The Triassic System in Warwickshire

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Abstract. Warwickshire's Triassic strata are a mainly clastic Scythian-Rhaetian succession. The Sherwood Sandstone and Mercia Mudstone groups are assigned to the three structural settings of the Hinckley and Knowle Basins separated by the Coventry Horst. In the basinal areas the Sherwood Sandstone fines up from pebbly braidplain facies (Polesworth and Kidderminster Formations) into sandy braidplain and meanderplain facies (Bromsgrove Sandstone). The basal Hopwas Breccia crops out on the western margin of the Hinckley Basin. The Bromsgrove Sandstone onlaps the horst, with fossils that can be assigned to both terrestrial and aquatic habitats. The overlying Mercia Mudstone Group attests to a Mid-Late Triassic continental desert environment with windblown dust, periodic floods and ephemeral lakes. Within the Mercia Mudstone, the Arden Sandstone represents a fluvial interval with some marginal marine influences, and has yielded a mixed terrestrial-aquatic biota in the Knowle Basin. The relatively fossiliferous Penarth Group attests to Late Triassic (Rhaetian) marine transgression. Key Triassic sites are protected as SSSIs and RIGS.

The central English county of Warwickshire (Fig. 1) occupies part of the wide outcrop of generally gently dipping Triassic and Jurassic strata that runs from the Dorset and Devon coast in southwest England to the Yorkshire coast in the northeast. The broadly spindle-shaped Warwickshire Coalfield diversifies the regional outcrop pattern (BGS, 2001). There, the bedrock geology is dominated by an Upper Carboniferous to Lower Permian red-bed succession (Warwickshire Group), fringed in the north by Coal Measures, Millstone Grit, and older igneous and sedimentary rocks of Palaeozoic and Neoproterozoic age, as in the Nuneaton Inlier (Shotton, 1960; Hains & Horton, 1969; IGS, 1983; Bridge *et al*, 1998; Fig. 1).

This paper focuses on Warwickshire's Triassic successions, dominated by the Sherwood Sandstone and Mercia Mudstone groups (Warrington *et al*, 1980; Fig. 2). The Sherwood Sandstone Group rests unconformably on rocks ranging from Precambrian (Neoproterozoic) up to early Permian in age (Warrington *et al*, 1980; Bridge *et al*, 1998), reflecting post-Variscan uplift and erosion. The Sherwood Sandstone and Mercia Mudstone are developed largely as non-marine sediments deposited in hot, semi-arid to arid continental settings, approximately 15-20º north of the equator, within the northern part of the Permian-Triassic Pangaea supercontinent (Ruffell & Shelton, 2000; Benton *et al*, 2002). Fossils are very rare in these rocks and standard Triassic stage boundaries cannot be accurately located. Present evidence suggests that the strata range through much of the Triassic System (Scythian Series up to Rhaetian Stage; Warrington *et al*, 1980; Fig. 2), though in places the basal Hopwas Breccia and lower part of the Sherwood Sandstone is possibly of Permian age (Worssam & Old, 1988). Above the Mercia Mudstone, the relatively fossiliferous latest Triassic (Rhaetian) Penarth Group is largely marine in origin. The Triassic-Jurassic (Rhaetian-Hettangian) boundary is defined in Britain by the first occurrence of the ammonite genus *Psiloceras* (Cope *et al*, 1980; Warrington *et al*, 1980). This occurs within the Wilmcote Limestone Member (basal Lias Group) in the Avon Valley region of southwestern Warwickshire (Old *et al*, 1991; Ambrose,

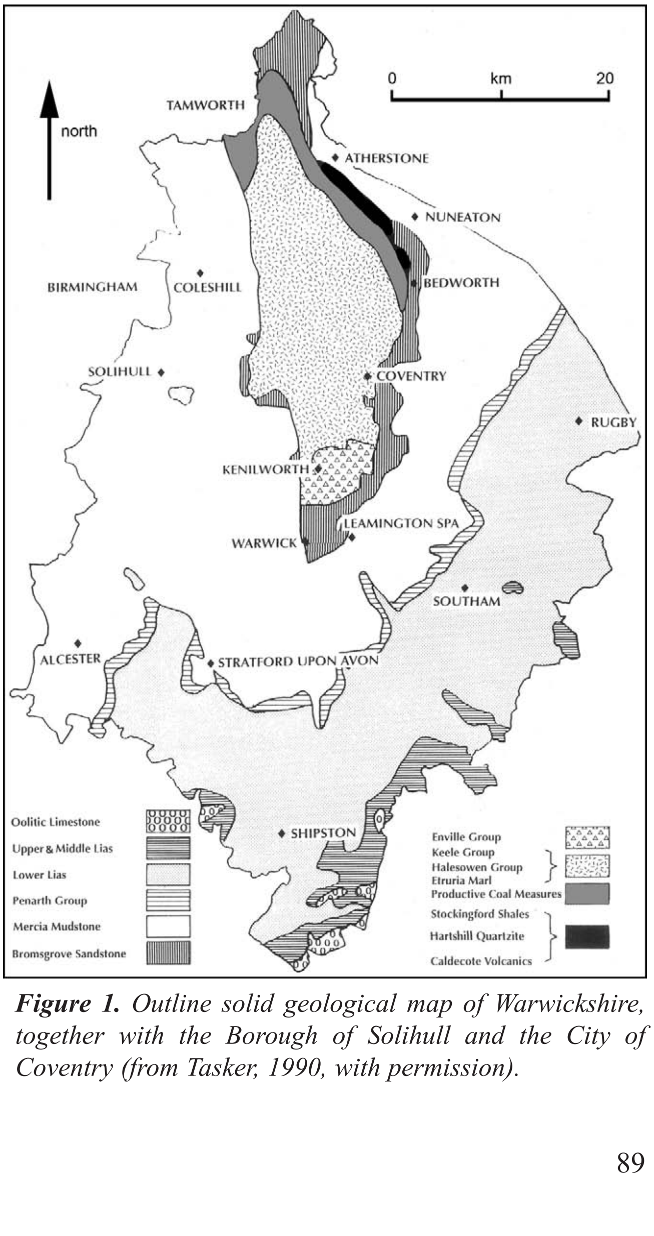

Figure 1. *Outline solid geological map of Warwickshire, together with the Borough of Solihull and the City of Coventry (from Tasker, 1990, with permission).*

2001) and in the Saltford Shale Member near Rugby (Old *et al*, 1987).

Overall, the Triassic strata demonstrate the shallow regional structural dip towards the southeast and crop out extensively around the coalfield. In the Avon Valley and Warwick-Rugby areas, the Mercia Mudstone outcrop is flanked down-dip by that of the overlying Penarth Group and Lias Group (Lower Jurassic) strata (Hains & Horton, 1969; IGS, 1983; BGS, 2001). An outlier of Penarth Group strata occurs at Copt Heath, Knowle (Brodie, 1865; Eastwood *et al*, 1925), 17 km north of the main outcrop.

Triassic strata were well exposed in sandstone quarries and clay pits during the nineteenth and early to mid twentieth centuries. Many of these sections are no longer extant. However small natural sections are common, albeit often deeply weathered. Accessible exposures also occur in canal cuttings, shallow road cuttings and sunken lanes. The Scythian-?Ladinian Bromsgrove Sandstone Formation (Sherwood Sandstone Group) and the Carnian Arden Sandstone Formation (Mercia Mudstone Group) formerly yielded building stone, seen in many towns and villages around the southern end of the coalfield (Matley, 1912; Old *et al*, 1987). Thinner sandstones within the Mercia Mudstone Group, termed 'skerries' (see below), have probably also been quarried. Rhaetian Langport Member ('White Lias') limestones have been quarried on a small scale for building stone, cement and agricultural lime along a narrow outcrop from the Stour Valley to Rugby (Richardson, 1912; Swift, 1995). It is still intermittently worked near Loxley, southeast of Stratford-upon-Avon. The Wilmcote Limestone of the Avon Valley has supplied flooring, paving and walling stone, as well as raw material for cement manufacture (Brodie, 1868). The red-brown mudstones of the Mercia Mudstone Group have been quarried for brick clay, as at Leamington, Knowle and Stonebridge, and were also used for 'marling' light land (Twamley, 1878; Old *et al*, 1991; Powell *et al*, 2000). Additionally they were mined for gypsum at Spernall, north of Alcester (Old *et al*, 1991). The Early Triassic Polesworth Formation has been dug for sand and gravel in north Warwickshire (Worssam & Old, 1988).

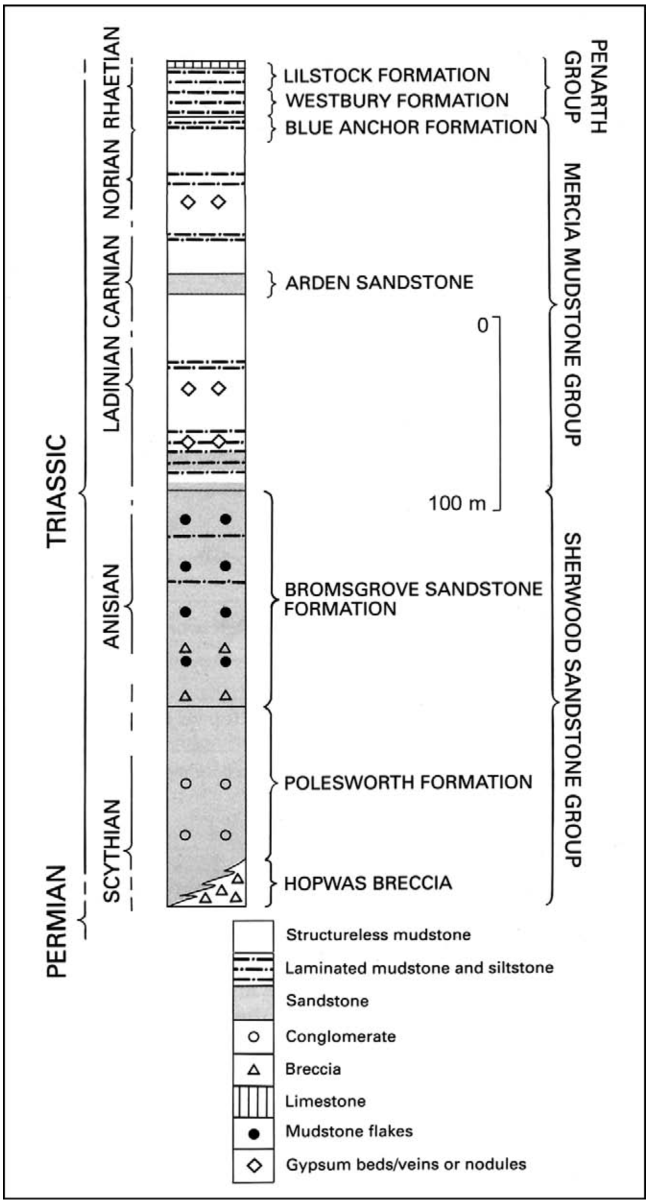

Figure 2. *Generalised vertical section of Triassic strata in Warwickshire (from Bridge et al, 1998, with permission).*

The Triassic strata of Warwickshire have a long research history, stemming from the early nineteenth century when exposures were more prevalent than they are today (see above). Historically, the succession has been associated with such eminent researchers as Roderick Murchison (1792-1871), Hugh Strickland (1811-1853), Peter Brodie (1815-1897), Linsdall Richardson (1881-1967), Leonard Wills (1884-1979) and Fred Shotton (1906-1990). Only a few of the more important older references are cited herein. Modern knowledge of the Warwickshire Triassic is due largely to investigation and interpretation of surface exposures and borehole sections by the British Geological Survey. Survey memoirs and Geological Conservation Review volumes cited herein should be consulted for more comprehensive details of earlier works.

Selected geological sites in the United Kingdom are afforded statutory and non-statutory protection as Sites of Special Scientific Interest (SSSIs) and Regionally Important Geological Sites (RIGS) respectively (Harley, 1994; Ellis *et al*, 1996). Warwickshire currently (2005) boasts three SSSIs and thirteen RIGS selected partly or wholly for their Triassic interest. Additionally, the Warwickshire Museum has recently produced a series of local geodiversity action plans (LGAPs) that will facilitate planned conservation and management of several Permian-Triassic fossil sites (Radley, 2004). This paper summarises Warwickshire's Triassic geology with reference to protected sites. For the purposes of this account the county is taken as the area defined by the 1974 local government reorganisation, and additionally, the Borough of Solihull and City of Coventry (Fig. 1).

Structural framework

Late Permian times in central England were marked by east-west crustal extension and continental rifting, attributed to tensional stresses linked to the opening of the North Atlantic Ocean (Ruffell & Shelton, 2000). This resulted in reactivation of favourably oriented faults in the Midlands Microcraton basement, predominantly those with north-south (Malvernoid) trends (Audley-Charles, 1970; Chadwick, 1985; BGS, 1996). Further reactivation probably occurred intermittently throughout much of the Triassic (Holloway, 1985b, c; Ruffell & Shelton, 1999), and the strata were deposited principally as syn-rift successions in the resultant range of graben and half-graben; some representing inverted Variscan 'highs' (Chadwick, 1985; Holloway, 1985a; Chadwick & Smith, 1988; Ruffell & Shelton, 2000).

Warwickshire's Triassic rocks largely occupy three structural units (Warrington *et al*, 1980; Bridge *et al*, 1998; Benton *et al*, 2002; Fig. 3), reflecting Late Permian to Early Triassic reactivation of major Malvernoid and NW-SE trending (Charnoid) faults (Audley-Charles, 1970), and Warwickshire's location near the apex of the concealed Midlands Microcraton (Lee, Pharaoh & Soper, 1990; BGS, 1996). Firstly, northeastern Warwickshire (Mease lowlands and parts of the High Cross plateau; Warwickshire County Council, 1993) marks the southwestern part of the Hinckley Basin (Figs 3, 4), generated through Late Permian structural inversion along the Charnoid Polesworth Fault of an area of relative Variscan uplift (Worssam & Old, 1988; Bridge *et al*, 1998). Parts of the Sherwood Sandstone Group thicken towards the Polesworth Fault, suggesting that the Hinckley Basin is a half-graben (Worssam & Old, 1988).

Secondly, west of the Polesworth Fault, the Warwickshire Coalfield and its concealed southern extension (Fig. 3) are characterised by a thin, relatively incomplete Triassic succession (Edmonds, Poole & Williams, 1965; Old *et al*, 1987). This area is accordingly modelled as a partly inverted Triassic 'high' (Warrington & Ivimey-Cook, 1992), termed the Coventry Horst (Old *et al*, 1987; Bridge *et al*, 1998). Thirdly, along the western edge of the coalfield, the Malvernoid Western Boundary (Meriden) and Warwick Faults mark the eastern margin of the Knowle Basin (Old *et al*, 1991; Powell *et al*, 2000; Fig. 3). The eastern part of the Knowle Basin fill occurs within western Warwickshire's Arden district between Alcester and Middleton. The Triassic succession there is thicker than that of the Hinckley depocentre, and similarly marks the site of an inverted Variscan 'high' (Holloway, 1985a).

Depocentre boundaries are poorly defined south and east of the coalfield. The subcropping Triassic strata thin overall to the south and east of Warwickshire, towards the London Platform (Hains & Horton, 1969; Warrington *et al*, 1980). West of Stratford-upon-Avon, the Malvernoid Inkberrow-Weethley Fault system marks part of the eastern margin of the major Permian-Triassic Worcester Basin (Old *et al*, 1991; Ambrose, *pers. comm.*), of which the Knowle Basin is a subsidiary (Chadwick & Smith, 1988). East of Kenilworth and Leamington, the Charnoid Princethorpe Fault (Fig. 4) might relate to the margin of the Hinckley Basin (Old *et al*, 1987).

Stratigraphy and palaeoenvironments

Southern British Triassic successions are characterised by three major lithostratigraphic divisions (Warrington *et al*, 1980). The lower, Sherwood Sandstone Group is a largely alluvial succession deposited under a hot, seasonal climatic regime with both humid and arid characteristics (Ruffell & Shelton, 1999). The overlying Mercia Mudstone Group provides evidence for a dominantly arid Late Triassic climate (see below) and a somewhat featureless, exposed landscape, bordered by extensively peneplaned massifs

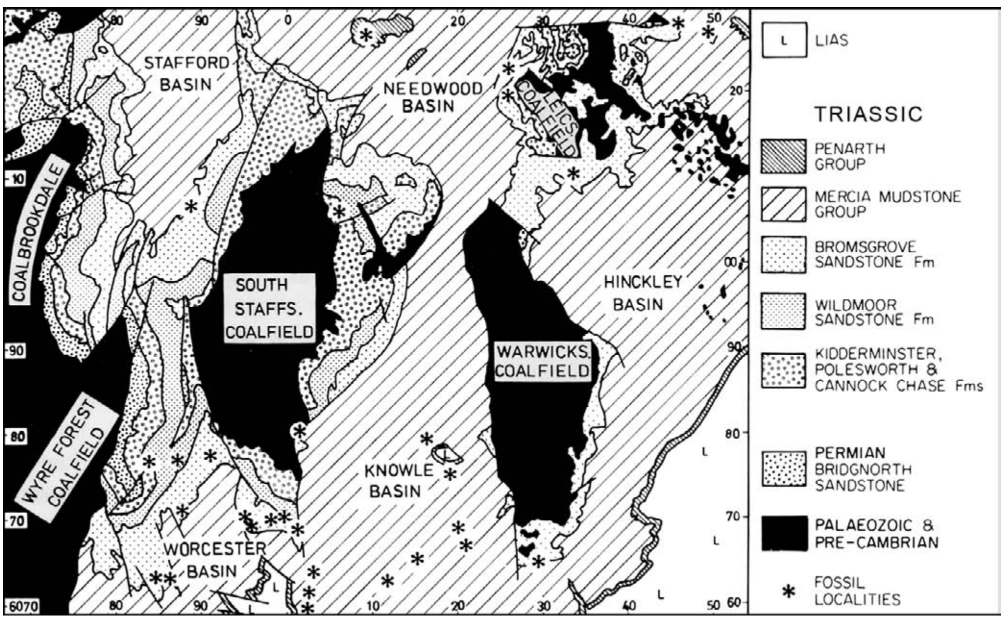

Figure 3. *Distribution of Triassic strata in the English Midlands (from Warrington et al, 1980, with permission).*

(Anderton *et al*, 1979; Audley-Charles, 1970; Warrington & Ivimey-Cook, 1992). Widespread reddening of the mudstones is due to early diagenetic oxidation, reflecting the prevailing aridity (Benton *et al*, 2002). Above, the Penarth Group includes fossiliferous mudstones and micritic limestones of transgressive marine origin (Richardson, 1912; Benton *et al*, 2002).

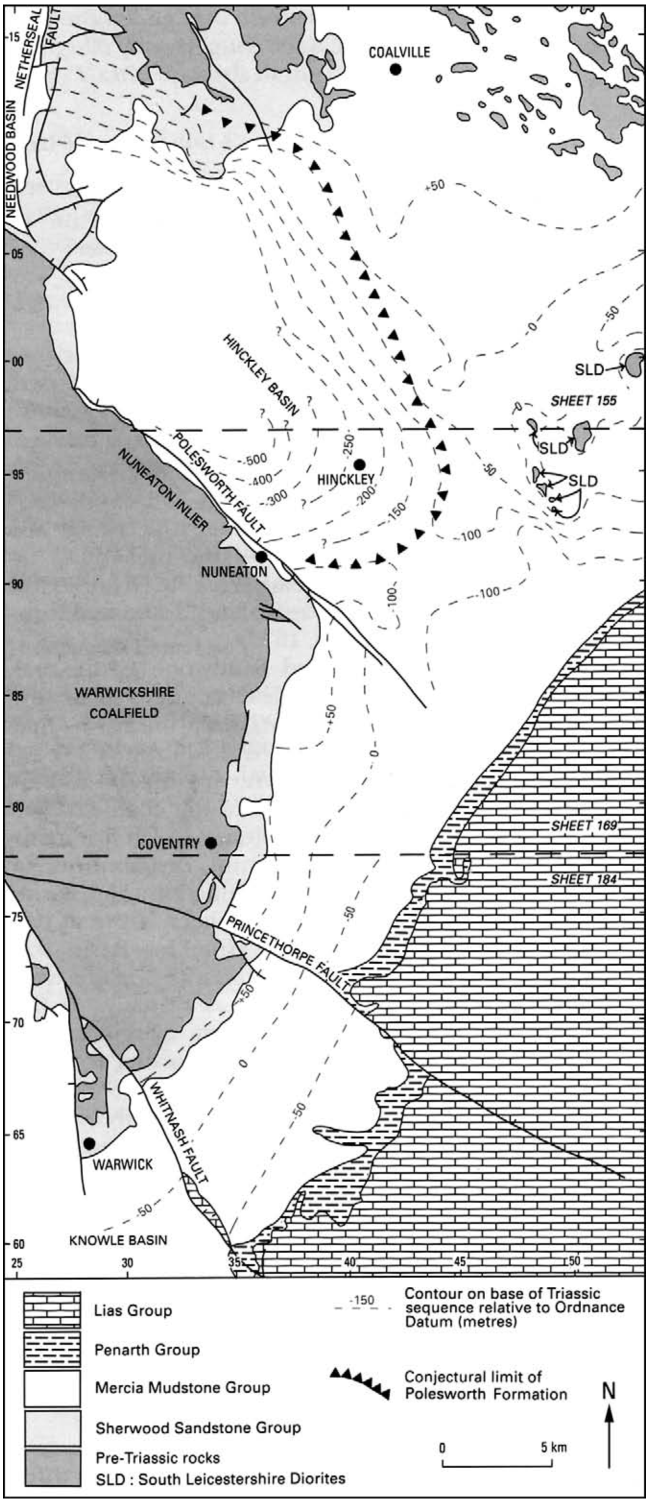

Figure 4. *Sketch map of the geological setting of the Hinckley Basin (from Bridge et al, 1998, with permission).*

Sherwood Sandstone Group

The Hopwas Breccia and overlying Polesworth Formation (Sherwood Sandstone Group) represent the oldest part of the Hinckley Basin fill in northeastern Warwickshire (Figs 2, 3, 4). The Hopwas Breccia is provisionally assigned an Early Triassic (Scythian) age, though it could equally be partly or wholly Late Permian in the absence of diagnostic fossils (Warrington *et al*, 1980; Worssam & Old, 1988). It thickens westwards towards the Polesworth Fault (up to around 12 m) and forms a narrow outcrop northeast of Polesworth. Several metres of red-brown sandy breccia are still exposed in the Stiper's Hill road cutting (SK271027; part of the Stiper's Hill RIGS). The coarse fraction comprises fragments of Cambrian sandstone and rarer Carboniferous limestone, as well as igneous and slatey metasedimentary lithologies (Brown, 1889). The breccia is currently interpreted as scree eroded mainly from the nearby horst margin, reworked by flash floods, and deposited in proximal fan settings on the adjacent basin floor (Warrington *et al*, 1980; Bridge *et al*, 1998).

The overlying Scythian Polesworth Formation comprises up to around 200 metres of poorly cemented sandstones, conglomerates and red-brown mudstones, outcropping close to the Leicestershire border between the Polesworth and Warton faults. A disused pit (now a RIGS) northeast of The Round Berry (SK277038), exposes about 7 m of buff sandstone and conglomerate (Fig. 5). The clast suites are dominated by well-rounded pale quartzites, with sparser vein-quartz and cherts. The conglomerates typify the widespread pebbly braidplain facies of the Sherwood Sandstone Group in southern Britain (Warrington, 1970; Steel & Thompson, 1983; Smith, 1990; Benton *et al*, 2002). Wills (1948, 1956, 1970) attributed the Polesworth Formation to a 'Polesworth River', draining from the 'Mercian Uplands' (London-Ardennes Landmass of Warrington & Ivimey-Cook, 1992) to the southeast of the Warwickshire Coalfield. However, the abundant quartzite clasts match those of the approximately contemporaneous Kidderminster Formation of the Worcester Basin (West Midlands; Fig. 3), suggesting fluvial sediment exchange across the horst (Worssam & Old, 1988; Warrington & Ivimey-Cook, 1992). It is generally agreed that the quartzites were sourced predominantly from the region of the Armorican massif (Brittany-Cornwall) by a large-scale, seasonally charged, axial river system ('Budleighensis River' of Wills, 1956, 1970) draining northwards and northeastwards through the subsiding graben system of the Worcester Basin, and its associated depocentres (Audley-Charles, 1970; Wills, 1970; Holloway *et al*, 1989; Warrington & Ivimey-Cook, 1992).

The considerable thickness of sediment involved indicates rapid subsidence on the hanging wall of the Polesworth Fault during Scythian times. Comparable Early Triassic conglomerates (assigned to the Kidderminster Formation) have been encountered in

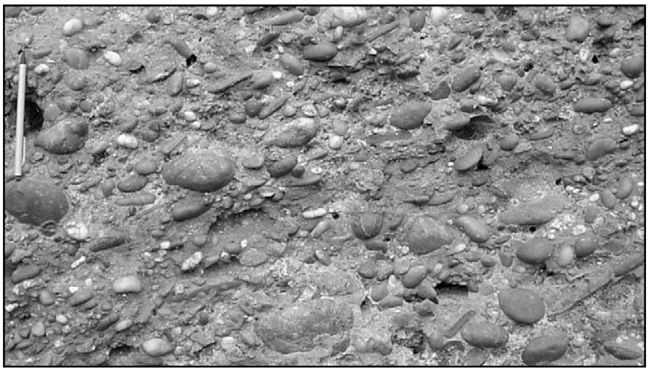

Figure 5. *Polesworth Formation pebble beds exposed in disused quarry northeast of The Round Berry, near Warton (SK277038). Beds are dominated by pebbles of quartzite and vein-quartz, and dip southeast. Pencil is 150 mm long.*

the subsurface of the Knowle Basin (e.g. Blyth Bridge Borehole; SP212898; Powell *et al*, 2000) and may locally persist as far eastwards as the Coventry Horst (Warrington, 1970; Old *et al*, 1991). The present-day distribution of the Polesworth and Kidderminster formations in Warwickshire (Fig. 1) mimics that defined by synsedimentary faulting in Triassic times (Warrington & Ivimey-Cook, 1992).

The Hinckley Basin had filled sufficiently by late Sherwood Sandstone times to allow alluvial deposition on the eastern margin of the Coventry Horst. Thus, the Scythian-?Ladinian Bromsgrove Sandstone Formation overlies and oversteps the Polesworth Formation. It rests unconformably on a palaeoslope of steeply dipping Cambrian sandstones at Midland Quarry RIGS, Hartshill (SP350925), near the eastern margin of the horst in the Nuneaton Inlier. There, a basal breccia comprises locally derived fragments of Cambrian sandstone and Ordovician intrusive igneous rocks and is overlain by up to 6 m of cross-bedded pebbly sandstone. Further south, boreholes and scattered exposures between Nuneaton and Coventry have revealed up to around 30 m of Bromsgrove Sandstone (Eastwood *et al*, 1923; Bridge *et al*, 1998). Fining-upward cycles have been recognised, several metres thick, each ranging from erosively-based, pebbly, feldspathic, calcite-cemented sandstones up into mudstones. Some of the latter enclose small calcareous nodules, possibly of pedogenic origin. Overall grain-size of the cycles decreases upward through the succession (Bridge *et al*, 1998).

On the southern end of the horst (Warwick district), the Bromsgrove Sandstone is up to about 30 m thick and rests unconformably on slightly folded Permian red-beds of the Warwickshire Group. It is similarly characterised by fining-upward cycles of pale, fine to medium-grained, calcite or feldspar-cemented, feldspathic and/or micaceous sandstones (some pebbly), and red-brown mudstones (Shotton, 1929; Wills, 1976; Old *et al*, 1987). Within the sandstones, cross-bedding on a variety of scales indicates flow from the south and west (Old *et al*, 1987; Warrington & Ivimey-Cook, 1992), and soft-sediment deformation is widespread. The Bromsgrove Sandstone thickens rapidly westwards across the Warwick Fault into the Knowle Basin. Thicknesses of nearly 50 m were seen in the Heath End and Shrewley boreholes (SP232609, SP222676); probably more than 70 m at Rowington (SP209688) and 182 m in the Blyth Bridge Borehole near Coleshill (Old *et al*, 1991; Powell *et al*, 2000). Further south, the highest part of the formation yielded a sparse assemblage of spores and organic-walled microplankton in the Knights Lane borehole (SP224550), Stratford-upon-Avon (Warrington, 1974). Boreholes in the Stratford area prove the presence of Upper Carboniferous and/or Permian red-beds (Warwickshire Group) beneath the Bromsgrove Sandstone (Richardson & Fleet, 1926; Williams & Whittaker, 1974; Chadwick & Smith, 1988). There, the basal breccias include probable ventifacts, suggestive of a deflation surface (e.g. Welcombe Fields Borehole, SP212562; Williams & Whittaker, 1974; Wills, 1976). The Bromsgrove Sandstone is the main source of the spa waters at Royal Leamington Spa (Richardson, 1928; Old *et al*, 1987).

West of the county boundary, beyond the Birmingham Fault, the late Scythian Wildmoor Sandstone intervenes between the Kidderminster and Bromsgrove Sandstone formations (Wills, 1976; Powell *et al*, 2000). However, borehole sections east of the Birmingham Fault in western Warwickshire confirm that the Wildmoor Sandstone is largely or wholly absent in the eastern Knowle Basin, beneath a significant non-sequence at the base of the Bromsgrove Sandstone. This might equate to the Hardegsen Disconformity, recognised in NW Europe as due to late Scythian earth movements (Warrington, 1970; Warrington & Ivimey-Cook, 1992).

The Bromsgrove Sandstone marks general maturation of the central English river systems by Anisian-Ladinian times. Widely recorded fining-upward cycles suggest ephemeral fluvial settings, and periodically rapid deposition from waning currents (Holloway, 1985b). Thicker sand bodies are interpreted as channel deposits, floored by conglomeratic lags. Intercalated thinly-bedded sandstones and mudstones are interpreted as overbank alluvium. The overall fining-upward Bromsgrove succession, well documented from the Coventry Horst (see above), suggests a general shift from low-sinuosity braidplain to meanderplain settings through time (Warrington, 1970; Warrington *et al*, 1980; Warrington & Ivimey-Cook, 1992). The record of microplankton near the top of the formation in the Knights Lane Borehole suggests a weak marine influence (Warrington, 1974), possibly equating to a marine transgression into the English Midlands from the North Sea area during the Middle Triassic (Audley-Charles, 1992; Benton *et al*, 2002). A similar record has been obtained from broadly contemporaneous strata (Sugarbrook Member) at Bromsgrove (Worcester Basin), west of Warwickshire.

During the nineteenth century, several quarries in the Bromsgrove Sandstone of the Warwick and Leamington area yielded a vertebrate fauna. Amongst these, Coten End Quarry SSSI (SP290655) was the source of numerous disarticulated remains of fishes, fish-eating amphibians, and terrestrial reptiles including herbivorous *Rhynchosaurus brodiei* Benton (Figure 6) and carnivorous *Bromsgroveia walkeri* Galton (Benton & Spencer, 1995 and references therein). Many or all of the fossils were from the 'Dirt-bed' (Murchison & Strickland, 1840); a poorly cemented unit in the lower part of the exposed succession (Old *et al*, 1987). Guy's Cliffe SSSI (SP293668; a quarried river cliff on the River Avon) yielded a lower jaw of the fish-eating amphibian *Mastodonsaurus* (Benton & Spencer, 1995 and references therein).

Mercia Mudstone Group

The Bromsgrove Sandstone fines up into the Mercia Mudstone Group through a series of thin-bedded sandstones, siltstones and red-brown mudstones, broadly of late Anisian-early Ladinian age, that reach around 12 m thick near Nuneaton (Bridge *et al*, 1998). This transitional unit, formerly known as the Waterstones (Hull, 1869) and Passage Beds (Richardson, 1928) is now correlated with the Tarporley Siltstone Formation of the Cheshire Basin (Ambrose, *pers. comm.*). The transition beds overstep the Hinckley Basin margin onto Precambrian (Charnian) volcanic rocks at Judkins' Quarry RIGS, Hartshill (SP348930). Though poorly exposed, the Mercia Mudstone crops out widely round the coalfield, forming the northeast Warwickshire lowlands, much of the Arden district, and underlying substantial parts of the Avon Valley and the Warwick-Princethorpe area (Shotton, 1960; IGS, 1983). Scattered outcrops occur on the Coventry Horst, as in the Binley and Walsgrave area (BGS, 1994).

Figure 6. *Type specimen of the skull of* Rhynchosaurus brodiei *Benton (Warwickshire Museum specimen G6097) and right dentary (G950); both from the Bromsgrove Sandstone Formation of Coten End Quarry, Warwick (SP290655). Scale is graduated in millimetres.*

The Mercia Mudstone is up to around 400 m thick in the Knowle Basin (Powell *et al*, 2000) and dominated by unfossiliferous, red-brown, largely structureless blocky mudstones and siltstones comprising clay minerals (Jeans, 1978), iron oxides, carbonates and quartz grains (some wind-polished). The mudstones include chemically reduced green spots and beds, thin siltstones, and lenticular, fine-grained, greenish-grey, calcite and/or dolomite-cemented sandstone beds informally termed 'skerries' (Jeans,1978; Old *et al*, 1987, 1991; Bridge *et al*, 1998; Powell *et al*, 2000). Small, radioactive nodules were noted in the Knowle Borehole (SP188778; Harrison *et al*, 1983). Veins and nodules of gypsum have been encountered in numerous boreholes (Richardson, 1928; Williams & Whittaker, 1974; Old *et al*, 1987, 1991; Bridge *et al*, 1998). Thick halite deposits, present in the Worcester Basin, are absent in Warwickshire. The Home Farm Borehole (SP432731), near Stretton-on-Dunsmore, also revealed dolomitic nodules and mud-flake breccias (Old *et al*, 1987). More rarely the mudstones are laminated, slickensided, suncracked, or reveal soft-sediment deformation (Old *et al*, 1987). Fining-upward cycles have been identified, typically comprising fine-grained sandstones passing up through dolomitic mudstones into less dolomitic mudstones (Old *et al*, 1991; Powell *et al*, 2000). Other cycles noted by Old *et al*. (1991) showed alternations of laminated and blocky mudstone similar to those described by Arthurton (1980). A section was formerly well exposed at Jackson's Brick Pit RIGS, Stonebridge (SP205826; Fig. 7). There, the higher part of a roughly 30 m succession of red-brown blocky mudstones featured thin, fine-grained, cross-bedded sandstones (Powell *et al*, 2000).

The Mercia Mudstone facies is extensive throughout both onshore and offshore Britain's Triassic basins, but its depositional environments remain poorly resolved. The upward transition from the Sherwood Sandstone into the Mercia Mudstone reflects breakdown of major river systems. This has been attributed to marine transgression (Warrington, 1970), geomorphic decay of source massifs (Warrington & Ivimey-Cook, 1992), as well as to increasing aridity, with or without rifting-induced fragmentation of drainage patterns (Ruffell & Shelton, 1999, 2002). The widespread oxidation of the mudstones confirms their deposition under an arid climatic regime (Benton *et al*, 2002). Some workers (e.g. Tucker, 1977; Milroy & Wright, 2000) have invoked an essentially lacustrine environment involving periodic emergence. Others have envisaged a mainly emergent setting, characterised by accretion of wind-blown dust on a damp surface with a high water table, as well as in shallow lakes (Arthurton, 1980; Barclay *et al*, 1997; Jefferson *et al*, 2002). Geochemical and sparse palaeontological evidence confirms a marine influence on deposition (Arthurton, 1980; Leslie *et al*, 1993; Ruffell & Shelton, 1999), implying periodic seawater incursions.

The models of Arthurton (1980) and Jefferson *et al* (2002) seem broadly applicable to the Warwickshire Mercia Mudstone, involving aeolian deposition of the massive mudstones on emergent flats, and of the laminated units in shallow water-bodies. Gypsum formed contemporaneously, close to the sediment surface, deposited from interstitial brines linked to the high, saline water table, or possibly in hypersaline lakes (Warrington & Ivimey-Cook, 1992). Thin siltstones and sandstones ('skerries') formed by rapid runoff from flash floods, giving rise to ephemeral braided streams (Powell *et al*, 2000). Arthurton (1980) compared the inferred Mercia Mudstone palaeoenvironments to those of the Rann of Kutch, arid coastal flats on the Indian-Pakistan border, periodically inundated by seawater as well as continental runoff (also see Glennie & Evans, 1976)

In the upper part of the Mercia Mudstone, the Arden Sandstone Formation typically comprises interbedded, grey-green, laminated, cross-bedded, bioturbated and massive sandstones, siltstones and red to grey-green mudstones. Palaeocurrent measurements from cross-bedding indicates easterly flow (Old *et al*, 1991). The formation outcrops extensively in southwestern Warwickshire (Knowle Basin), where it reaches a maximum thickness of around 11 m (Old *et al*, 1991). It is also well known from the Warwick-Princethorpe area (BGS, 1984). Exposures in the Shrewley and Rowington areas, west of Warwick, have yielded an important suite of body- and trace fossils. Good sections still occur within canal cuttings at both localities (Shrewley SSSI; SP212674; Rowington RIGS; SP200692), figured by Old *et al*. (1991). The biota discovered at Shrewley includes land plants (conifers), badly preserved bivalve shells of marine aspect, conchostracans ('clam-shrimps'), remains of sharks, bony fishes and amphibians (Old *et al*, 1991; Benton *et al*, 2002 and references therein). Reptile trackways were also encountered (Sarjeant, 1974; Tresise & Sarjeant, 1997; Fig. 8). Simple burrows occur within fine-grained sandstones at the nearby Rowington cutting. Palynomorph assemblages from the Arden Sandstone at Rowington confirm a late Carnian age (Old *et al*, 1991).

The Arden Sandstone signifies important environmental change. The presence of a terrestrial-aquatic biota with probably marine or quasi-marine elements (notably the molluscs and hybodont sharks) suggests a marginal marine environment at times, and possibly an attendant increase in humidity and/or rainfall (Benton *et al*, 2002). Sandstones and mudstones are interpreted as distributary channel and interdistributary bay deposits respectively, in an estuarine or deltaic setting (Old *et al*, 1991; Barclay *et al*, 1997). Reptile trackways attest to local subaerial exposure. The increased drainage has been tentatively attributed to Carnian isostatic lowering of parts of southern Britain, following cessation of rifting (Warrington & Ivimey-Cook, 1992). The marine influence recorded by the Arden Sandstone and its correlatives (Warrington & Ivimey-Cook, 1992) could therefore reflect enhanced connection with Tethyan sources. By early Norian times, much or all of Warwickshire had reverted to the continental environment with flash-floods, playa lakes and possible periodic marine incursions, in which the upper Mercia Mudstone accumulated (Warrington & Ivimey-Cook, 1992; Ruffell & Shelton, 1999).

The Blue Anchor Formation (Warrington *et al*, 1980; Fig. 2) at the top of the Mercia Mudstone Group comprises grey-green mudstones and siltstones, reaching around 7 m thick at Marlcliff RIGS (SP092505), a slumped and overgrown river cliff on the River Avon southwest of Stratford (Richardson, 1912). Scattered dinocysts (as in the Knowle Borehole) indicate an increasing marine influence prior to the mid-late Rhaetian (Penarth Group) transgression (Warrington & Ivimey Cook, 1992).

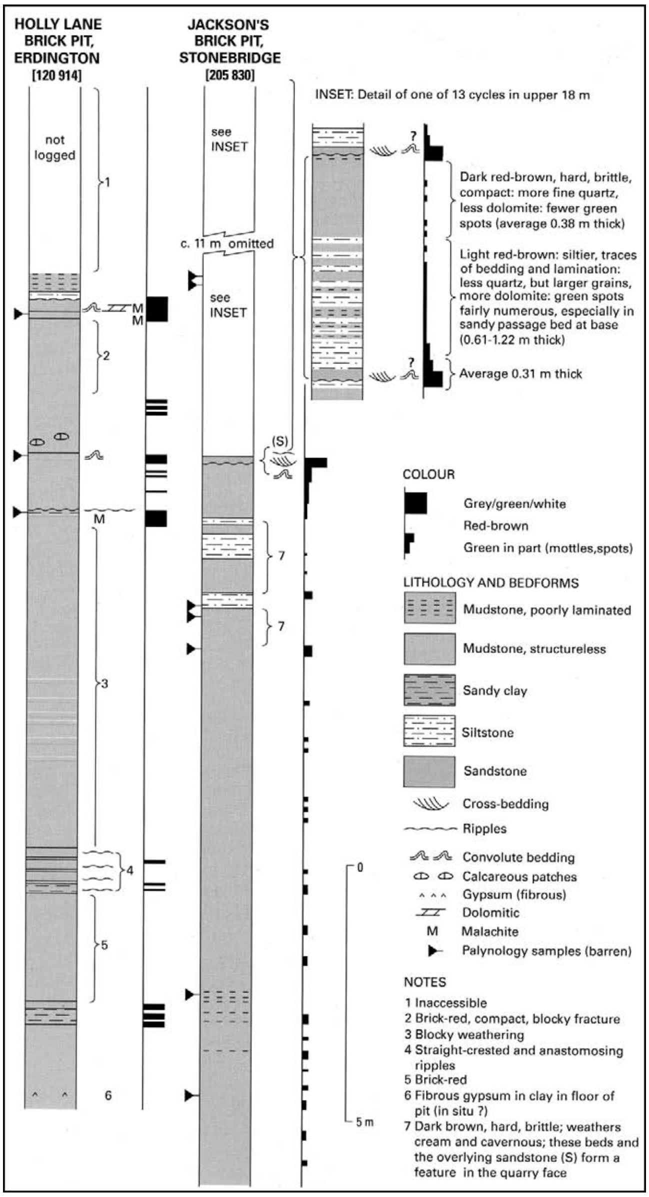

Figure 7. *Graphic log of part of the Mercia Mudstone Group at Jackson's Brick Pit, Stonebridge (SP205830) (from Powell et al, 2000, with permission).*

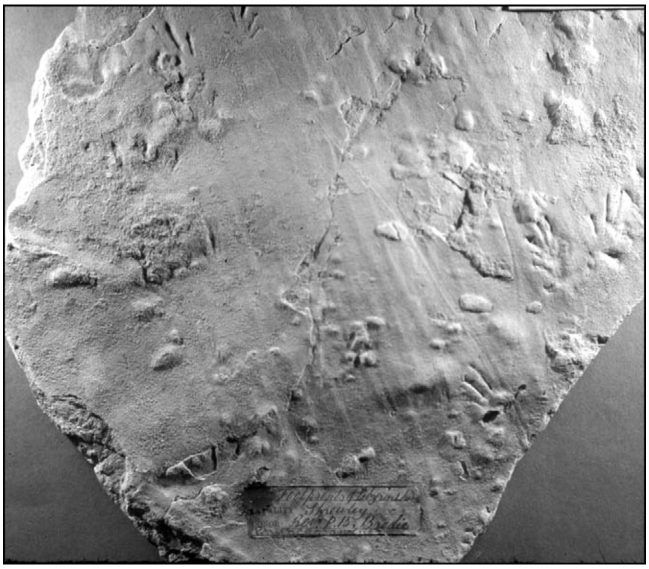

Figure 8. *Reptile tracks* (Rhynchosauroides) *preserved in thin-bedded fine-grained sandstone (Warwickshire Museum specimen G9437). Arden Sandstone Formation, Shrewley. Image is 240 mm across.*

Penarth Group

The Penarth Group (Fig. 2) marks an abrupt change in sedimentary style, replacing the continental Mercia Mudstone with fossiliferous mudstones, siltstones and limestones of quasi-marine to fully marine origin. Overlying the eroded top of the Blue Anchor Formation, the widespread but poorly exposed Westbury Formation comprises up to 8.5 m of dark-coloured, pyritic, laminated mudstone enclosing siltstone and sandstone lenticles. A synsedimentary slump structure, possibly attributable to seismic shock (Simms, 2003; Hallam & Wignall, 2004), was noted at the top of the formation in the Home Farm Borehole (Old *et al*, 1987). The mudstones yield a macrofauna dominated by epibenthic and shallow-burrowing marine bivalves, and fish debris (Richardson, 1912; Williams & Whittaker, 1974; Old *et al*, 1987). Palynological samples from Westbury mudstones in the Stockton Locks Borehole (SP430649) revealed abundant miospores, organic-walled microplankton and foraminiferal test linings (Old *et al*, 1987).

Black fissile mudstones of the Westbury Formation were formerly exposed above the Blue Anchor Formation at Marlcliff (Richardson, 1912; and above). Further northeast, the Westbury Formation is absent at Round Hill road cutting RIGS (SP143618) near Wootton Wawen, where the overlying Cotham Member (see below) rests directly on the Blue Anchor Formation. This is probably due to the proximity of the Malvernoid Vale of Moreton Axis that evidently functioned as a structural 'hinge' on the eastern margin of the Worcester Basin in the Late Triassic to Early Jurassic (Old *et al*, 1991). Following general marine transgression through northwest Europe (Warrington & Ivimey-Cook, 1992), the Westbury Formation confirms establishment of shallow marine environments over much of central England. The laminated, organic-rich nature of the sediments suggests that bottom waters were generally poorly oxygenated (Swift, 1999 and references therein), but periodically colonised by a bivalve-dominated fauna.

The Westbury Formation is overlain by the Cotham Member; the lowest unit of the Lilstock Formation (Fig. 2). The Cotham Member reaches 12 m thick at Rugby (Old *et al*, 1987). The dominant lithologies are buff- to grey-green calcareous mudstones enclosing lenticular siltstones, yielding sparse macrofaunas that include conchostracans, and bivalves of marine aspect. These, and the presence of dinocysts and foraminifera (e.g. Knowle and Stockton Locks boreholes; Old *et al*, 1987, 1991), suggest marine-influenced, lacustrine or lagoonal environments (Warrington & Ivimey-Cook, 1992). Calcareous mudstones at the top of the member are exposed at the Ufton Landfill Site RIGS (SP393617) and at Southam Cement Works RIGS, Long Itchington (SP420630), east of Leamington.

In the Avon Valley of southwest Warwickshire, the highest subdivision of the Lilstock Formation, the Langport Member (see below), is absent. There, the Cotham Member is normally overlain by the alternating grey-coloured, argillaceous limestones (some nodular and/or shelly) and calcareous mudstones of the Late Triassic and Early Jurassic Wilmcote Limestone Member (Blue Lias Formation). These strata reach about 8 m thick at Temple Grafton (Ambrose, 2001) and are still exposed at the Wilmcote Quarry SSSI (SP151594) and Temple Grafton quarry RIGS (SP121539). There, they formerly yielded many marine fossils including ammonites, crustaceans, fishes and reptile remains (Brodie, 1868; Simms *et al*, 2004). The basal Jurassic ammonite *Psiloceras planorbis* has been collected from the lower part of the member (Old *et al*, 1991).

The Wilmcote Limestone disappears to the southeast across the Vale of Moreton Axis, towards the London Platform (Ambrose, 2001). East of the Stour Valley, the Cotham Member is overlain by the Langport Member, the highest division of the Penarth Group (Swift, 1995). This is developed as grey to cream coloured, dominantly micritic and frequently bioturbated limestones with thin mudstone seams, reaching over 4 m thick at Rugby (Richardson, 1928; Old *et al*, 1987). Low-diversity macrofaunas, including solitary corals, echinoid debris, bivalves and gastropods, augment the lithological evidence for a shallow-water, restricted marine environment (Warrington & Ivimey-Cook, 1992; Swift, 1995). The member is exposed at the Southam Cement Works Quarry RIGS. Conglomeratic limestone (Fig. 9) in its upper part indicates early cementation of carbonate substrate and its subsequent disruption by storm activity (Hallam & Wignall, 2004), or possibly seismic shock (Swift, 1995; Radley & Swift, 2002).

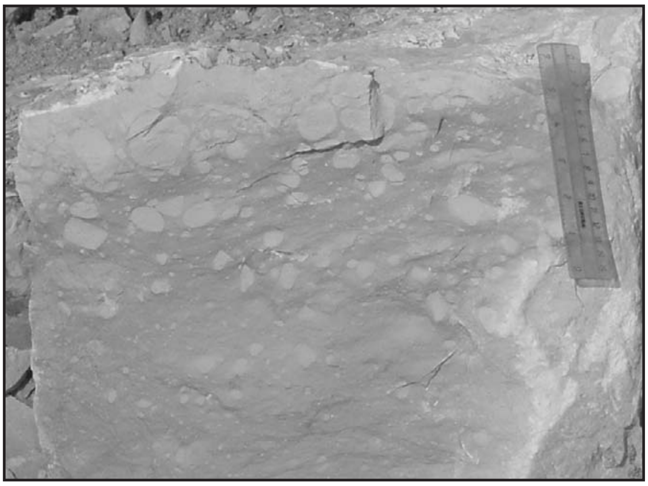

Figure 9. *Conglomeratic limestone from the upper part of Langport Member, in the Southam Cement Works Quarry. (SP419629) Ruler is 150 mm long.*

Conclusions

Much of the Triassic outcrop corresponds to three depositional settings generated through Permian to Early Triassic extensional reactivation of major basement faults. These are the Hinckley and Knowle Basins separated by the Coventry Horst. Triassic sediments are thinner on the horst, which preserves a depositional margin of the Knowle Basin in the Nuneaton inlier. The Triassic System in Warwickshire exemplifies the principal overall fining-upward facies development documented throughout southern Britain. The pebbly and arenaceous Sherwood Sandstone Group, deposited mainly in semi-arid fluvial settings, is overlain by the predominantly argillaceous Mercia Mudstone Group, comprising red-beds with subordinate sandstones. The Mercia Mudstone provides evidence for hot, arid, subaerial and subaqueous deposition with both freshwater and marine influences. Sparse macrobiotas from both groups provide evidence for terrestrial and subaeqeous habitats. The overlying Penarth Group confirms a Late Triassic marine transgression, heralding establishment of open shelf environments in the Early Jurassic.

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