallow bay (George 2001), or as a well-developed interfluve (Hampson 1998).

In the Bristol Coalfield, the Quartzitic Sandstone Formation forms the entire thickness of the Marros Group and is similar in appearance to the Twrch Sandstone Formation of South Wales. It consists of hard, pale grey quartzitic sandstone, sometimes conglomeratic with pebbles of white quartz, chert and ironstone, particularly above erosive surfaces (Kellaway & Welch 1993). Grey mudstone, including some *Lingula* bands, and seatearths with thin carbonaceous or coaly beds, occur as interbeds. The formation is up to 300 m thick in the northern part of the Bristol Coalfield, thinning southward.

Westphalian and Stephanian: coal swamps and redbeds

Introduction

Westphalian and Stephanian strata in England and Wales were deposited in three distinct depositional areas; the Pennine Basin extending from the Southern Uplands of Scotland to the Wales–Brabant High, and the Variscan foreland basins located to the south of the Wales–Brabant High, including the South Wales and Culm basins.

Although the Pennine Basin and South Wales Basin were linked at times, there was relatively little flux of sediment between them, as the Wales–Brabant High was an upland area for most of the time. These basins show a common evolution from grey Fluvio-lacustrine ('Coal Measures') lithofacies association during early Westphalian times to Alluvial (Barren Measures) lithofacies in late Westphalian and Stephanian times (Figs 9.9e, f).

The Pennine Basin continued to subside during early Westphalian times as a consequence of thermal crustal sagging caused by cooling of the asthenosphere beneath the thinned lithosphere. Deposition occurred in a fluvio-lacustrine environment, with marine transgressions that became less common through time (Calver 1968, 1969). The humid tropical climate resulted in a largely waterlogged depositional plain. The northerly sediment source persisted from Namurian times into the Westphalian. In the northern part of the Pennine Basin (Northumberland and Durham) this northerly source continued to Bolsovian times. However, in the southern part of the Pennine Basin a western source became predominant during the Langsettian and Duckmantian. This westerly source persisted until Bolsovian times when a source from the SE supplied additional sediment supply. Towards the southern and northern margins of the basin the Coal Measures successions are condensed and rest unconformably upon older rocks. Primary red bed facies associated with periodic well-drained soils commenced early in the Westphalian at the extreme southern margin of the Pennine Basin and became more extensive by Bolsovian times. This marked the demise of the predominantly fluvio-lacustrine environments and the onset of predominantly alluvial sedimentation. The reasons for the change are complex, involving factors that include tectonic inversion associated with the Variscan Orogeny, and the introduction of an increasingly arid climate to the north of the developing

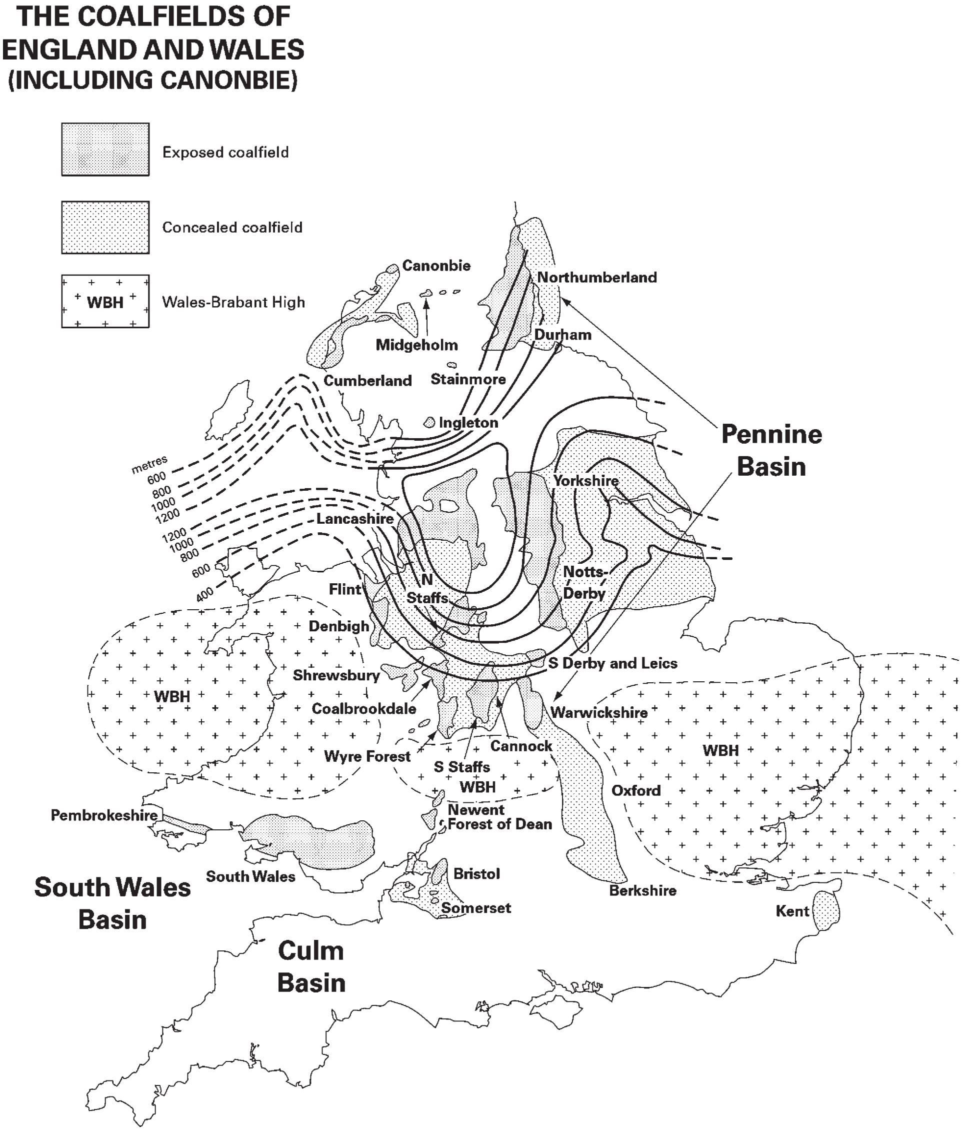

Fig. 9.24. Distribution of Westphalian coalfields at outcrop and within the subsurface of England and Wales (after Ramsbottom *et al.* 1978 and Powell *et al.* 2000*a*, with additions). Restored and generalized isopachs of the Lower and Middle Coal Measures within the Pennine Basin, modified from Calver (1968) and Kirby *et al.* (2000).

Variscan mountain belt (Besly 1988*a*). The Variscan deformation isolated previously contiguous Coal Measures strata into a number of separate coalfields (Fig. 9.24).

The South Wales and Culm basins evolved during the Westphalian and Stephanian as flexural foreland basins, developed in front of a northward propagating Variscan Orogen. The fluvial 'Pennant' facies, derived from the evolving Variscan thrust-fold belt to the south, prograded northwards across southern England and South Wales during late Westphalian and Stephanian times, eventually spilling across the Wales–Brabant High barrier into the southern margin of the Pennine Basin.

There was a resurgence in volcanic activity, notably along the southern margin of the Pennine Basin, after a period of quiescence during the Namurian. Alkaline igneous activity produced dolerite sills and lavas in the East Midlands, and sills in the West Midlands. In addition, explosive volcanicity produced tuffs and thin ash-fall clays, generally a few millimetres–centimetres thick, which are referred to as bentonites or tonsteins, and are typical Westphalian volcanic products. Acidic ash-fall deposits generally cover very large areas and have been associated with Variscan volcanic activity at a destructive plate margin to the south of Britain (Spears & Lyons 1995). Basic bentonites are more locally developed. Thermal subsidence is not normally associated with igneous activity (Leeder 1982), leading to suggestions that Variscan deformation south of the Wales–Brabant High resulted in reactivation of deep-seated basement lineaments, which acted as conduits for upward migration of magma (Waters *et al.* 1994).

Chronostratigraphy

The base of the Westphalian Series is taken at the base of the *Gastrioceras subcrenatum* ammonoid Zone, which broadly equates with the first incoming of thick coal seams in England and Wales. The series is subdivided into four stages (Fig. 9.25). The informal nomenclature of A, B, C and D has been superseded by the formal definition of the Langsettian (Westphalian A), Duckmantian (B) and Bolsovian (C) stages with boundary stratotypes (Fig. 9.11) defined in the East Pennine Coalfield of England (Owens *et al.* 1985). Westphalian D has, as yet, no formally defined stratotype and remains unnamed. The bases of the three formally defined stages are taken at the base of marine strata (marine bands), which display the earliest occurrence

STAGE	AMMONOIDS	CONODONTS	PALYNOMORPHS		MACROFLORA		NON-MARINE BIVALVES	
			Index	Zone			Zone	Subzone
Cantabrian					*Odontopteris cantabrica*		*Anthraconauta tenuis*	
					Lobatopteris vestita	*Dicksonites plueckenetii*		
Westphalian D			XI	*Thymospora obscura*		*Lobatopteris micromiltoni*		
					Linopteris bunburii			
Bolsovian			X	*Torispora securis*	*Paripteris linguaefolia*		*Anthraconauta phillipsi*	
							'Upper *similis-pulchra*'	
			IX	*Vestispora magna*				
								adamsi-hindi
Duckmantian							'Lower *similis-pulchra*'	*atra*
			VIII	*Dictyotriletes bireticulatus*	*Lonchopteris rugosa*	*Sphenophyllum majus*		
								caledonica
						Neuropteris hollandica		*phrygiana*
					Lyginopteris hoeninghausii	*Laveineopteris loshii*	*Anthraconaia modiolaris*	*ovum*
			VII	*Schulzospora rara*				
								regularis
Langsettian								
								cristagalli
			VI	*Radiizonates aligerens*			*Carbonicola communis*	*pseudorobosta*
						Neuraleth-opteris jongmansii		*bipennis*
								torus
			SS	*Triquitrites sinan – Cirratriradites saturni*			*Carbonicola lenisulcata*	*proxima*
	Gastrioceras listeri	*Idiognathoides sulcatus parvus*						
								extenuata
	Gastrioceras subcrenatum							*fallax-protea*
		Idiognathoides sinuatus – Idiognathoides primulus (part)						

Fig. 9.25. Westphalian chronostratigraphy and biostratigraphical zonations. Biozonation is derived from authors referred to in the text.

of certain diagnostic ammonoid faunas that can be recognized extensively across Western Europe. The key faunas are those of *Gastrioceras subcrenatum* (base Langsettian), *Anthracoceratites vanderbeckei* (base Duckmantian) and *Donetzoceras aegiranum* (base Bolsovian) marine bands.

The Stephanian Series was originally defined in the Central Massif of France with three stages, referred as Stephanian A, B and C. The Stephanian A has been formally renamed the Barruelian Stage. The recognition of a non-sequence in the Central Massif and identification of an additional Stephanian succession in Cantabria, northern Spain, led to the recognition of a Cantabrian stage, which is older than the Barruelian. Only strata of Cantabrian age have been recognized in England and Wales.

Biostratigraphy

Much reliance is placed on the thick-shelled ammonoid biostratigraphy in the definition of the Langsettian, Duckmantian and Bolsovian stages (see above). Ammonoid-bearing marine bands have also been used as marker beds to allow correlation of successions within and between coalfields. These key marine bands, identified on Fig. 9.25 after Ramsbottom *et al.* (1978), are named after diagnostic ammonoid species. In contrast to the Namurian, the Westphalian Series includes relatively few marine bands with thick-shelled ammonoids. Marine bands broadly decrease in abundance upwards, with none recorded in Britain above the Bolsovian Cambriense Marine Band. Correlation in the Westphalian is aided by the presence of an additional framework of marine and near-marine bands that contain less diagnostic faunas, such as thin-shelled ammonoids (*Anthracoceras*), marine bivalves (e.g. *Dunbarella*), brachiopods (*Lingula*) and crustacea (ostracodes, estheriids), which are invaluable for detailed correlation. These marine bands typically have geographical names (see Fig. 9.26).

Non-marine bivalve biozones for the Westphalian were defined by Trueman & Weir (1946), see Figure 9.25, though with time the zonal boundaries have been fixed at prominent coals or marine bands and recognized as chronozones. The zonation is of particular importance in the correlation of late Westphalian strata, which lack marine bands. Notably, the base of Westphalian D is taken to correspond with that of the *Anthraconauta tenuis* Zone (Calver 1969).

Miospore zonations have been developed for Westphalian coal seams by Smith & Butterworth (1967), but realize greatest importance within late Westphalian strata lacking alternative biostratigraphical control (Fig. 9.25). The base of the *Thymospora obscura* miospore Zone equates with that of the non-marine bivalve *Anthraconauta tenuis* Zone (Calver 1969), at the base of Westphalian D. Advances in microfloral zonation have provided an improvement to the early attempts at macrofloral biostratigraphical zonation, initially developed by Kidston (1905) and refined by Dix (1934) and Crookall (1955), which can be used for coarse correlation. Recent advances in macrofloral zonation show the importance of plant fossil biostratigraphy, particularly for Westphalian D and the Cantabrian (Cleal 1991).

Sequence Stratigraphy

The application of sequence stratigraphic principles to the Coal Measures of the Pennine Basin has proved less successful than within the underlying Millstone Grit Group. Marine bands, representing maximum flooding surfaces, are present within the Coal Measures succession. However, the decrease upward in number of marine bands indicates a reduction in marine influence within the basin with time. Lowstands of sea level produce incision of rivers and the development of well-drained palaeosols on interfluves. However, regionally developed well-drained palaeosols are not common and major fluvial sandbodies show only limited basal incision of up to 5 m, exceptionally up to 8 m (Rippon 1996). This may reflect distance from the sea, with incision of river channels having insufficient time to work upstream from the coast before the next flooding

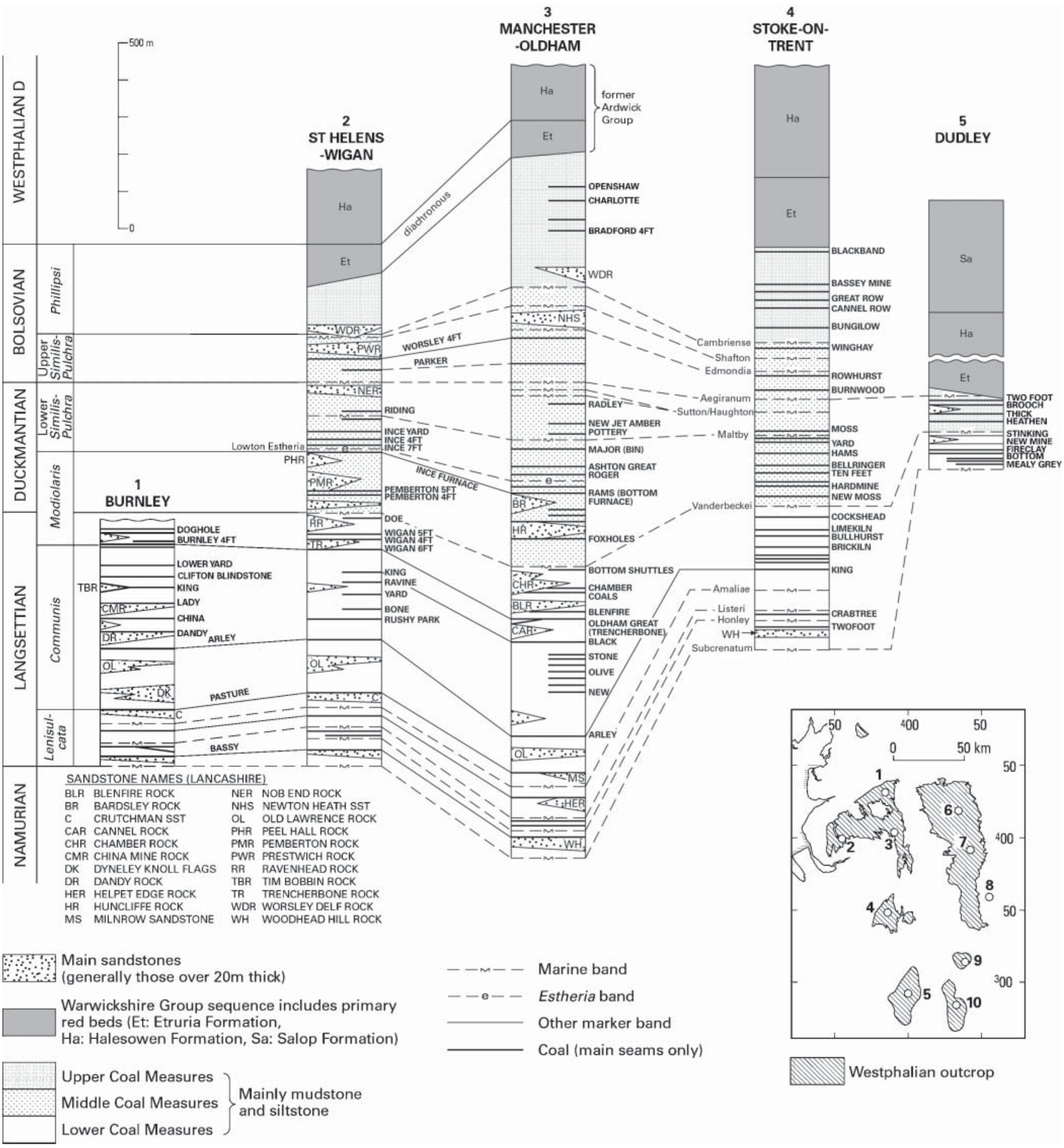

Fig. 9.26. Correlation of Pennine Coal Measures Group sandstones, coals and marine bands within: (**a**) the western part of the Pennine Basin; (**b**) eastern part of the Pennine Basin (amended after Aitkenhead *et al.* 2002).

event (Aitkenhead *et al.* 2002). Alternatively, it may relate to the enclosed nature of the basin. Only the highest global sea level rises would result in a rapid base-level rise within the basin, with the subsequent fall in sea level leaving an isolated basin for which base levels may fall comparatively slowly as it continues to be fed water by rivers.

The Langsettian Crawshaw Sandstone of the East Midlands Shelf is less than 70 km wide and has well defined margins with identifiable interfluves (Church & Gawthorpe 1994; Hampson *et al.* 1999). This is the last representative of this style of fluvial deposition, at least from the onshore UK. Subsequent fluvial systems are characterized by less laterally extensive sandstone bodies associated with less basal erosion, that were developed on a low-lying alluvial (?coastal) plain (Davies *et al.* 1999).

Duckmantian and Bolsovian sandstones examined by Aitken & Chisholm (1999, 2000) and Aitken *et al.* (1999) can also have local basal erosional relief and are complex, multistorey sandstone bodies. The basal Duckmantian Thornhill Rock cuts through the Vanderbeckei Marine Band (Lake 1999) and reaches thicknesses of 37–45 m in the Huddersfield and Wakefield areas. The Late Duckmantian Woolley Edge Rock has a locally erosive base and averages 30 m in thickness.

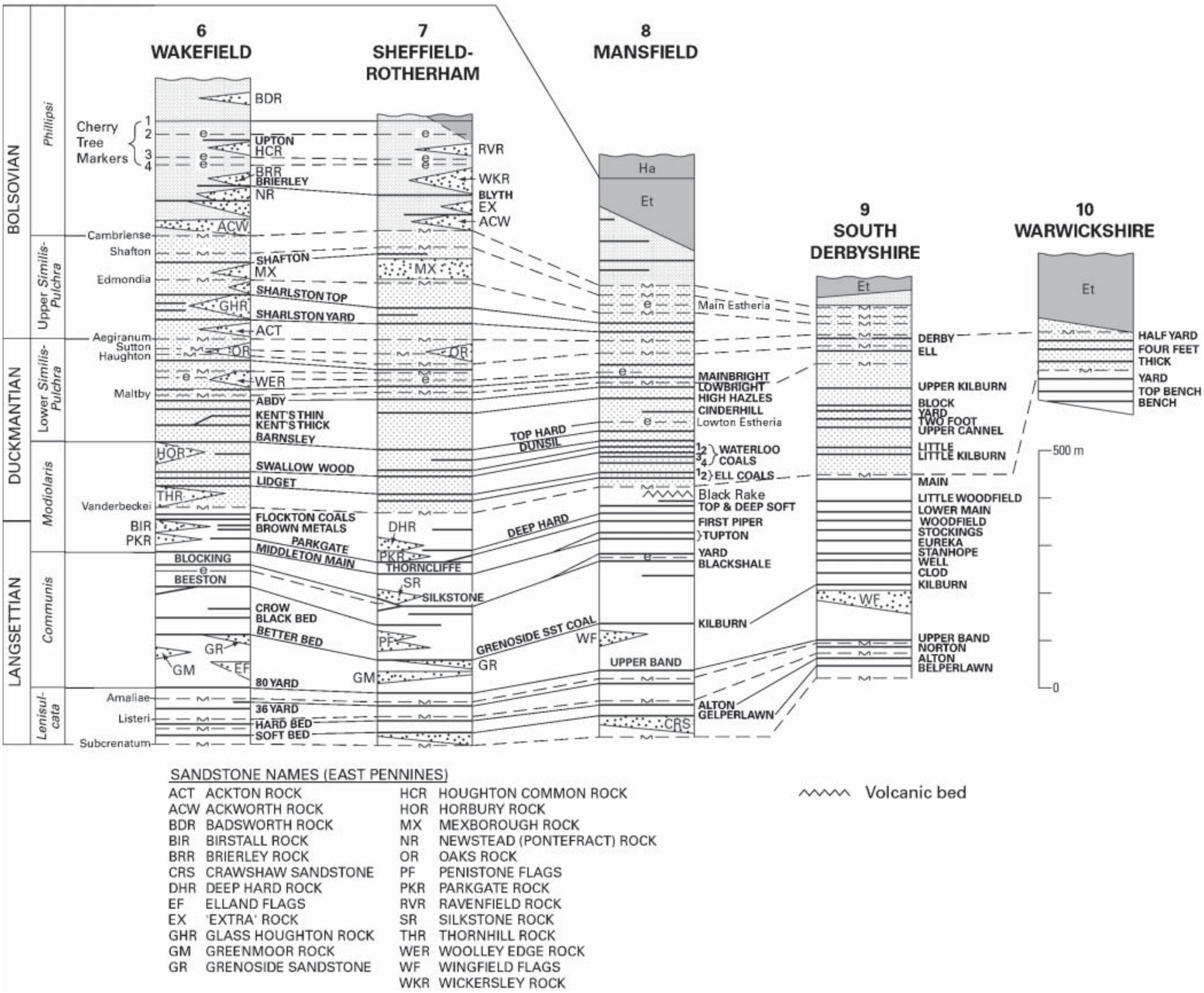

Fig. 9.26. Continued.

Outcrop and subsurface mapping suggest an approximate width for this sandstone of 23 km. The Bolsovian Glass Houghton Rock and Mexborough Rock, also average 30 m in thickness but reach maximum thicknesses of 60–80 m locally. The width of the Glass Houghton Rock cannot be determined, but is at least 15 km. The Mexborough Rock is 15–30 km wide and both bodies can be traced for some 80–90 km in a depositional dip sense. Research on these sandstones suggest a relationship between the channel sandstones and their adjacent strata that includes high ash contents in coals, coal splitting towards channels and an increase in interbedded sandstone layers in proximity to the channel bodies (Bedrock 1984; Guion *et al.* 1995; Aitken *et al.* 1999). These observations imply that overbank flooding events from the channels occurred during peat accumulation and leads these authors to believe that the channel systems were aggradational, as opposed to having filled previously incised valley systems.

Westphalian cyclicity is characterized by the Coal Measures coarsening-upward cyclothem (Plate 15), analysed by Duff & Walton (1962) for the East Pennines Coalfield. In excess of 80% of the approximately 100 cycles recognized within the East Pennines Coalfield contain non-marine shales at their base. It is probable that deposition in these cyclothems occurred in areas distant from marine influences, with the cyclicity reflecting autocyclic delta lobe switching, augmented by local tectonic influences. Duff & Walton (1962) determined that non-marine cycles have a mean thickness of 7.3 m, as opposed to 11.6 m for the much rarer marine cycles. This suggests cyclothems generated in response to sea-level rise provided greater accommodation space for the deltaic sediments. The Subcrenatum, Vanderbeckei and Aegiranum marine bands occur within significantly thicker cyclothems, on average 18.6 m thick, suggesting that these reflect extreme sea-level rises.

A regular rhythmic repetition of arenaceous and argillaceous beds within a small interval of the Lower Coal Measures (Langsettian) of Lancashire has been interpreted as annual monsoonal deposition, of sand during the wet seasons and silt during dry seasons (Broadhurst *et al.* 1980). Groupings of thicker and thinner sandstone beds suggest systematic climatic variations over longer periods.

Regional Developments

Pennine Basin

Pennine Coal Measures Group

The Westphalian Pennine Coal Measures Group of the Pennine Basin extends at outcrop or at subcrop across northern England, to the west and east of the Pennine Anticline, central

England and North Wales (Fig. 9.24). The Coal Measures have historically had a chronostratigraphical connotation synonymous with Westphalian plus Stephanian strata, including both coal-bearing and barren 'red-bed' successions. However, the name has now been defined lithostratigraphically, to describe the main body of coal-bearing strata of Westphalian age (Powell *et al.* 2000*a*).

The Coal Measures have traditionally been divided into three formations, as defined by Stubblefield & Trotter (1957): Lower Coal Measures (Langsettian age); Middle Coal Measures (Duckmantian–Bolsovian age); Upper Coal Measures (Bolsovian–Westphalian D in age). The bases of the two lower formations are taken at the bases of key marine bands; the Subcrenatum Marine Band for the Lower Coal Measures, Vanderbeckei Marine Band for the Middle Coal Measures. The Upper Coal Measures are defined as lacking marine shales, the base of the formation being drawn at the top the Cumbriense Marine Band. The formation is limited to strata of the Fluviolacustrine ('Coal Measures') lithofacies association, so excludes barren or red measures in the Pennine Basin and 'Pennant' measures in the South Wales Basin.

By the end of the Namurian, the inherited Dinantian basinal topography had been largely infilled by fluvio-deltaic sediments of the Millstone Grit Group. Early Westphalian strata are marked by a gradual change to deposition in a delta-plain environment with lakes and distributary channels (Guion & Fielding 1988; Guion *et al.* 1995). This Pennine Coal Measures Group comprises cyclic sequences that are thinner, tens of metres, and more numerous than in the underlying Millstone Grit Group, the sandstones are typically finer, and widespread marine transgressions are less common.

The main distributary channels of the Coal Measures, up to 20 m thick and 10 km wide, were filled by relatively thick, sharp-based sands. Between the channels were freshwater lakes where mudstones were deposited. Upward-coarsening siltstones–sandstones, deposited as small deltas and crevasse splays, filled the lakes. Near-emergent surfaces were colonized by plants and became swamps or raised peat bogs, which formed coals following burial. Subsidence rates were lower along the southern margin of the Pennine Basin resulting in a relatively few thick seams (Fig. 9.26a, b). Northwards, towards the basin depocentre, subsidence rates were greater and seams split. Some of the cycles, particularly in the early Langsettian, commence with laterally widespread marine bands. Within the main basin depocentre, the Subcrenatum, Listeri, Vanderbeckei, Aegiranum and Cambriense Marine Bands represent notably widespread marine flooding events that are useful for correlation between separate coalfields (Fig. 9.26a, b). In basin-margin areas, marine influence was less strong and marine bands are dominated by foraminifera, *Lingula*, fish remains and shallow-marine, benthonic productoid faunas; correlation is less certain here.

The Coal Measures have been subdivided into deposits of 'lower and upper delta-plain' environments (Guion & Fielding 1988). Within the lower delta plain the number and duration of marine flooding events were greater and the time available for peat accumulation, principally as low-lying swamps, was shorter, resulting in coals that are thin and of relatively poor quality. Within the upper delta plain, marine influences were less frequent, and prolonged periods of peat accumulation, mainly as raised mires, resulted in the formation of thick coals with comparatively low ash and sulphur contents.

The lithofacies comprise cyclothems of alternating sandstone, siltstone and mudstone, with frequent coal seams, ironstone nodules or beds, and seatearth (palaeosol) horizons (Plate 15). The base of each cycle is marked by dark grey mudstones, commonly with non-marine faunas, less commonly with marine faunas. Both are of importance in the correlation of strata. The mudstones are typically grey and well-bedded, commonly carbonaceous and sometimes fissile. They include ironstones comprising siderite with clay and silt (clayband ironstone) or carbonaceous laminae (blackband ironstone). Palaeosols present within argillaceous rocks may occur as unleached gley seatearths with abundant roots and polished (listric) surfaces, which formed where water tables were at or above ground level for prolonged periods. Pale grey and ochreous mottled seatearths (fireclays) also occur where palaeosols were better drained. Siltstones are usually grey, laminated and sometimes burrowed, and grade into mudstone or sandstone. Sandstones are typically pale grey, buff-weathered, very-fine- to fine-grained and constitute less than 30% of the total cycle thickness. Sandstones in the Durham–Northumberland coalfields are more commonly coarser and may form up to 50% of the cycle thickness (Rippon 1996). Sandstone palaeosols range from rooty sandstones to leached ganisters. Coal seams typically rest on seatearths and can have a wide range in thickness. Many of the worked seams had a typical thickness of 1–3 m, but the Thick Coal of South Staffordshire represents an amalgamation of coal seams to form a single coal up to 17 m thick (Fig. 9.26a). Most of the coals in England and Wales are bituminous, although higher rank anthracite coals are present in South Wales.

The thickest development of the group is up to 1900 m near Manchester, located in the basin depocentre (Fig. 9.24). A condensed succession is developed at the basin margins, with as little as 150 m present in the South Staffordshire Coalfield (Fig. 9.26). The base of the group generally rests conformably upon the Millstone Grit Group. Along the southern margin of the basin, the Pennine Coal Measures Group oversteps the Millstone Grit Group and rests unconformably upon pre-Carboniferous strata of the Wales–Brabant High. This topographical feature, persistent throughout most of the Carbonifereous, appears to have been subdued, and provided little clastic material into the Pennine Basin during the Westphalian. In many areas the top of the group is defined by the sub-Permian unconformity, which developed in response to end-Carboniferous basin inversion. A variable thickness of secondary reddening is evident beneath this unconformity. In other places, especially at the basin margins the Pennine Coal Measures Group is overlain conformably, or locally unconformably, by primary Westphalian strata of 'Red-bed' facies, including the Warwickshire Group of the English Midlands (Plate 15) and the Whitehaven Sandstone Formation in Cumbria.

The lower part of the Lower Coal Measures, broadly equating with the non-marine bivalve *Lenisulcata* Zone, shows comparable features across the Pennine Basin and maintains aspects of deposition established during the late Namurian. Within the basin depocentre, this interval, between the Subcrenatum Marine Band and the 80 Yard (Pasture) Coal (Fig. 9.26a, b), includes numerous marine bands, the sandstones are typically micaceous, ganisters are common and coals thin (Aitkenhead *et al.* 2002). The feldspathic sandstones are considered to have the same source from the north or NE as the underlying Millstone Grit Group (Chisholm *et al.* 1996; Hallsworth & Chisholm 2000; Hallsworth *et al.* 2000). The Crawshaw Sandstone of Derbyshire is a coarse-grained sandstone, which has the appearance of a Millstone Grit sandstone. It shows palaeocurrents from the east, which appear to be tectonically constrained within the Edale Gulf and Widmerpool Gulf (Guion & Fielding 1988), but was also derived from the same northern source. In the Durham Coalfield this interval is recognized as lower delta-plain deposits by Fielding (1984). These deposits comprise major distributary channels, including a set of coarse-grained sandstones known as the 'Third Grit', with palaeocurrents predominantly towards the south. The interdistributary bay fill sediments show common wave reworking and the presence of brackish water faunas. Quartz arenitic sandstone bodies represent shoreline and shallow-marine wave-reworked deltaic sands. Marine bands are more common within this interval, though not as abundant as within the equivalent interval near the basin depocentre. In comparison with the southern sections, coal seams are relatively uncommon, and where present are generally thin (up to 0.8 m) and laterally discontinuous within this interval.

Within the basin depocentre the middle part of the Lower Coal Measures, between the 80 Yard Coal and Kilburn (Better Bed, Arley) Coal, comprises three basin-wide cyclothems characterized by thin and rare coal seams and very restricted marine band faunas (Fig. 9.26a, b). The sandstones are either micaceous and sourced from the north, or greenish grey, weakly micaceous and clay-rich, sourced from the west (Chisholm 1990; Chisholm *et al.* 1996; Hallsworth & Chisholm 2000). The latter contain grains of chrome spinel indicative of an origin from ophiolitic rocks, possibly as distant as the Appalachian–Labrador–Newfoundland area. The upper part of the Lower Coal Measures, from the Kilburn Coal to the base of the Vanderbeckei Marine Band, is a succession of laterally impersistent cyclothems, which lack true marine bands and have thick coals with many seam splits. The sandstones in this interval continue to be sourced from the west (Chisholm *et al.* 1996; Hallsworth & Chisholm 2000; Hallsworth *et al.* 2000). This source direction agrees with the predominance of W–E-oriented distributary channels across the region (Rippon 1996). Within the Durham Coalfield the middle and upper part of the formation are interpreted as upper delta-plain deposits (Fielding 1984) dominated by distributary sandbodies with variable palaeocurrents. These distributaries display both diagonal and vertical stacking patterns, indicative of compaction-assisted subsidence and tectonic subsidence, respectively. The inter-distributary lacustrine deposits lack marine influence. Coal seams are common, laterally extensive and may be up to 4 m thick within this interval.

The lower part of the Middle Coal Measures is similar across much of the Pennine Basin and represents a continuation of the features evident within the upper part of the Lower Coal Measures. Within the basin depocentre of Lancashire and Yorkshire this succession, between the Vanderbeckei Marine Band and Maltby Marine Band (Fig. 9.26a, b), includes sandstones sourced from the west (Hallsworth & Chisholm 2000). In the succession above the Maltby Marine Band, marine and estheriid faunal bands are common and coals are comparatively thin, interpreted as a return to lower delta-plain deposition in the Durham Coalfield (Fielding 1984). In Yorkshire, sandstones are generally thicker and coarser than is typical of the underlying Coal Measures (Aitkenhead *et al.* 2002). Heavy minerals suggest the start of a new influx, this time from the east and SE (Hallsworth & Chisholm 2000). This new source appears to be in central Europe, probably associated with the Variscan fold-belt, with isotopic signatures indicative of erosion of rocks affected by Variscan, Cadomian, Acadian and Sveco-Norwegian orogenies (Evans *et al.* 2001). The river systems rising from the Variscan Highlands appear to have passed to the east of the Wales–Brabant High into the eastern part of the Pennine Basin.

The Upper Coal Measures, here, as elsewhere throughout England and Wales, lack marine bands, although beds with estheriids are common, and coal seams are thin. In Yorkshire there are locally common medium-grained sandstones with continued derivation from the east or SE (Fig. 9.26b). Over much of the west Cumbria coalfield strata from the Upper *Similis-pulchra* Zone appear to be cut out below the unconformable base of the Whitehaven Sandstone.

Following a period of practically no igneous activity within the Pennine Basin during the Namurian, the Westphalian saw resurgence in activity along the southern margins of the basin. In the East Midlands evidence of igneous activity during the Westphalian is limited to the subsurface, revealed by coal and oil exploration (Burgess 1982). Olivine–basalt lavas occur within the Langsettian Lower Coal Measures. Extrusive igneous activity appears to have terminated abruptly at the end of the Langsettian. Olivine–dolerite sills, up to 40 m thick also occur, intruded into strata up to early Duckmantian in age. Both sills and lavas vary in composition from tholeiitic to alkaline basanite and basalt, basaltic hawaiite and hawaiite (Kirton 1984).

Warwickshire Group

The predominantly primary 'Red-bed' facies strata that overlie the Pennine Coal Measures Group have, in the past, been referred to collectively by informal terms such as the 'Barren (Coal) Measures' and 'Red Measures', and a new formal name, the Warwickshire Group, has been introduced to replace these (Powell *et al.* 2000*a*). The group is best developed along the southern margin of the Pennine Basin, notably in Warwickshire (Plate 15), the type area, in Staffordshire and North Wales (Fig. 9.27). The group is also proved, mainly in the subsurface, in Lancashire, South Yorkshire, Nottinghamshire and Lincolnshire. The group includes red-bed formations and interbedded coal-poor, grey formations, and ranges in age from Duckmantian to Autunian. Primary red measures are also found in the northern margin of the Pennine Basin, with the Bolsovian–Westphalian D Whitehaven Sandstone Formation present in west Cumbria. These Warwickshire Group 'red-beds', have undergone oxidation at, or close to, the time of deposition. The sediments were deposited within alluvial and lacustrine environments, with no marine influences. The Warwickshire Group consists of interbedded mudstone, siltstone, sandstone and conglomerate, typically red, brown, purple or grey, often mottled. The succession is divided into formations, some of which can be correlated between coalfields (Fig. 9.27). The formations typically include siliciclastic material derived from erosion of the Wales–Brabant High; the exception is the Halesowen Formation, which includes lithic arenites similar to the Pennant Sandstone Formation and indicative of a more distant southerly source.

The Warwickshire Group has its thickest development, 1225 m, in the Warwickshire Coalfield (Fig. 9.27). The lower boundary is taken generally at the base of the lowest red-bed formation (generally Etruria Formation) of late Carboniferous age (Plate 15). There is commonly a passage by alternation from grey strata of the Pennine Coal Measures Group into the Etruria Formation. Locally, the base is erosional (the Symon Unconformity) in Warwickshire (Plate 15), Coalbrookdale and Lincolnshire. A higher unconformity, below the Westphalian D Halesowen Formation, is traceable throughout most of the southern part the Pennine Basin, but has not been recognized in the northern basinal successions of South Yorkshire and Lancashire (Waters *et al.* 1994). A further unconformity (or disconformity) is present at the base of the Clent Formation in the southern part of the South Staffordshire Coalfield. The boundary becomes gradational in the north of the coalfield. The upper boundary of the group is taken at the base of unconformable (post-Variscan) Permian, or younger strata.

The well-drained alluvial floodplain deposits of the Etruria Formation mark the onset of red-bed' deposition. The formation comprises predominantly mudstone, coloured red, purple, brown, ochreous, green and grey mottled, with pedogenic horizons common (Glover *et al.* 1993). Subordinate lenticular sandstones and conglomerates (Plate 15) commonly include locally derived volcanic and lithic clasts. Thin coal seams are present in places. The Etruria Formation is generally Bolsovian in age, but ranges from late Duckmantian to early Westphalian D. The lower boundary is highly diachronous (Fig. 9.27), with primary red-beds forming earlier in the Pennine Basin margins (Besly 1988*b*; Waters *et al.* 1994). In Lancashire, the base of the formation contains non-marine bivalves of the *A. phillipsii* and *A. tenuis* zones (Trotter 1954), suggesting a Bolsovian–Westphalian D age for the onset of primary 'Red-bed' facies deposition (Fig. 9.26a).

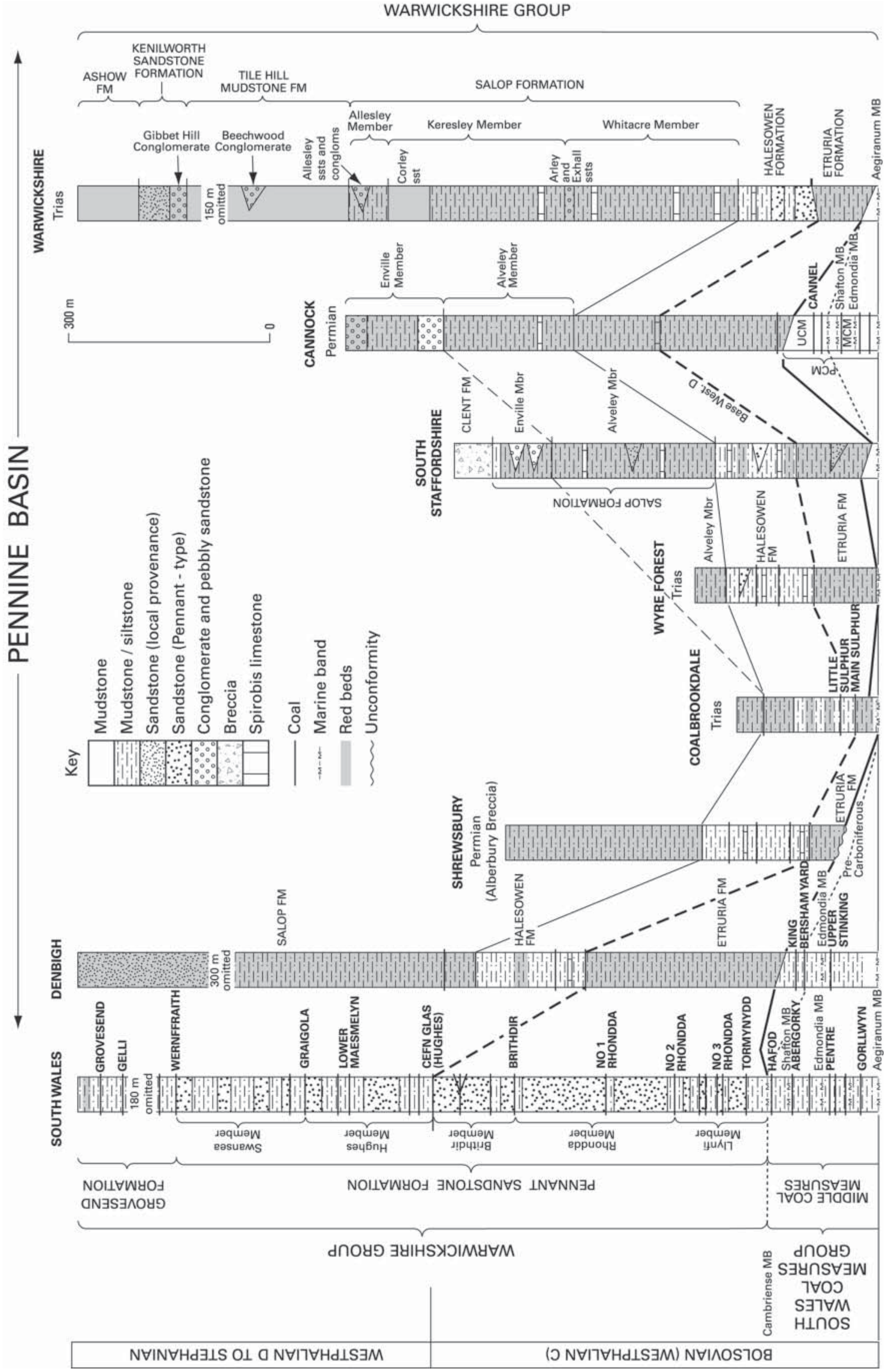

Fig. 9.27. Correlation of late Westphalian to early Permian Warwickshire Group from the southern part of the Pennine Basin and South Wales (from Powell *et al.* 2000*a*).

The succeeding Halesowen Formation represents a widespread return to fluvial deposition in association with relatively high water tables. The formation comprises grey-green, micaceous sandstone (litharenite) and grey-green mudstone, with thin coals, beds of *Spirorbis* limestone, local intraformational conglomerate, and pedogenic carbonate (caliche). The Halesowen Formation is interpreted as the northward equivalent of the 'Pennant' facies sandstone of the South Wales Basin (Besly 1988b). The Halesowen Formation has yielded miospores (Butterworth & Smith 1976; Smith & Butterworth 1967), plant macrofossils (Besly & Cleal 1997; Clayton *et al.* 1977; Cleal 1984) and non-marine bivalve faunas (Edwards 1951) with *Anthraconauta tenuis*, that indicate a Westphalian D age. Zircon grain ages indicate a source terrain of Variscan and Cadomian age, possibly from the Armorican Massif to the south (Hallsworth *et al.* 2000). A strong similarity in zircon isotopic dates suggest the Halesowen Formation has a similar source to the late Duckmantian and Bolsovian sandstones of Yorkshire (Hallsworth *et al.* 2000). However, northerly palaeocurrents within the Halesowen Formation suggest that these river systems followed a different path, crossing breaches within the Wales–Brabant High.

The Salop Formation and Tile Hill Mudstone formations represent a return to well-drained, alluvial plain settings with localized shallow lakes, and semi-arid conditions. The Salop Formation comprises red and red-brown interbedded mudstone and sandstone, with beds of pebbly sandstone and conglomerate. Thin *Spirorbis* limestone beds, calcrete and rare thin coals are present in the lower part. The sandstones are mostly sublitharenite, and conglomerate clasts include Carboniferous limestone and chert. The Tile Hill Mudstone Formation is limited to the southern part of the Warwickshire Coalfield where it rests conformably upon the Salop Formation (Fig. 9.27). It comprises red-brown mudstone with subordinate thin red-brown and green flaggy sandstones and sparse thin conglomeratic lenses. The Salop and Tile Hill formations are Westphalian D–Stephanian or Early Permian in age (Waters *et al.* 1995; Besly & Cleal 1997). Poorly preserved plant material from the Wyre Coalfield suggests the inclusion of early Stephanian (Cantabrian) beds in the Salop Formation (Besly & Cleal 1997).

In South Staffordshire the Salop Formation is overlain by the Clent Formation, which shows a rapid northward transition from breccia to red mudstone (Fig. 9.27). The Clent Formation is interpreted as proximal alluvial fan deposits with pebble clasts derived locally from uplifted hinterland blocks associated with the Wales–Brabant High to the south. The Clent Formation is probably Early Permian, or possibly late Stephanian in age (Waters *et al.* 1995).

A limited development of primary or early diagenetic red measures comparable to the Warwickshire Group occurs along the northern margin of the Pennine Basin, in west Cumbria. This is the Whitehaven Sandstone Formation, which is at least 300 m thick, and unconformably overlies the Pennine Coal Measures Group. The lower 100 m consists of red–deep purple or purplish brown, cross-bedded, micaceous, medium- to coarse-grained sandstone, known as the Whitehaven Sandstone (Akhurst *et al.* 1997). There are interbeds of pink–red or grey mudstone and siltstone, and thin palaeosols are present locally. The sandstones are overlain by a heterogeneous, dominantly red succession of mudstone, sandstone and marl with thin coals and limestones with *Spirorbis*. The lower part of the formation is interpreted as deposits from a major braided river system that flowed from the NE. The upper part of the formation represents deposition in interdistributary bay or lacustrine environments with minor river channels (Akhurst *et al.* 1997). Plant remains and the presence of the nonmarine bivalve *Anthraconauta phillipsii* (Eastwood *et al.* 1931) indicate a late Bolsovian–early Westphalian D age for the formation. To the NE similar strata have a Westphalian D *Tenuis* Zone fauna (Eastwood *et al.* 1968).

The Carboniferous igneous rocks of the West Midlands are predominantly alkaline olivine–dolerite sills (Kirton 1984). The sills are believed in many cases to have been emplaced into still-wet sediment of Bolsovian age. The sills are more limited in composition than those in the East Midlands, ranging from basaltic hawaiites to hawaiites.

The Barrow Hill Complex, located west of Dudley, is notably distinct from the other West Midlands intrusions in comprising vent agglomerate and dolerite with associated volcaniclastic rocks (Glover *et al.* 1993; Waters 2003*b*). The country rock of Etruria Formation, of Bolsovian age, appears to have been relatively wet and unlithified at the time of intrusion, suggesting emplacement at or near the contemporaneous ground surface. The interaction of hot, gassy magma with groundwater resulted in explosive activity in which dykes of sedimentary and igneous material were forced underground for some distance marginal to the vent. The surface expression of the explosive activity is seen as ash-fall deposits, hot, gaseous surge deposits and a thick breccia, similar in composition to the agglomerate present in the vent. The site is also of importance for the presence of anatomically well-preserved, conifer-like stems, which were buried by ash falls from this volcanic centre (Galtier *et al.* 1992).

In northern England a short-lived period of tholeiitic magmatism during the Stephanian resulted in intrusion of the quartz–dolerite Whin Sill-complex (Plate 19), together with associated ESE- and ENE-trending dyke-swarms (Fig. 9.11). There are no associated extrusive rocks. The Great Whin Sill is considered to be saucer-shaped (Francis 1982) and intruded into strata ranging in age from Dinantian to Westphalian. The intrusion changes stratigraphical level in a series of commonly fault-controlled transgressive steps.

Southern England–South Wales

South Wales Coal Measures Group

During early Westphalian times, the deposition of the South Wales Coal Measures Group in South Wales and southern England includes lithologies and environments of deposition that are essentially the same as those described for the Pennine Basin. Despite the broad similarity of Fluvio-lacustrine ('Coal Measures') lithofacies association to the north and south of the Wales–Brabant High, the evolution of the two successions in largely isolated basins has warranted the definition of two separate groups (Waters *et al.* 2006*a*). The South Wales Coal Measures Group of the Variscan Foreland Basin extends across South Wales, the Bristol region and the subsurface Berkshire and Kent coalfields.

Transitions between lower and upper delta plain appear to be synchronous between the two basins, suggesting a long-term eustatic control (Hartley 1993*a*). The group is predominantly argillaceous, with widespread sandstones rare. The succession is dominated by grey or black lacustrine mudstone, coarsening-upwards into lacustrine deltaic siltstones and sandstones. The sandstones are typically dark grey with variable grain-size, common lithic fragments and a dominant palaeocurrent direction towards the NE (Rippon 1996). The group is thickest in the west and SW of the South Wales Coalfield (about 900 m) and attenuated in the East Crop (about 240 m), adjacent to the Usk Anticline (Fig. 9.28). Coal seams thicken and amalgamate towards this anticline. The Pembrokeshire Coalfield is an attenuated westward extension of the main South Wales Coalfield. In England the group ranges from about 550 m thick in the Bristol area, 141 m in the Berkshire Coalfield to 285 m thick in the Kent Coalfield (Fig. 9.29a & b). In South Wales and the Bristol region the group rests conformably upon Namurian strata of the Marros Group, whereas in the Berkshire and Kent coalfields the Lower Coal Measures rest unconformably upon Dinantian or Devonian strata.

During late Langsettian–late Bolsovian times, E–W growth folds such as the Pontypridd Anticline developed in response to

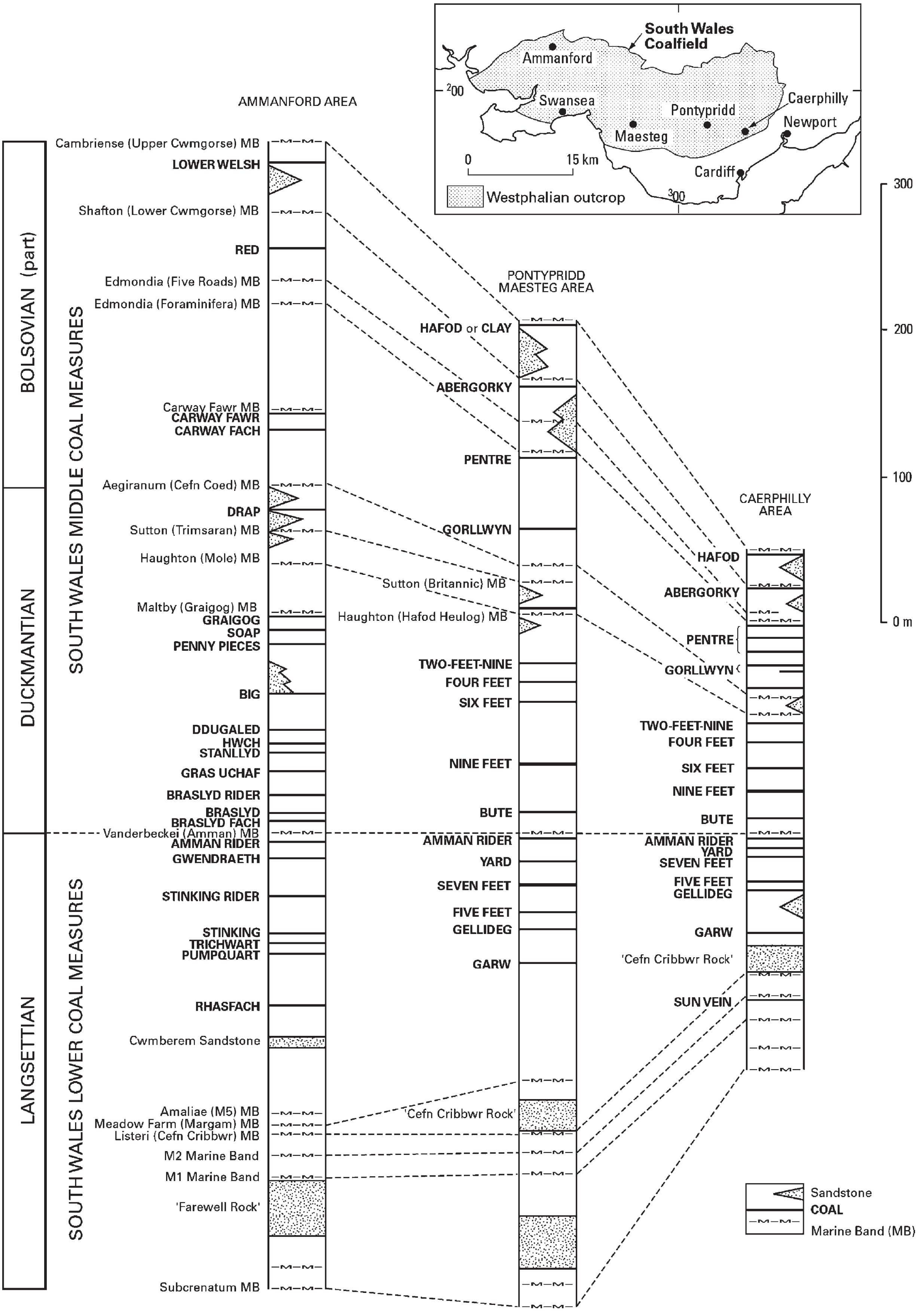

Fig. 9.28. Correlation of Westphalian strata of the South Wales Coal Measures Group within the South Wales Coalfield, adapted from Thomas (1974).

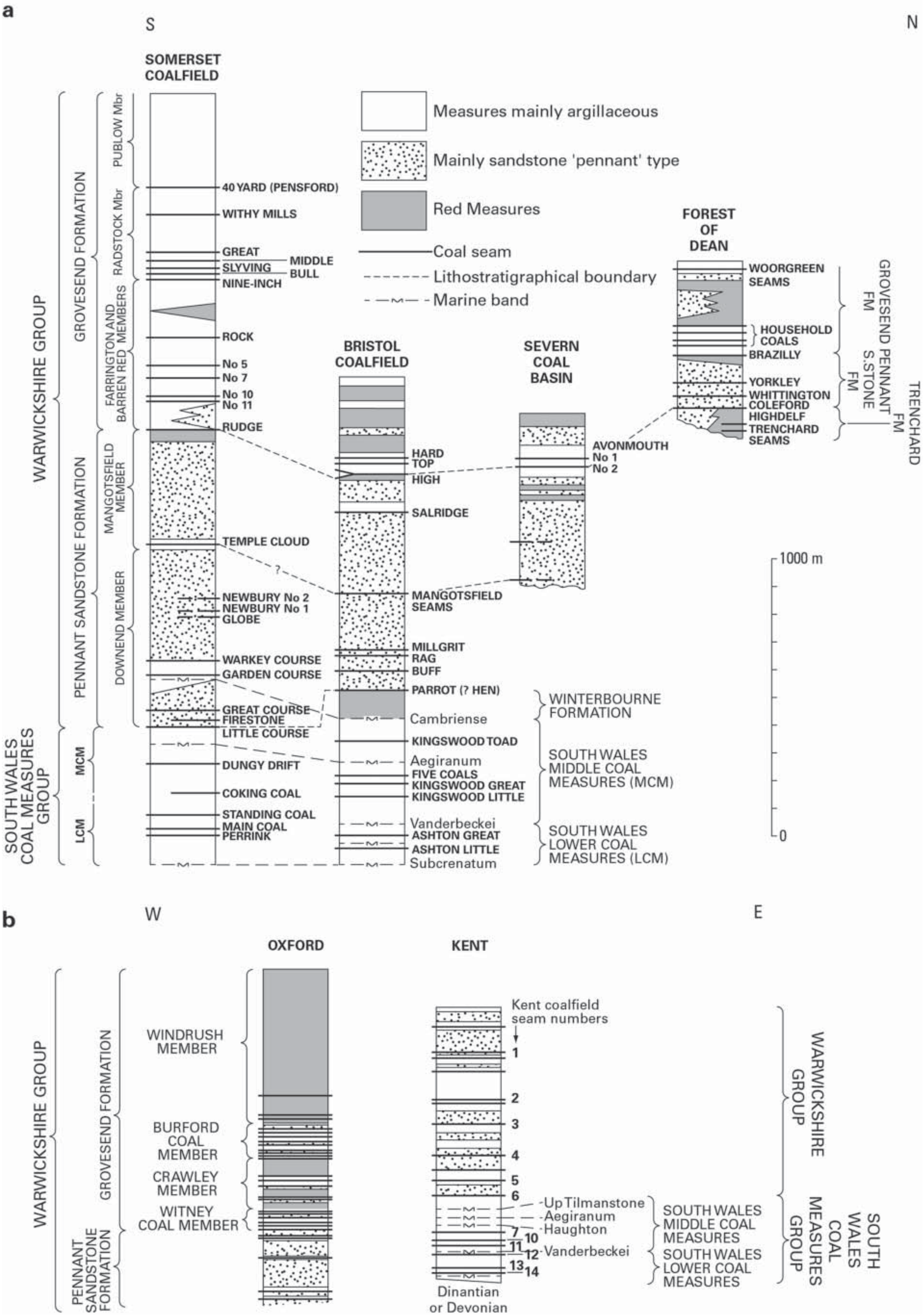

Fig. 9.29. Correlation of Westphalian strata within southern England: (**a**) N–S section from Forest of Dean to Somerset coalfields, adapted from Green (1992); (**b**) Vertical sections from the Oxfordshire and Kent coalfields (after Ramsbottom *et al.* 1978).

the early stages of Variscan compression. These folds actively controlled drainage patterns, with coal seam splits occurring within synclines (Jones 1989*a*). Seam splits and vertically stacked channel washouts also appear to be influenced by episodic movements on NNW–SSE oriented faults, inferred to be synsedimentary transtensional faults (Hartley 1993*a*).

A notable feature of the Coal Measures of South Wales is the increase in coal rank from bituminous, within the South and East crops, to anthracite along the North Crop, especially within the Pembrokeshire sub-basin. Illite crystallinity and vitrinite reflectance values for coals near the base of the group indicate maximum maturity temperatures for anthracites of 200–250 °C, whereas fluid inclusion studies suggest temperatures for bituminous coals of *c.*150 °C (Bevins *et al.* 1996). This does not appear to solely reflect depths of burial, as the depocentre occurs to the south of the area of highest rank. The heating appears to have been rapid, occurring soon after deposition and with high geothermal gradients, atypical of geothermal gradients within a foreland basin setting. The relationship of the thermal event to Variscan deformation has not been fully ascertained. Bevins *et al.* (1996) contend that the metamorphism occurred prior to deformation, but migration of hot fluids along thrusts has also been invoked.

The South Wales Lower Coal Measures show two distinct lithological variations in South Wales. As with the Pennine Basin, there is a lower succession, which equates with the *Lenisulcata* Biozone, that includes thin and impersistent coal seams and relatively common *Lingula*-bearing marine bands (Fig. 9.28). Sandstones within this interval, collectively known as the Farewell Rock, represent mainly southward-prograding delta lobes, or fluvial sands with channelled bases. Some thick, lenticular, coarse and pebbly, quartzitic sandstones on the East and South Crops formed as littoral or sublittoral sandbodies (Kelling & Collinson 1992). The sequence thins eastward toward the Usk Anticline, marine bands become impersistent and coals thin. The upper part of the formation is distinguished by thick coals, seatearths and sideritic ironstones, and relatively few marine bands. Locally, in the Berkshire Coalfield, Langsettian basic volcanic and intrusive rocks are dominant (Foster *et al.* 1989), including the 100 m-thick Aston Tirrold Volcanic Formation.

The South Wales Middle Coal Measures maintain broad lithological similarities with the upper part of the Lower Coal Measures. Thick, extensive coal seams, seatearths and numerous ironstone bands are common and a minor component of sandstone is present. A return to numerous marine bands and thin coals is recorded within the upper part of the formation. Southward-prograding delta lobes with high sinuosity fluvial channels are localized in the NE of the South Wales Coalfield, sourced from a subdued Wales–Brabant High (Hartley 1993*a*). However, in the west and notably in the Pembrokeshire Coalfield, fluvio-deltaic sandbodies appear to be northward prograding and include lithic arenites, precursors to the fluvial deposits of the Pennant Sandstone Formation.

The South Wales Upper Coal Measures is now restricted to the grey measures above the Cambriense (Upper Cwmgorse) Marine Band within a small area of the eastern part of the South Wales Coalfield. The formation is up to 14 m thick in the Kent Coalfield (Bisson *et al.* 1967). In the concealed Berkshire Coalfield the equivalent strata are absent beneath the Warwickshire Group (Foster *et al.* 1989).

The Warwickshire Group barren red-measures succession is present between the Cambriense Marine Band and the base of the Pennant Sandstone Formation in both the East Crop of the South Wales Coalfield (Deri Formation), Bristol Coalfield (Winterbourne Formation) and Forest of Dean (Trenchard Formation). These 'red-beds' are comparable to those present within the Warwickshire Group of the Pennine Basin and were deposited on a well-drained alluvial plain in the vicinity of the modern Severn Estuary. The raised topography associated with the Usk Anticline/Severn Axis enhanced drainage, resulting in a primary reddened succession, and providing a local source for conglomerate. The Deri Formation of the East Crop of the South Wales Coalfield consists of interbedded red, purple and green mottled mudstones and siltstones and channelized quartz arenites that are commonly pebbly and conglomeratic. The formation thickens eastward towards the Usk Anticline, but thin coals progressively fail toward this active structure. The conformable and diachronous base of the Deri Formation rises westwards above the Upper Coal Measures, the western limits of the formation being in the Taff Valley area (Downing & Squirrell 1965). The Winterbourne Formation of the Bristol Coalfield is up to 180 m thick (Fig. 9.29a) and comprises grey and red mudstone with common thin and lenticular beds of quartz-conglomerate and pebbly sandstone. The Deri and Winterbourne formations are of late Bolsovian to possibly early Westphalian D age. The Trenchard Formation of the Forest of Dean Coalfield consists of grey or pinkish grey quartzose sandstone, with quartzose conglomerate beds common at the base of the formation, increasing in thickness and clast size toward the north (Jones 1972). This formation, of possible late Westphalian D age, rests unconformably upon Dinantian and older strata. The formation is up to 120 m thick in the north of the coalfield, thinning southwards as it passes into the Pennant Sandstone Formation (Fig. 9.29a).

The Pennant Sandstone Formation comprises strata dominated by 'Pennant' facies sandstones, located south of the Wales–Brabant High. The formation extends across South Wales, Bristol, Somerset and the Forest of Dean, and the concealed Oxfordshire, Berkshire and Kent coalfields. A mudstone-dominated late Westphalian D–Stephanian succession is identified in South Wales as the Grovesend Formation. This name is now extended to include similar facies found in the Somerset, Bristol, Forest of Dean and Oxfordshire coalfields, formerly referred to as Supra-Pennant Measures. The Grovesend Formation of Bristol, Somerset and Oxfordshire includes some red-bed members.

The late Westphalian sedimentation of the area south of the Wales–Brabant High was dominated by a broad alluvial braidplain, with low- to moderate-sinuousity rivers flowing northward from the rising Hercynian mountain belt to the south (Kelling & Collinson 1992). This component of the Warwickshire Group is dominated by thick litharenite sandstone beds, with subordinate mudstone and thick coal seams in its lower part (Pennant Sandstone Formation), and a mudstone-dominated succession with subordinate sandstone in its upper part (Grovesend Formation). The Pennant Sandstone Formation is subdivided into members using marker coal seams, whereas the Grovesend Formation is subdivided into members using lithological variations between coal-bearing and barren measures (Fig. 9.27 & 9.29). In the Bristol region, marker coal seams can rarely be correlated with any confidence between coalfields. The Oxfordshire succession shows strong similarities with that in the Bristol region (Poole 1969). In the Kent Coalfield the Warwickshire Group cannot be subdivided into the component formations seen elsewhere. The group rests above a non-sequence upon Upper Coal Measures in the Kent Coalfield.

The Pennant Sandstone Formation is characterized by the presence of bluish grey, weathering green, coarse-grained, locally conglomeratic, feldspathic and micaceous lithic arenites of southern provenance. These sandstones are distinct from the quartz arenites of the South Wales Coal Measures Group, which are of northern provenance. There is a slight upward increase in grain size within the sandstones, representing northward progradation of alluvial facies with time. Typically, the formation thins northward towards the Wales–Brabant High (Fig. 9.29), but also over the Usk Anticline. The base of the formation is diachronous, with a broadly northward younging of the first incoming of 'Pennant'-type sandstones. The base of the formation in the SW of the South Wales Coalfield occurs at, or just above, the top of the Cambriense Marine Band. The base ranges from up to 180 m below the Cambriense Marine Band in the Somerset Coalfield, to 180 m above the same marine band in the Bristol area. In the Oxfordshire Coalfield the formation rests unconformably upon strata of Devonian or older age. The formation is thickest in the Swansea area of the South Wales Coalfield, up to 1150 m, decreasing in thickness towards the East Crop. The formation is about 1100 m thick in the Somerset Coalfield, whereas further towards the north in the Forest of Dean it is only 180–300 m, thinning towards the north as it onlaps the Wales–Brabant High (Fig. 9.29a). Within the concealed Oxfordshire Coalfield, the thickness is 335 m (Fig. 9.29b). The formation ranges from Bolsovian to late Westphalian D.

During the late Westphalian D there was a change to dominantly floodplain sedimentation of the Grovesend Formation, evident as mainly shales and sandy shales, with subordinate 'Pennant' type sandstone beds and thin coals. In the Somerset, Bristol and Oxfordshire coalfields, red mottled mudstone, seatearth, 'Pennant' type sandstone, but no coal seams typify the barren members of the formation. The formation is about 1400 m thick in the Somerset Coalfield, thinning northwards to 340 m in the Forest of Dean (Fig. 9.29a). In the Oxfordshire Coalfield, there is a comparable northwards thinning, with a maximum of about 1000 m recorded (Fig. 9.29b). The thickness is about 450 m in South Wales (Fig. 9.27). The Grovesend Formation is late Westphalian D in age, possibly in part Cantabrian (early Stephanian) in age in South Wales and the Forest of Dean (Ramsbottom *et al.* 1978) and Oxfordshire (Besly & Cleal, 2006). The top of the Warwickshire Group is truncated by the Permo-Triassic unconformity in England.