Carboniferous: oblique-slip basins, intraplate magmatism and the Variscan Orogeny

Abbreviated title: Carboniferous

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Introduction

The fundamental global changes seen during Carboniferous times are reflected in this account of the geological record of this Period in Scotland. Following the end-Devonian mass extinction events, some vertebrate animals adapted to live on land for the first time early in the Carboniferous, and major radiations among fish communities and land plants occurred. The last led to the rise, and demise, of the lycopod-dominated forests that formed the basis of the planet's vast coal resources. Later Carboniferous times saw the final assembly of the supercontinent of Pangaea, reconfiguration of the climate zones, and the growth of major ice-caps in the southern hemisphere that significantly affected sea-level movements in equatorial regions.

At the onset of the Period, Scotland was situated in low latitudes on the southern margin of Laurussia (Domeier and Torsvik 2014). During the ensuing 60 million years, the Laurussian plate migrated northwards through equatorial latitudes, with clockwise rotation (Edel *et al.* 2018). Scotland was located in the foreland of a collisional zone of compressional deformation that developed within the Variscan Orogenic belt in the south of the UK and in Europe (Fig 10.1a). Oblique dextral collision between Laurussia and Gondwana began in latest Devonian times and resulted in the fragmentation of parts of the Laurussian continental margin during the early Carboniferous. In Scotland and neighbouring northern England and Ireland, a complex set of basins formed in which up to 5 km of Carboniferous sedimentary and volcanic rocks accumulated. As the continental fragments moved relative to each other, these basins evolved through phases of extensional, oblique-slip and transpressional tectonics. Assembly of Pangaea was completed in late Carboniferous times, orogenic events peaked (Fig 10.1b) and a widespread Variscan (sub-Permian) orogenic unconformity subsequently developed. Latest Carboniferous and early Permian events record the start of post-orogenic extension and magmatism.

For much of the Carboniferous, rivers, deltas, lakes and shallow seas deposited clastic sediments in the Midland Valley of Scotland (MVS), the borderlands of southern Scotland, and parts of the Forth Approaches and Outer Moray Firth (Figs 10.2, 10.3). The rocks commonly comprise cyclical sequences of mudstone, siltstone, sandstone, coal and/or limestone. Volcanism was renewed in the latest Devonian, following almost 50 million years of magmatic quiescence across most of Scotland since the cessation of Caledonian igneous activity in the Early Devonian, and coeval with the onset of extension in the Northumberland–Solway Basin. The magmatism was intraplate in character and continued intermittently across Scotland for approximately 100 million years into the mid-Permian (Fig. 10.4; Upton *et al.* 2004; see also Chapter 11). It represents the earliest episode of this type in the British Isles. Large-scale mid-Visean volcanism was of transitional to mildly alkaline basalt, accompanied by lesser amounts of more-differentiated compositions (Macdonald 1976; Upton *et al*. 2004), erupted as lavas and pyroclastic deposits. By contrast, the late Visean to Permian magmatism was of silica-poor, alkalic basic magmas that were markedly more primitive than their predecessors. These magmas increasingly formed intrusions as the thicknesses of clastic sediments in the MVS basins increased. Alkaline magmatism was interrupted briefly in the Stephanian by the large volume tholeiitic Midland Valley sills and dykes.

Basin formation began in the Late Devonian–early Carboniferous, related to the north-easterly expulsion of the former Baltica segment of Laurussia (Coward 1993; Fig. 10.1a). By late Carboniferous times, the Baltica fragment moved back southwestwards within a dextral transpressional zone across Scotland, synchronous with Variscan inversion events to the south (Fig. 10.1b). Systematic sets of intrabasinal Carboniferous fault and fold orientations and styles developed in response to these changing stress fields, in part influenced by the orientation of inherited Caledonoid structures, together resulting in different structural basin interpretations on either side of the Southern Uplands which seems to have partitioned strain significantly. The Highland Boundary Fault was a significant Carboniferous Fault at the northern margin of the MVS (McKay *et al*. 2020), notwithstanding its role in earlier events (see for example Chapter 6, this volume). The Great Glen Fault, also an important and long-lived, regional-scale structure, is a persistent and significant influence throughout the development of the Carboniferous geology of Scotland (Fig. 10.2; Speight and Mitchell 1979; Coward 1993; Underhill and Brodie 1993; Kemp *et al.* 2019).

Carboniferous strata record the interplay, through time, of varying tectonic, magmatic, sea-level, sediment-supply and climatic controls. With the benefit of extensive prior research, a robust stratigraphical and chronological framework and palaeogeographical basin evolution history is presented here, constrained by seismic, mining, borehole and outcrop data. That framework is described in this chapter in eight distinct time slices (TS1–8; Fig. 10.5).

Following on from Late Devonian sinistral strike-slip, extension and fluvial deposition, the Tournaisian Stage is characterized by monsoonal coastal marshlands (TS1; Fig. 10.6a). During this time, vertebrates in Scotland completed their transition to land (Clack 2012). Discovery of these globally significant fossils in Scotland has led to a step-change in our understanding of the evolution of life on Earth. The first significant change in the MVS occurred during early Visean times (TS2), with extensive subaerial volcanism, and the development of major unconformities. In contrast, clastic sedimentation occurred offshore and in southern Scotland. Active tectonism is indicated, but a synthesis is elusive due to the overprinting of younger events. Volcanism became more localized into the late Visean (TS3); however, the remnant and active volcanic topography exerted a major control on sedimentary environments including, for example, localized lake development with deposition of oil-shales. The variety of depositional environments in TS3 is notable; farther east, and in southern Scotland and the North Sea, fluvio-deltaic and shallow marine deposition dominated (Fig. 10.6b).

From the latest Visean and into the early Namurian (TS4), glacio-eustatically controlled sea-level variations resulted in widespread cyclical fluvio-deltaic sequences with coal mires and repeated marine incursions. Relatively uniform deposition traced by correlative limestones and marine bands across basins was nevertheless influenced by active faulting and folding indicative of oblique-slip tectonics. As global sea level reached a significant lowstand in the mid to late Namurian (TS5; Mississippian–Pennsylvanian boundary), fluvial influx interacting with tectonic-driven drainage reorganization occurred with localized incision and the formation of unconformity surfaces (Figs. 10.5, 10.6c). Cyclical fluvio-deltaic sedimentation with extensive coal mires became established in the Westphalian (TS6), with basin structures now indicating increasingly dextral transpression overall. These transpressional events culminated in the latest Westphalian representing peak Variscan orogenic response. Apart from in isolated locations, an unconformity developed as regional-scale basin inversion occurred. Into the Stephanian (TS7), transpression continued to the south of the Southern Uplands. However, in the MVS swarms of tholeiitic sills and dykes accompanied conspicuous easterly trending faults cutting across the older Westphalian transpressional structures, representing the first stages of post-orogenic extension. Finally, into the latest Carboniferous and earliest Permian (TS8), alkaline magmatism and NW- to NE-trending extensional faulting in the MVS and offshore mark the transition to post-orogenic extension. The locus of tholeiitic magmatism and dextral transtension moved to the south of the Southern Uplands.

Scottish Carboniferous stratigraphy has developed over more than one hundred years. Browne *et al.* (1999) provided the basis for a consistent modern terminology; the detailed account of Waters *et al.* (2011) includes southern Scotland and the offshore regions. The nomenclature adopted here (Figs 10.7, 10.8) is updated to incorporate: the re-assignment of the Kinnesswood Formation into the Devonian (Marshall *et al.* 2019); dating of igneous rocks and improved constraints from deep exploration well data (Monaghan and Pringle 2004; Monaghan and Parrish 2006; Monaghan and Browne 2010; Monaghan *et al.* 2014, Monaghan 2014; ^{40}Ar–^{39}Ar dates from 2004, 2010 publications have been recalculated to the same decay constants as in the 2014 work, *see supplementary info*); palynomorph constraints on successions in Fife (Owens *et al.* 2005); biostratigraphical assignment of the Lower Limestone Formation (Cózar and Somerville 2021); and correlations onshore–offshore (Kearsey *et al.* 2019a) that are more readily compatible than the formal offshore nomenclature of Cameron (1993a,b). This account draws heavily on Read *et al.* (2002), integrates BGS mapping and subsurface studies using seismic and deep exploration well data, and incorporates extensive borehole and mining data (onshore: Monaghan 2013, 2014; Monaghan *et al.* 2012. Offshore: Arsenikos *et al.* 2018). For brevity, these publications are not repeatedly cited below. Extensive descriptions of the igneous rocks are by Stephenson *et al*. (2003), and of the coal-bearing Clackmannan Group and Coal Measures groups in BGS regional guides, memoirs, coalfield memoirs and maps. Local nomenclature for coals is given in McLean (2018).

Before examining the characteristics and differentiating features of each of the time slices, this chapter summarizes the extraordinarily diverse and globally significant fossil discoveries that continue to be found in the Scottish Carboniferous.

Internationally significant fossils

Many Mississippian fossil sites in Scotland are internationally important for our understanding of the evolution of specific palaeobiological groups (Fig. 10.9). One of the most critical discoveries of recent years has been the rich and diverse Tournaisian tetrapod fauna from East Lothian and the Scottish Borders, providing insights into their terrestrialization and evolution following the end Devonian mass extinction events (Clack 2017; Clack *et al.* 2016). Limbs first evolved in Late Devonian times, marking the transition from lobe-finned fish to tetrapod. These early tetrapods were mostly aquatic, having for example fish-like tails and paddle-like to multi-digitated limbs (e.g. Ahlberg 2018; Clack 2006, 2012). They became extinct at the end of the Devonian and their place was taken by the ecologically diverse forms that are seen from the Tournaisian onwards (see also topic box).

Tetrapod adaptation to life on land occurred alongside other significant changes. Some fish groups that dominated the Devonian fauna became extinct and their niches in continental brackish to freshwater environments were occupied in the early Carboniferous by lungfish and gyracanthid fish (Friedman and Sallan 2012). Changes occurred in the body size and shape of ray-finned (actinopterygian) fishes, and sharks (chondrichthyans) underwent a major evolutionary radiation (Sallan and Galimberti 2015). Ray-finned fishes are the commonest vertebrate fossils at the Tournaisian site of Foulden, near Berwick-upon-Tweed (Wood and Rolfe 1985) and include species that are critical for studies of the early evolution of all living bony fishes (Gardiner 1985).

The Asbian site at Glencartholm in the Northumberland–Solway Basin is one of the most important Carboniferous fossil fish sites in the world yielding a large number of complete actinopterygian species and sharks (Wood 2018). The cartilaginous skeleton of sharks is rarely preserved in the geological record, so those from Bearsden, north of Glasgow represent the best known from the Paleozoic (Wood 1982). Lungfish (dipnoans) have been shown to be considerably more diverse than previously known with important finds from the Tournaisian at Burnmouth (Challands *et al.* 2019), East Lothian, the Scottish Borders and Heads of Ayr (Smithson *et al.* 2016), and from the late Mississippian at Loanhead, Edinburgh (Smithson *et al.* 2019).

Though conodont elements have proved an important tool in the correlation of marine Carboniferous strata, the identity of the animal from which they were derived had long proved elusive. From the 1980s, near complete eel-like animals with remarkably well preserved soft-tissues and containing conodont elements were identified from the Granton Shrimp Bed (Gullane Formation), Edinburgh (Briggs *et al.* 1983; Aldridge *et al.* 1993). These discoveries, among very few others of any age worldwide, are pre-eminent in understanding the physiology of this curious animal and its phylogenetic position within the chordates (Aldridge and Purnell 1996).

Some of the world's most important Paleozoic fossil plant sites occur in the Scottish Mississippian (Cleal and Thomas 1996) where both petrifactions and compression floras have contributed significantly to understanding the rapid evolution of plant groups at this time (e.g. Scott *et al.* 1984; Scott and Galtier 1996). Petrifactions of many Tournaisian taxa in the Tweed Basin were described by A G Long in a series of papers in the 1960s and 1970s (see Scott *et al.* 1984). Later material comes from Oxroad Bay in East Lothian, and Loch Humphrey Burn and Glenarbuck in the Kilpatrick Hills, north of Glasgow (Bateman and Scott 1990; Bateman *et al.* 2016). The important mid-Visean sites are at Pettycur and nearby Kingswood in Fife (Rex and Scott 1987). East Kirkton Quarry revealed an important Brigantian flora (Galtier and Scott 1993). By contrast, the preservation in situ of the stumps of arborescent lycopods in the Limestone Coal Formation in Victoria Park, Glasgow is important for public understanding of the ancient forests which led to the formation of the coal resources of the UK, upon which our industrial heritage is based (Gastaldo 1986).

Topic box - Closing Romer's Gap: tetrapod adaptation to life on land

In early Carboniferous times, limbed vertebrates – tetrapods – emerged from their aquatic habitats adapting to, and colonizing, the terrestrial realm. This key event in the evolution of life on Earth followed the late Devonian mass extinction events (Kaiser et al. 2016; Marshall et al. 2020). Tetrapod fossils from the period immediately following the extinctions are extremely rare, but the Ballagan Formation in Scotland is one of only two places worldwide from where Tournaisian tetrapods are currently known (Smithson et al. 2012): the second is Blue Beach in Nova Scotia, Canada (Mansky and Lucas 2013; Anderson et al. 2015). Furthermore, nine of the dozen sites worldwide that have yielded Visean tetrapods are also in Scotland (Smithson 1985a; Smithson et al. 2017). Consequently, the Mississippian rock record in Scotland has been paramount in the search for understanding the emergence and diversification of tetrapod life on land. The Tournaisian to mid-Visean interval of about 25 million years had remained almost unrepresented for fossil tetrapods and became known as 'Romer's Gap' in honour of the distinguished American palaeontologist, A. S. Romer, who first recognized it (Coates and Clack 1995).

In 1971 a single specimen of an animal that was named later as Pederpes finneyae (Fig. topic box a, b; Clack 2002; Clack and Finney 2005) was found in a dolomite-cemented siltstone from the Ballagan Formation in Auchenreoch Glen, near Dumbarton, western Scotland. Initially thought to be a rhizodont fish, preparation of the specimen revealed it to be an almost complete, articulated tetrapod skeleton. Since then, many other new taxa from sites in SE Scotland have been described from horizons throughout the formation, confirming that collection failure was the reason for Romer's Gap (Clack et al. 2016, 2019a; Otoo et al. 2019). Among the abundant undiagnosed specimens is the earliest known limb with five digits (Smithson et al. 2012). Many of the animals are small with skulls less than 80 mm long. Some larger sized beasts are also known, even from quite early in the Tournaisian of Scotland and their existence had been inferred from trackways in Nova Scotia. Tetrapod diversification during the Tournaisian was thus well established, and included close relatives of Devonian species living alongside new forms. Representatives of the precursors of both the major groups of tetrapods – amphibians (frogs, salamanders) and amniotes (reptiles, birds, mammals) – are present among the Visean collections at East Kirkton and possibly among the Tournaisian taxa showing that this important evolutionary divergence had already occurred by Visean times and perhaps earlier (Clack 1998; Clack et al. 2016).

The anatomy of some of the Tournaisian tetrapods shows that they were fully capable of walking on land (Smithson and Clack 2018). Supporting a terrestrial lifestyle, the beasts occur alongside millipedes (Ross et al. 2018) and preserved in beds of sandy siltstone that overlie palaeosols. The last indicate vegetated land surfaces that were then inundated by debris flows emplaced during monsoonal storms (Bennett et al. 2016). Disarticulated bones are also found in conglomerate at the base of fluvial channels. The sedimentary environments show that the animals inhabited a coastal wetland with a mosaic of juxtaposed habitats including ponds, lakes, marshes and rivers, interspersed with drier vegetated areas including forest (Kearsey et al. 2016). Tetrapod evolution and diversification can be placed in the context of increasing vegetation cover through the later Paleozoic and development of diverse and complex rooting systems that promoted the wider formation of clays in soils through chemical weathering, profoundly impacting on river morphology and alluvial environments (Gibling and Davies 2012; Corenblit et al. 2015). Wetland ecosystems with closely juxtaposed habitats that include fluvial, lacustrine, swamp, marsh and forest are renowned for their abundant and diverse flora and fauna and may have provided the right combination of evolutionary pressures and niche variations that enabled tetrapods to make the transition to a terrestrial life (e.g. Greb et al. 2006).

TS1 Tournaisian and Chadian: monsoonal coastal marshlands

The opening 13 million years of Carboniferous times saw a striking change in sedimentary environment in the Midland Valley of Scotland (MVS), from the semi-arid, fluvial red-beds and calcrete palaeosols of the Upper Devonian Kinnesswood Formation, to the seasonal wetland represented by the grey mudstone – dolostone succession of the Ballagan Formation and its offshore correlative the Cementstone Formation (Kearsey *et al.* 2019a). Meanwhile in the Northumberland–Solway basin a narrow coastal floodplain (Sherwin 2018) with marginal alluvial fans within the Ballagan Formation flanked the Southern Uplands and passed southwards into the marginal marine, clastic, carbonate and evaporitic regime represented by the Lyne Formation (Fig. 10.7; Border Group; Leeder 1974; Ward 1997). This change was likely brought about by the opening of transtensional basins through the region, combined with global climate change (Coward 1993; Falcon-Lang 1999a; Marshall *et al.* 2020).

Crustal extension to form the ENE-trending asymmetrical graben of the Northumberland–Solway Basin had begun in Late Devonian times with eruption of the Birrenswark and Kelso basalts. Sedimentation in the basin continued through the Tournaisian and seismic data indicate that up to 3400 m of strata accumulated in the depocentre in the hanging wall of the Maryport–Stublick–Ninety Fathom Fault System on the south side of the basin (Chadwick *et al.* 1995; Figs 10.3, 10.10a, 10.11).

Tectonic control and the relative importance of oblique-slip on Tournaisian sedimentation in the MVS is less well understood because of fewer data and the impact of mid-Visean unconformities (Millward *et al.* 2019, fig. 1; TS2). However, it is probable that displacement on major ENE- and NE-trending faults such as the West and East Ochil, Dura Den and Southern Upland faults (Fig. 10.3b) provided accommodation space for 150 to 350 m of strata across the MVS. To the west of the NNE-trending Largs Fault, the Ballagan Formation thickness ranges from a few tens of metres on the Isle of Bute and the Cumbrae islands, to 80 m in north Arran (Young and Caldwell 2012). In East Lothian more than 400 m are preserved in the hanging wall of the Dunbar – Gifford Fault and up to 520 m in the Tweed Basin, bound to the south by the Pressen – Flodden Fault (Bennett *et al.* 2021). For the *c.* 13 million years of the Tournaisian, a delicate balance between subsidence, compaction and sedimentation rate meant that the floodplain was maintained to within a few metres of sea-level during aggradation of the Ballagan Formation (Fig. 10.8; Millward *et al.* 2019;).

The wetland was connected in the west through Northern Ireland (Fig. 10.11) to a fully marine environment in the south of Ireland (Clayton and Higgs 1979; Clayton *et al.* 1986). A broken chain of uplands that included the present-day Southern Uplands, the Longford – Down massif in Ireland, the Cheviot massif and the Dogger High (Arsenikos *et al.* 2018; Fig. 10.1) separated the MVS from the Northumberland–Solway Basin and its extension offshore. Gaps in the upland chain provided further connection to the shallow-marine seaway (Fig. 10.6a). Later, the Chadian saw a return to a more arid climate with deposition of the dominantly fluvial Clyde Sandstone Formation in the north and west of the MVS (Fig. 10.4).

A late Tournaisian, CM Biozone age had been determined previously for the Ballagan Formation in the MVS (Stephenson *et al.* 2002, 2004a, b). However, Marshall *et al.* (2019) showed that miospore biozones at Burnmouth in the Tweed Basin span the entire Tournaisian, with the succession overlain disconformably by the Fell Sandstone (Fig. 10.7). In East Lothian, the formation extends into the early Visean Pu Biozone (Neves *et al.* 1973; Neves and Ioannides 1974).

Tournaisian coastal wetlands in the Midland Valley and Tweed basins

Grey siltstone and thin beds of micritic ferroan dolostone, historically classified as cementstone, epitomize the Ballagan Formation (Fig. 10.12). Additionally, and in varying proportions, are fluvial and overbank sandstone, flood-deposited sandy siltstone, palaeosols and evaporite-rock (Fig. 10.13a). The spatial and temporal distribution of these facies implies a highly complex and dynamic mosaic of sedimentary environments consisting of saline-hypersaline lakes, fluvial systems and overbank deposits (Fig. 10.11; Anderton 1985; Andrews *et al.* 1991; Bennett *et al.* 2016, 2021; Kearsey *et al.* 2016; Millward *et al.* 2019).

A generally sparse and low-diversity invertebrate fauna of bivalves (particularly *Modiolus latus*), ostracods, shrimps and other arthropods dominates these rocks (Brand 2018; Cater *et al.* 1989; Ross *et al.* 2018), along with rarer *Spirorbis*, and *Serpula* (Bennett *et al.* 2017). By contrast, the vertebrate fauna is diverse with actinopterygians, dipnoans, chondrichthyans, acanthodians and tetrapods (Fig. 10.14; Andrews 1985; Challands *et al.* 2019; Gardiner 1985; Clack 2002; Clack and Finney 2005; Smithson *et al.* 2012; Carpenter *et al.* 2015; Clack *et al.* 2016, 2019a; Otoo *et al.* 2019; Smithson and Clack 2018). Notably, the dentitions of sharks and lungfish were adapted to crush food with a hard shell, such as bivalves, shrimps and ostracods (Richards *et al.* 2017; Smithson *et al.* 2016). A well-preserved arthropod fauna includes myriapods (millipedes and related taxa; Ross *et al.* 2018), malacostracan crustaceans (Briggs and Clarkson 1985; Schram 1979) and rare horseshoe crabs (Bicknell and Pates 2019; Waterston 1985). The earliest Carboniferous spore populations reveal a low diversity community of small plants (Higgs *et al.* 1988), but this was replaced later in the Tournaisian by a varied flora, reported mainly from East Lothian and the Tweed Basin (Scott and Meyer-Berthaud 1985; Scott and Galtier 1988).

Saline – hypersaline lakes

The abundance of dolostone beds within the succession varies across the region, with the greatest in the Tweed Basin (Millward *et al.* 2019). The average bed thickness is 9 to 37 cm. Bennett *et al.* (2021) identified five facies in the Tweed Basin: cemented siltstone and sandstone; homogeneous dolomicrite; intercalated beds or laminae of dolostone and siltstone; mixed calcite and dolomite; and dolomite with gypsum or anhydrite. The first three of these form most beds. Some dolostones preserve the anatomy of some plant parts (Scott *et al.* 1984; Scott and Mayer-Berthaud 1985; Scott and Galtier 1988), testifying to the early lithification of these rocks. Bulbous tops or bases to some dolostones at Burnmouth preserve casts of lycopsid trunks (Bennett *et al.* 2021).

The dolomite was precipitated in the sediment substrate of shallow floodplain lakes of variable salinity through evaporation, iron reduction, the actions of sulphate-reducing bacteria, and methanogenesis (Bennett *et al.* 2021). Many of the dolostones in the Tweed Basin contain an ichnofauna dominated by *Chondrites*. The single tier of dense burrows in thin beds indicates colonization during brief periods of environmental stress; the trace makers probably originated in the marine realm and were transported inland during storms (Bennett *et al.* 2017). Some of the dolostones are pedogenically altered suggesting that these lakes became vegetated saline marsh (Bennett *et al.* 2021).

Through evaporation, some of the hydrologically closed saline lakes in the Tweed Basin became increasingly hypersaline leading to deposition of gypsum; sabkha, marsh and microbial mats surrounded some of these (Millward *et al.* 2018, fig 6). As a result, small-scale evaporite deposits are distributed throughout the succession in the MVS and Tweed Basin, but are absent locally from the Lothians, the Campsie Fells and from areas adjacent to the Southern Upland Fault. Gypsum is present at shallow depths in the MVS, though anhydrite occurs deeper in boreholes from the Tweed Basin (Millward *et al.* 2018). Calcite and dolomite pseudomorphs after gypsum occur at outcrop at Burnmouth (Scott 1986). Siltstone pseudomorphs after halite crystals are recorded locally (Browne 1980; Cater *et al.* 1989).

Fluvial environments

In the east of the MVS and Tweed Basin, thick packages of fluvial sandstone, and a dominance of overbank siltstones over floodplain lakes, suggest that a major fluvial tract and riparian strip persisted in this area for much of the Tournaisian (Fig. 10.11). Sandstone units from a few metres up to 30 m thick comprise almost half of the thickness of the succession in the Edinburgh and East Lothian areas and in the Tweed Basin (Bennett *et al.* 2016; Millward *et al.* 2019). Fourteen sandbodies occur in the succession exposed at Burnmouth (Scrutton and Turner 1995). The thicker sandstone units are multistorey and multilateral. A lenticular channel-lag conglomerate at the base of one of the sandbodies at Burnmouth contains a remarkably rich assemblage of disarticulated vertebrate bones, including both small animals or juveniles and adults of tetrapods and fishes (Fig. 10.13a, Burnmouth section, 383 m; Clack *et al.* 2019a).

Erosive bases and laterally accreted units suggest that meandering systems dominated (Fig. 10.12), though braided systems are also represented. In the Tweed Basin, palaeocurrents indicate transport to the south, presumably contributing to the sediment budget of the Northumberland–Solway Basin. The fluvial systems appear to be integral components of the Ballagan palaeoenvironment (Bennett *et al.* 2016), and no valley regimes are recognized at outcrop.

Lake deposits, flooding and fossil soils

Grey and red siltstone, with lenticular very fine- and fine-grained sandstone and sandy siltstone represent a combination of overbank flood and crevasse-splay deposits, floodplain-lake deposits and palaeosols (Bennett *et al.* 2016). The lakes are inferred to have been up to a few metres deep and a few kilometres across and ephemeral, though thicker, grey siltstone successions, for example in Ayrshire and the Kilpatrick Hills, may represent perennial lakes. The lakes are thought to have formed during intense rainfall events and during overbank or marine flooding (Millward *et al.* 2019; Bennett *et al.* 2021).

The fauna of the lacustrine siltstones includes bivalves, malacostracan crustaceans (Briggs and Clarkson 1985), *Spirorbis* and sporadic monospecific accumulations of *Modiolus* and ostracods (Stephenson *et al.* 2004a; Williams *et al.* 2005, 2006). Additional invertebrates present include fragmentary eurypterids and xiphosurids (Waterston 1985). Some beds contain a rich flora, including lycopods, sphenopsids and pteridosperms (e.g. Scott and Meyer-Berthaud 1985). Sporadic marine invertebrate fossils are recorded from these beds in the east and west, including orthocone nautiloids, bivalves and *Lingula mytilloides* (Millward *et al.* 2019), suggesting episodic marine flooding.

Fish communities have been described from lacustrine siltstones in the Isle of Bute (Carpenter *et al.* 2015), at Coomsdon Burn, in north Northumberland (Moy-Thomas 1938) and Foulden, near Berwick-upon-Tweed (Wood and Rolfe 1985; Fig. 10.11). Putative juvenile actinopterygians from the Isle of Bute suggest that the lake there may have been a nursery. The Foulden fish fauna includes five species of actinopterygians, along with *Gyracanthus* spines, rhizodonts and a coelacanth; one bed contained large numbers of acanthodians ('spiny sharks'; Andrews 1985; Forey and Young 1985; Gardiner 1985). This fish bed began development as a lycopod wetland, became a floodplain lake which then silted-up to return the area to a floodplain environment (Clarkson 1985). The beds of complete fish probably represent mass-mortality events. Thin laminated siltstone units containing conchostracans are widespread and inferred to represent temporary, small and probably freshwater lakes typically less than about 0.4 hectares in extent (Millward *et al.* 2019).

Desiccation cracks are widespread and abundant, indicating temporary drying out of the floodplain. By contrast, palaeosols represent episodes of established vegetation cover. These have been noted from the Isle of Bute (Carpenter *et al.* 2015) and described from the Tweed Basin (Kearsey *et al.* 2016). Abundant rooted horizons without pedogenesis (Entisols) represent brief vegetated intervals in active floodplain areas. Also common are Inceptisols, more developed soils that probably formed near to river channels. Less common are the grey, gleyed Inceptisols, which probably formed in marshes and contain carbonized roots. Intervals of centuries to perhaps thousands of years of stabilized floodplain and soil formation occur in the upper part of the succession, represented by Vertisols. Near Foulden, Retallack and Dilcher (1988) inferred that gleyed Inceptisols were populated by small shrubby ferns such as *Lyrasperma scotica* and Vertisols by tall forest trees such as the reconstructed *Stamnostoma huttonense*. Waterlogged palaeosols were the likely habitat of the lycopod *Oxroadia*, the spores of which are abundant where tetrapods have been located at Burnmouth (Clack *et al.* 2016).

Thin beds of matrix-supported sandy siltstone containing millimetre-sized rock clasts and bioclasts overlie many of the Inceptisols and Vertisols, and also infill cracks in desiccated horizons. The upper parts of some of these palaeosols are gleyed, indicating that they became waterlogged. Bennett *et al.* (2016) inferred that the sandy siltstone beds formed during intense rainfall events as unconfined, cohesive debris flows swept across the floodplain. Closely associated and semi-articulated bones of at least five tetrapod species have been found in these beds from Burnmouth (Fig. 10.13a) and from the Whiteadder Water near Chirnside (Clack *et al.* 2016; Otoo *et al.* 2019).

Climate

Though previous accounts of the Scottish Tournaisian have inferred a semi-arid climate (e.g. Andrews *et al.* 1991; Williams *et al.* 2005), growth rings in fossil wood are more compatible with a markedly seasonal climate possibly related to monsoonal circulation in this tropical region (Falcon-Lang 1999a). Tropical seasonality is supported by the co-occurrence of abundant cracked surfaces and evaporite deposits, episodic flooding, the assemblage of palaeosols and a mean annual precipitation of 1000–

1500 mm estimated from palaeosol geochemical proxy data (Fig. 10.15; Kearsey *et al.* 2016). The extensive low-lying terrain and the narrow connections to the seaways in southern Ireland and to the southern North Sea would have aided the reach of storm flooding into the MVS, giving rise to a widespread seasonal marshland with a range of habitats and niches in which the various vertebrate groups radiated and enabled the tetrapods to conquer the land for the first time (Millward *et al*. 2019).

Chadian fluvial environments in the Midland Valley

In East Lothian, the uppermost 100 m or so of the Ballagan Formation have yielded Pu Biozone miospores indicating that sedimentation continued into Chadian times (Davies *et al.* 1986). Reddened siltstone in coastal sections south of Tantallan Castle and at Cove (Fig. 10.9) contain carbonate nodules and rhizoliths, interpreted as calcrete palaeosols (Andrews and Nabi 1998). Thin limestone beds contain tetrapod bones (Chen *et al.* 2018). The uppermost fluvial sandstones in the formation at Oxroad Bay in East Lothian contain an allochthonous, anatomically preserved flora of lycopsids, including *Oxroadia*, along with a few poorly preserved ferns and progymnosperms (Scott and Galtier 1988; Bateman and Rothwell 1990).

Contemporaneously in the north and west, uplift adjacent to the basin resulted in the development of fluvial environments ranging from braided streams to meandering rivers represented by the Clyde Sandstone Formation (Fig. 10.7). These strata consist of white and pale greenish-grey sandstones, commonly pebbly, with beds of red-brown, greenish or grey overbank mudstone (Fig. 10.13a). Carbonate nodules and beds of calcrete formed on stable alluvial plains. In far northern areas of the MVS some of the conglomeratic sandstones contain pebbles of quartz and Dalradian lithologies. Elsewhere the clasts are largely of limestone, dolostone or mudstone. The presence of calcretes may suggest a more arid climate than in the Tournaisian.

On the west coast of the Kintyre peninsula, resting on Dalradian rocks and overlain by basalts correlated with the Clyde Plateau Volcanic Formation (Stephenson *et al.* 2003, pp. 99-104), is a succession of fluvial sandstone and conglomerate and mudstone intercalations with pedogenic carbonate. Jutras (2017) described both phreatic and vadose calcretes from this area, including three units of the geologically rare host-replacing phreatic calcrete hardpan; development of the hardpans implies the nearby presence of an evaporitic lake. Though previously considered as Kinnesswood Formation (British Geological Survey 1996b), Jutras (2017) classified these rocks as Clyde Sandstone Formation.

Northumberland–Solway Basin in the Tournaisian and Chadian

Along the southern margin of the Southern Uplands massif (Fig. 10.11), the Birrenswark Volcanic Formation became buried beneath fluvial sands of the Whita Sandstone (Lumsden *et al.* 1967) at the base of the Ballagan Formation. The 500 m of massive and cross-bedded sandstone were interpreted by Leeder (1974) as fluvial channel deposits derived from the Southern Uplands massif. Bordering the Solway Firth, coarsely clastic alluvial fan deposits built up adjacent to the active syn-depositional Solway–Gilnockie faults (Maguire *et al.* 1996). Thin beds of siltstone and dolostone are interbedded with the sandstone, but there are few palaeosols. Abundant nodules and layers of gypsum proved in the Hoddom Borehole, near Ecclefechan, indicate the location of perennial brine pans (Millward *et al.* 2018).

Southeastwards the succession becomes increasingly dominated by marine rocks across, for example, the Tarras Water Fault and the Ballagan Formation passes into the Tournaisian to early Visean Lyne Formation (Fig. 10.7; Leeder 1974; Armstrong and Purnell 1987). The carbonate rocks present in the Lyne Formation are mainly limestone, contrasting with dolostone in the Ballagan Formation. Some limestone beds include stromatolitic bioherms and oncolite beds, whereas others contain an abundant and diverse marine fauna including crinoids, foraminifers and brachiopods (Leeder 1975a, b; Brand 2018). A sheltered lagoon environment is represented in Whitrope Burn near Langholm where carbonate rocks deposited by high density turbidity currents contain an abundant assemblage of holocephalan shark teeth (Richards *et al.* 2017). Prograding deltas, supplied with sediment along the axis of the Solway Basin, along with lime muds and storm emplaced sheet sands were deposited in a shallow offshore region (Maguire *et al.* 1996). The lower part of the Lyne Formation contains a substantial number of anhydrite beds (Ward 1997).

The position of contemporary, migrating coastlines is seen at Coldstream and in the River Coquet, south of the Cheviot massif where a vegetated floodplain facies containing vertebrate remains in the Ballagan Formation is intercalated with near-shore facies and mixed shallow marine carbonate and coarsening-upward clastic bay-fill deposits of the Lyne Formation (Sherwin 2018).

Igneous activity

With the recent biostratigraphical dating of the Kelso Volcanic Formation as latest Devonian (Marshall *et al.* 2019), volcanism is not known to have occurred during the Tournaisian of Scotland. Whilst most of the numerous basaltic plugs in the Southern Uplands are probably associated with emplacement of the Kelso and Birrenswark volcanic formations, some may be later. The Eildon Hills rhyolite laccolith (Fig. 10.16) yielded a mid-Tournaisian ^{40}Ar–^{39}Ar age of 355.7 ± 2.5 Ma (Monaghan and Pringle 2004). This is one of a small number of alkaline and peralkaline intrusions in the region, including ENE-trending dykes, near Melrose and the quartz-trachyte, riebeckite trachyte and riebeckite-aegirine phonolite of Skelfhill Pen, SSW of Hawick (Fig. 10.16; Upton *et al.* 2007).

Offshore Scotland

Offshore eastern Scotland, upper parts of the sandstone- and mudstone-dominated Tayport Formation have yielded Tournaisian palynomorphs (CM biozone) in exploration wells from the Outer Moray Firth (Kearsey *et al.* 2019a; Fig. 10.8). The unit forms part of the reservoir in the Buchan oil field (Quadrant 21; Edwards, 1991; Fig. 10.1). The Cementstone Formation has only tentatively been recognized in one well (26/07-1) in the Forth Approaches Basin (Kearsey *et al*. 2019a).

West of Shetland, Devono-Carboniferous sandstones form the fractured reservoir of the Clair oil field (Fig. 10.1). Fluvial sandstones and mudstones with pedogenic calcretes containing Tournaisian spores are conformably overlain by Visean marine siltstones and thin sandstones (Allen and Mange-Rajetzky 1992).

TS2 Early to Mid Visean (late Chadian–early Asbian) unconformities and subaerial volcanism

In the Midland Valley (MVS) subaerial conditions continued through a period of some ten million years from the late Chadian to early Asbian. Considerable thicknesses of Chadian, Tournaisian and Devonian strata may have been removed to create the substantial unconformity across much of the region (Fig. 10.4; Stephenson *et al.* 2004b). This was achieved through uplift of differentially reactivated fault blocks, localized folds and possibly through the rise of magmas into the MVS crust. This was the prelude to the construction of volcanoes, preserved principally as the Garleton Hills, Arthur's Seat and Clyde Plateau volcanic formations (Strathclyde Group; Figs 10.4, 10.7, 10.10b, 10.16). Meanwhile, to the south of the Southern Uplands, in the Solway part of the Northumberland–Solway Basin sedimentation apparently continued uninterrupted, though a much briefer erosional episode was the prelude to major sediment influx in the east.

The extent of the Visean unconformity varies substantially across the MVS (Figs 10.4, 10.7), with a pronounced hiatus in the SW. The length of the time gap differs across the Inchgotrick and Kerse Loch faults with strata as young as late Brigantian Lower Limestone Formation overlying Devonian Strathclyde Group rocks locally. In the Renfrewshire Hills (Fig. 10.16), the Clyde Plateau Volcanic Formation oversteps all formations of the Inverclyde Group southwards to overlie Lower Devonian strata. In the east of the MVS, in the Lomond Hills of Fife, the Brigantian Pathhead Formation oversteps the Ballagan and Kinnesswood formations north of the East Ochil Fault, probably the result of uplift on the north side of that fault.

Inverclyde Group strata between the north-trending Cumbrae and NNE-trending Largs faults (Fig. 10.3b) were folded to form the north-trending Leap Moor Syncline and Loch Thom Anticline, possibly linked to fault displacements associated with the bend in the Highland Boundary Fault (Young and Caldwell 2019). The axial region of the anticline was eroded prior to the onset of Clyde Plateau volcanism (Paterson *et al.* 1990). Northeast of Glasgow, transpressive re-activation of the Campsie West and East fault zones (Fig. 10.17), led to erosion and unconformity along the southern margin of the Campsie Fells. The fault zone is sinuous and multi-stranded, having the form of a weakly positive flower structure (Millward and Stephenson 2011). The zone of deformation is narrow and to the north the volcanic rocks overlie the Clyde Sandstone Formation with apparent conformity.

In summary, TS2 is marked by extensive fault movements, causing uplift, erosion and extension to provide pathways for magmas to reach the surface (Figs 10.4, 10.10b). The regional network of major faults may be consistent with a sinistral transpressive regime, and influenced by major tectono-magmatic events in the Variscan Orogeny (340–335 Ma in Domeier and Torsvik 2014; 335–330 Ma in Edel *et al.* 2018) that may have resulted in stress changes in the Variscan foreland. The Visean volcanic rocks are transitional to mildly alkalic basalt, hawaiite and mugearite, characterized by relatively small amounts of normative hypersthene or nepheline. These are accompanied by lesser amounts of the more differentiated benmoreite, trachyte and rhyolite that were related through crystal-liquid fractionation (Macdonald 1976). The varying phenocryst size, quantity and combinations were used formerly to classify these rocks (MacGregor 1928), but the scheme has been replaced by international rock names that are related to their felsic mineral content and geochemistry (Stephenson *et al.* 2003, pp. 357-360). Trace-element and isotopic characteristics imply that these magmas were generated through partial melting of slightly heterogeneous asthenosphere at depths of 80 to 60 km (Macdonald 1976, 1980; Smedley 1986a, b). Assimilation of a lithospheric component to the magmas was most conspicuous in the lavas of the western MVS (Wallis 1989).

Garleton Hills volcanic field

Volcanic activity began in the southeastern MVS in early Visean times (*c.* 345–343 Ma; Monaghan and Pringle 2004) with the Garleton Hills Volcanic Formation. These rocks crop out NW of the Dunbar – Gifford Fault (Figs 10.3, 10.16). An abrupt conformable passage from Pu miospore biozone Ballagan Formation into the overlying volcanic succession was proved in the East Linton Borehole (Fig 10.11 for location; McAdam and Tulloch 1985). The earliest phreatomagmatic eruptions of basaltic tuff and lapilli-tuff formed a coalesced group of tuff-rings or tuff cones, each typically less than 1 km in diameter. Many of the remnants of cones, vents and necks are well exposed along the North Berwick coast (Stephenson *et al.* 2003, pp. 47-55). Locally, the pyroclastic deposits were reworked by streams and flash-floods. These rocks form the 50–150-m thick North Berwick Member (Francis 1962; McAdam and Tulloch 1985; Davies *et al.* 1986). At Oxroad Bay (Fig. 10.9) these rocks contain organs of at least 11 plant species, including lycopsids, sphenopsids, pteropsids and arborescent gymnospermopsids (Bateman and Rothwell 1990; Bateman and Scott 1990). One of the lycopods, *Oxroadia gracilis* probably formed dense thickets and is abundant as burnt vegetation in some beds.

Increased magma output produced a succession of lavas up to 160 m thick, with transitional olivine basalt, hawaiite, mugearite and benmoreite compositions (McAdam and Tulloch 1985). Flows are 4 to 16 m thick and the numbers present locally suggest eruptions from multiple vents merged to form a plateau lava field. The latest eruptions (Bangley Member) were of silica-saturated or silica-oversaturated trachyte resulting in up to 160 m of lava and possibly sills, individually more than 20 m thick (McAdam and Tulloch 1985; Upton 1982). In coastal exposures at the base of the Bangley Member, a 10 m-thick succession of interbedded pumice lapilli-tuff, cross-stratified and swaley-bedded tuff, eutaxitic tuff and massive tuff, is identified as the Marine Villa tuffs and is thought to include welded ignimbrite (Upton *et al.* 2020; Fig. 10.18). These rocks formed by pyroclastic fall-out and pyroclastic density currents generated by Plinian eruptions. The Bangley Member formed from a substantial trachyte volcano, but whether it comprises a collection of lava domes (Stephenson *et al.* 2003, pp. 56-60) or is related to caldera formation and fill (Upton *et al.* 2020) remains speculative.

An unusual feature of this volcanic-field is its apparent geographical association with high-level intrusions, which include the phonolite laccolith of Traprain Law and the plugs of phonolitic trachyte at North Berwick Law and the Bass Rock. Such highly undersaturated rocks are not represented within the extrusive succession (Smedley 1986a). However, a single sheet of analcime-bearing hornblende trachybasalt at the base of the Garleton Hills Formation near Traprain Law, and xenoliths of similar composition in the Traprain Law phonolite (Tomkeieff 1952), suggest that early magmas may have evolved along an undersaturated trend; these unusual intrusions might represent their most extreme products (Stephenson *et al.* 2003, pp. 60-64; Upton *et al.* 2007).

Arthur's Seat Volcano

The imposing craggy features of Arthur's Seat, Carlton Hill and Castle Rock dominate the city of Edinburgh's landscape (Fig. 10.19) and, together with the thinner succession at the Craiglockhart Hills to the SW, represent the remnants of a subaerial basaltic stratovolcano, possibly up to 5 km in diameter and up to about 1000 m high (Black 1966). The 200 m-thick volcanic succession of mugearite, subordinate basalt and volcaniclastic rocks that crop out in the Corston Hill area (Fig. 10.16), about 5 km SE of Livingston was equated with the later part of the Arthur's Seat succession by Peach *et al.* (1910).

The Arthur's Seat Volcanic Formation is younger (Fig. 10.4; 341–335 Ma; Monaghan *et al.* 2014) than the Garleton Hills Volcanic Formation and partly coeval with the Clyde Plateau Volcanic Formation. Detailed description and interpretation of the Arthur's Seat Volcanic Formation is given by Black (1966) and Stephenson *et al.* (2003, pp. 64-74). The 400–500 m-thick succession consists mainly of basalt to hawaiite lavas, with subordinate mugearite lavas, each up to 30 m thick, and thin beds of tuff. Initial eruptions were phreatomagmatic, and volcaniclastic interbeds in the lower part of the succession contain plant and fish fossils suggesting a shallow water, possibly lacustrine, setting.

Coarse pyroclastic breccias fill the two central Lion's Head and Lion's Haunch vents, as well as the smaller Crags Vent (Fig. 10.19). The vents contain several basaltic intrusions and the later Lion's Haunch Vent also incorporates lavas and sedimentary interbeds, probably confined within a crater lake (Black 1966). Castle Rock is composed of a columnar-jointed basaltic plug that may have been intruded into the conduit of a parasitic vent. Basaltic sills within and underlying the volcanic strata are thought to be contemporaneous with the extrusive rocks, though the analcime-dolerite of the striking Salisbury Crags Sill is interpreted to be later.

Clyde Plateau volcanic fields

The youngest (*c.* 338–335 Ma; Monaghan and Parrish 2006), most extensive and voluminous subaerial Visean volcanic field is preserved in the western MVS as the Clyde Plateau Volcanic Formation (Figs 10.4, 10.7, 10.16). These rocks form a near-continuous arc of hills to the north, west and south of Glasgow. Thin lava successions on the islands of Little Cumbrae, Bute and Arran show dramatic thinning westwards from the mainland outcrops. Also, the lava fields may not have extended far to the NW of the present outcrops (Whyte and MacDonald 1974), though they are present close to the Highland Boundary Fault near Helensburgh (Paterson *et al.* 1990). The formation terminates abruptly southwards at the Inchgotrick Fault.

Major faults divide the main outcrop into blocks, each with its own succession in which stratigraphical units have some degree of lateral persistence, suggesting the presence of multiple volcanic centres (Francis *et al.* 1970; Paterson *et al.* 1990; Forsyth *et al.* 1996; Hall *et al.* 1998; Monro 1999). These are the Campsie Fells – Gargunnock Hills, Kilpatrick Hills, Renfrewshire Hills, Beith – Barrhead and Lanarkshire blocks (Fig. 10.16). The succession is up to 1000 m thick in the Renfrewshire Hills, thinning markedly southwards towards Ardrossan (Fig. 10.3b). North of the River Clyde, in the Kilpatrick Hills and the Campsie Fells, the formation is 400–500 m thick, thinning eastwards in the prominent escarpment of the Gargunnock Hills. In the Beith–Barrhead Hills, between the Paisley Ruck and the

Dusk Water Fault, the lava succession is probably less than 300 m thick, but farther to the SE in the Lanarkshire Block, thickness estimates range from 500–900 m (MacPherson *et al.* 2000).

North of the River Clyde, the lavas are thought to have been erupted from relatively small volcanoes aligned along three NE-trending linear vent systems parallel to the Milngavie–Kilsyth and East Campsie faults (Fig. 10.17; Craig 1980; Hall *et al.* 1998; Stephenson *et al.* 2003, pp. 85-90). The chains of upstanding plugs, volcanic necks and thick accumulations of bedded tuff and coarse scoriaceous pyroclastic rocks represent the remains of cinder cones that fed these lavas. The pyroclastic rocks were reworked locally by mass-flow and fluvial processes. Later eruptions were dominated by basaltic to mugearitic aa-lavas typically 5–30 m thick. Laterally more-extensive flows can be traced at least 6 km in the escarpment of the Gargunnock Hills (Francis *et al.* 1970). Thick red-brown lateritic boles occur on the tops of many flows, marking tropical weathering during quiescent interludes.

Volcaniclastic interbeds between the lavas are typically only a few metres thick. The exception is the Greenside Volcaniclastic Member in the Kilpatrick Hills (Fig. 10.17) which lies about 140 m above the base of the formation and comprises up to 40 m of bedded sedimentary and volcaniclastic rocks (Hall *et al.* 1998). Thin coal seams, plant-bearing beds, and mudstone with fish occur at the top of the member in Loch Humphrey Burn and at Glenarbuck. Depositional environments included fluvial, flood plain, lacustrine and swamp, the last dominated by lycopsids and ferns *s.l.* (Bateman *et al.* 2016). Scott *et al.* (1984) and Scott (1990) obtained a late Tournaisian miospore assemblage from this succession and thought that these rocks lay at the base of the volcanic succession. This is at odds with the outcrop nearby of Chadian Clyde Sandstone Formation and implied that the volcanic succession north of the Clyde was significantly earlier than that to the south. However, re-examination of the floral data by Bateman *et al.* (2016) indicated that a mid-Visean age for the Greenside Volcaniclastic Member was most probable.

The abundant trachytic extrusive rocks in the Renfrewshire Hills and Lanarkshire blocks imply that higher stratovolcanoes may have developed in this region (MacPherson *et al.* 2000). The 8 km-wide Misty Law trachytic centre in the Renfrewshire Hills comprises trachytic pyroclastic rocks, massive lavas of trachyte and rhyolite and trachytic plugs and necks (Johnstone 1965; Paterson *et al.* 1990). Flow banding indicates that these lavas were viscous and may have formed steep-sided lava domes. MacPherson and Phillips (1998) described a rare example of welded airfall lapilli-tuff interbedded with trachyandesite from the Eaglesham area. Rare phonolitic trachytes occur as plugs or laccoliths in the Lanarkshire block (e.g. Loudoun Hill) and in the Campsie Fells at Fintry (Upton *et al.* 2007).

The Waterhead Centre in the Campsie Fells is a large multiple neck, plugged by various rock types, and enclosed within an oval 2 by 2.5 km ring-fault (Fig. 10.17). The centre is underlain by a positive gravity anomaly (Cotton 1968) and the enclosed basic lavas show intense brecciation and hydrothermal alteration; they are intruded by a variety of dykes, some of which are silicic (MacDonald 1973). The Waterhead centre may represent the remains of a caldera (Craig 1980; Forsyth *et al.* 1996). Trachytic pyroclastic rocks in the adjacent tephra cone of Meikle Bin have been attributed to the centre.

Volcaniclastic rocks at Laggan, in NE Arran contain a lycopod flora, including arborescent and small herbaceous forms, accompanied by equisetopsids (horsetails) and pteridosperms, probably reflecting a flora growing in swampy lowlands. Growth of the lycopod trees has been studied in detail from the unusual preservation in which higher parts of the tree collapsed into the stump after the plant died, additionally trapping fragments of its branches (Cleal and Thomas 1996, pp. 152-155).

Other volcanic successions

NW of the Highland Boundary Fault, around Machrihanish (Fig. 10.16), up to 400 m of olivine basalt, mugearite and benmoreite, topped with trachyte lava domes, are preserved within a graben (Stephenson *et al.* 2003, pp. 99-104). As the succession rests in part upon Clyde Sandstone Formation (Jutras 2017), and is overlain unconformably by volcaniclastic beds similar to the Kirkwood Formation and by the Lower Limestone Formation, it has been assigned to the Clyde Plateau Volcanic Formation, albeit probably an entirely separate centre (Fig 10.4).

East of Stirling, thin volcanic successions close to the West Ochil Fault near Dollar (Fig. 10.3b; Browne and Thirlwall 1981) and in the Cleish Hills may be contemporaneous with, but separate from, the Clyde Plateau activity. Farther south, beneath the Central Coalfield, the Rashiehill Borehole, near Slamannan (Fig. 10.3b) terminated in 67 m of altered porphyritic basalt that have been equated with Clyde Plateau volcanism (Cameron *et al.* 1998). Seismic evidence suggests that these strata thin abruptly farther east into the West Lothian Oil-Shale Formation.

On the SW Ayrshire coast at Heads of Ayr, a volcanic neck and probable contemporary pyroclastic rocks of the Greenan Castle Pyroclastic Member (Stephenson *et al.* 2002) were described as the remains of a modest-sized volcano (Stephenson *et al.* 2003, pp. 104-108). The neck contains basaltic tuff, lapilli-tuff and pyroclastic breccia with petrographic characteristics similar to the pyroclastic member and resulted from phreatomagmatic eruptions. Xenoliths and crystals derived from the middle to lower crust (Badenszki *et al*. 2019) and from the mantle (Stephenson *et al*. 2003, pp. 104-108), make this neck unusual among the Visean volcanoes.

Tweed and Northumberland–Solway basins

In contrast to the MVS, sedimentation in the west of the Northumberland–Solway Basin continued apparently uninterrupted through TS2 into the Asbian (Fig. 10.7). Accommodation space was made through continued movements on the ENE-trending faults; the local eruption of up to about 30 m of Kershopefoot basalt in late Holkerian times, suggests that extension may have been pulsed.

In the Langholm and Bewcastle area (Figure 10.3b), the upper part of the Lyne Formation comprises marine limestone and mudstone interbedded with deltaic sandstone. An abundant shelly fauna of crinoids, brachiopods, corals and bivalves is present. The Chadian and lower Arundian strata contain evaporite beds, proved in the Easton Borehole, north of Carlisle (Ward 1997). Later, the succession became more peritidal with thin algal and ooidal limestone and passes upward into the Holkerian Fell Sandstone Formation (Larriston Sandstone of Lumsden *et al.* 1967). To the west, in the Solway area sand deposition, probably sourced locally from the north was in mixed fluviodeltaic, shallow marine and tidal lagoonal environments (Lintern and Floyd 2000; Maguire *et al.* 1996).

The Fell Sandstone is part of a fluvio-deltaic system that extends from east of the Grampian High/Peterhead Ridge and Halibut Horst southwards across the Forth Approaches Basin, the Mid North Sea High and Northumberland–Solway Basin (Kearsey *et al.* 2019a; Fig. 10.2 for locations). It may just reach the Scottish coast SE of the Dunbar–Gifford Fault as the Kip Carle Sandstone (Clough *et al.* 1910). In the Tweed Basin, pebbly, very coarse-grained sandstone rests with an erosive base on CM biozone Ballagan Formation (Greig 1988). Miospores indicative of the TS zone were recovered from the uppermost part of the Fell Sandstone in the Marshall Meadows Borehole, a few kilometres north of Berwick-upon-Tweed (Neves *et al.* 1973; Waters *et al.* 2011). Southwestwards, in the Northumberland–Solway Basin, the Fell Sandstone becomes finer grained and passes into Lyne Formation strata of Arundian to Holkerian age (Chadwick *et al*. 1995; Howell *et al*. 2022).

TS3 Late Visean (mid Asbian–mid Brigantian): lakes, deltas and volcanism

Following the extensive volcanism and significant unconformities developed in the early and mid Visean in the Midland Valley (MVS), the next 5 million years record spatially variable sedimentary rocks and more localized volcanic rocks up to 2 km thick in a number of sub-basins. Deposition is dominated by fluviatile, lacustrine and fluvio-deltaic deposits including carbonaceous beds of oil-shale and coal, and with sporadic marine incursions which were most frequent in the south and east. The MVS succession retains significant differences from those in the Outer Moray Firth and southern Scotland, in having significant volcanism (e.g. Kinghorn and Bathgate volcanic formations; Figs 10.4; 10.16) and numerous oil-shale beds within the West Lothian Oil-Shale Formation. Thin oil-shales have also been recognized in offshore exploration wells and in the Tweed and Dunbar–Oldhamstocks basins (Fig. 10.3a). Offshore, the time-equivalent Scremerston Formation (Fig. 10.8) contains a significant cumulative thickness of coal, forming a potential source rock interval for hydrocarbon resources. The West Lothian Oil-Shale Formation formed a significant historical hydrocarbon resource, and was extensively mined and processed (Chapter 17).

Lacustrine sedimentation in the central parts of the MVS occurred between barriers formed by the remnants of the Clyde Plateau volcanic field in the west and contemporaneous volcanic centres in the east (Fig. 10.20). Meanwhile, eastern Fife, East Lothian and the Northumberland–Solway Basin were located on the western margin of a large, southerly flowing fluvial to fluvio-deltaic system aligned with the proto-Viking graben in the North Sea, and passing southwards into marine environments in the southern North Sea (Fig. 10.6b). Fluvio-deltaic siliciclastic facies spread across the North Sea and Northumberland–Solway Basin from Asbian times and finally invaded the MVS from mid-Brigantian times, with fluvial flow more to the WSW in the onshore basins (Fig. 10.20). This process was repeatedly interrupted by marine transgressions and carbonate deposition, resulting in high-frequency, stacked marine to terrestrial Yoredale-type sedimentary cycles. The interplay of many facies during delta-lobe progradation, including mouth bar, bay, storm, crevasse splay, marsh, distributary channel and beach-barrier facies has been demonstrated by sedimentological studies of some siliciclastic intervals (e.g. Elliott 1975; Reynolds 1992). In contrast, the carbonate part of the cycle is understood in less detail. The causes of cyclicity probably include a combination of glacio-eustatic, tectonic and autocyclic processes (Leeder and Strudwick 1987; Manifold *et al.* 2020; Fielding 2021)).

Figure 10.20 Asbian paleogeography

A palaeogeographic reconstruction (Figs. 10.6b) incorporates northerly-derived provenance interpretations for the source of Brigantian sediments in the Outer Moray Firth. Provenance analysis also indicates that supplementary material was derived from the Scottish landmass, either directly or recycled through Devonian Old Red Sandstone (Morton *et al.* 2001). In the MVS, Lower Paleozoic detrital muscovite ages identified from the Scandinavian–Greenland Caledonian Orogen (Laurentia - Baltica terranes) were interpreted to be supplied through the drainage system established in the area of the proto-Viking graben (Stuart *et al.* 2001). U–Pb provenance data from Asbian sandstones in Fife support a dominant source from Laurentian terranes, including recycling of Devonian sedimentary rocks present offshore north and east of the MVS (McKenna 2021). This source continued to dominate younger, Brigantian sandstones with additional material interpreted from the Grampian High/Peterhead Ridge, local redeposition of Carboniferous volcanic material, and sediment sourced from the Southern Uplands (McKenna 2021; Fig. 10.20).

Structural development

Basin-fill successions of extremely variable thickness were deposited during TS3, reflecting deposition on a complex palaeotopography together with active tectonism and volcanism. However, understanding the structural development is challenging because constraining data are relatively sparse; the strata were buried to depths of up to 5 km (Fig. 10.21a) and overprinted by younger events.

The west of the MVS was an area of low subsidence during late Visean times. Thin successions of the Kirkwood and Lawmuir formations (Table 1) overlie the Clyde Plateau volcanic palaeotopography unconformably. Excepting the Lawmuir Formation, TS3 strata are notably thin to absent in Ayrshire, Arran, Bute, Great Cumbrae and Machrihanish (Monro, 1999; Smith *et al.* 2013). A similar unconformity exists in the Douglas Basin (Fig. 10.3a) where the Lawmuir Formation overlies the Inverclyde Group or pre-Carboniferous strata (Lumsden 1967a). In contrast, more than a kilometre of volcanic and sedimentary rocks was deposited in central parts, including West Lothian (Table 1, Fig. 10.3a). Significant syn-depositional movement occurred on east–west faults. For example, the footwall succession of the East Ochil Fault in the Lomond Hills is 40 m of Pathhead Formation above an unconformity, contrasting with over 1000 m of Strathclyde Group in the hanging wall (Table 1; Browne and Woodhall 2000).

In the eastern MVS, a pattern of NNE-trending basins developed that would dominate the later Carboniferous (Fig. 10.21a). However, two mutually inconsistent interpretations have been advanced to explain the genesis, controlling structures and stress regimes that operated (see Fig. 10.10g, h for idealized strain ellipses reflecting the regional stress). A seismic interpretation in the Firth of Forth shows growth into the major Midlothian–Leven Syncline and thinning on to flanking Burntisland and D'Arcy-Cousland anticlines from Visean times, under dextral oblique slip (Underhill *et al.* 2008; Fig. 10.22b). An alternative interpretation is that N- or NNE-trending normal faults controlled the eastern side of the Midlothian–Leven and Clackmannan depocentres in the Visean and early Namurian, under sinistral oblique slip, followed by later inversion under dextral oblique slip (Rippon *et al.* 1996; Ritchie *et al.* 2003). The NNE-trending 'Bo'ness line' that connects the Bathgate Hills and Saline Hills volcanism (Fig. 10.16) on the eastern margin of the Kincardine Basin (Read 1988) is inferred to mark the position of the controlling fault structure in the interpretation of Rippon *et al.* (1996). Offshore in the Forth Approaches Basin, the structural style changes, with syn-depositional growth of the Scremerston Formation (Asbian) seismic package towards a NE-trending fault (Arsenikos *et al.* 2018).

In the Northumberland–Solway Basin, movements on the ENE-trending syn-extensional faults that had been initiated in Late Devonian times entered their final stages by early Asbian times, accompanied on the northern flanks of the basin by basaltic eruptions of the Glencartholm Volcanic

Member (Fig. 10.16). The region then settled into a period of post-extension thermal subsidence and crustal sag that was to last through Brigantian and early Namurian times (Chadwick *et al.* 1995).

Regionally, syn-depositional faulting occurred on NE to easterly trending structures in TS3. In the eastern-central MVS, faulting and NNE-trending basins started to develop under oblique-slip tectonics. However, whether the structural development of TS3 points towards the regional sinistral oblique slip and 'expulsion' tectonics of Coward (1993; Fig. 10.1a), dextral oblique slip tectonics and 'insertion' (Fig. 10.1b), or varying stress fields in the Variscan foreland influenced by events in the orogen (Edel *et al.* 2018), remains to be defined further.

Igneous activity

Volcanism was generally less intense and confined to smaller centres during TS3 compared with TS2. Several minor volcanic units interdigitate with the Gullane and Anstruther formations that are dated as TC miospore zone. These include the Charles Hill Volcanic Member in south Fife, which comprises at least 30 m of olivine-basalt lava flows and beds of lapilli-tuff, and *c.* 70 m of basalt in the Midlothian-1 Well (Fig. 10.4; 10.16).

Volcanic successions of the Salsburgh Volcanic Formation have been proved in two exploration wells in the area between Motherwell and Bathgate (Fig. 10.3b), and may have been contemporaneous with later phases of the Clyde Plateau volcanism (Cameron *et al.* 1998). Near Forth (Fig. 10.3b), the Levenseat Well (Fig. 10.16) proved volcanic rocks intercalated with sedimentary rocks of TC miospore biozone age, overlying Pu biozone rocks interpreted as Ballagan Formation. The Salsburgh 1A Well (Fig. 10.16) proved putative Early Devonian igneous rocks overlain by some 100 m of basaltic tuffs and basalt with interbeds of limestone and mudstone. In this well, the volcanic rocks are overlain directly by a freshwater limestone and the succession is taken as equivalent to the Seafield–Deans Ash and Burdiehouse Limestone of Asbian age (Figs. 10.3, 10.23). In West Lothian, the Crosswood Ash lies at the top of the Gullane Formation, and the Port Edgar and Barracks Ash are interbedded with the Hopetoun Member (Fig. 10.23). The top of the Hopetoun Member contains thick and widespread pyroclastic rocks marking the base of the Bathgate Hills Volcanic Formation, described in TS4.

The Kinghorn Volcanic Formation is the remains of an olivine-basalt lava field associated with the Burntisland High between Kinghorn and Kirkcaldy in Fife (Figs. 10.3b, 10.4, 10.16). The lavas are interbedded with thin units of tuff and reworked volcaniclastic detritus along with intercalations of late Visean sedimentary rocks of the Sandy Craig and Pathhead formations (Browne and Woodhall 2000). The *c.* 485 m thick succession comprises subaerial flows, mostly 5 to 30 m thick, emplaced during Hawaiian or Strombolian-type eruptions. The volcanic landscape was populated by diverse plant communities (Rex and Scott 1987) and the tops of some lavas weathered to bole. Pillow lava and hyaloclastite in the upper part of the succession indicate that some basalt was either erupted subaqueously or flowed into the sea. Correlative volcanic units occur offshore beneath the Firth of Forth, including in the Firth of Forth-1 Well (Fig. 10.20).

Commencing with the Kinghorn Volcanic Formation, magma composition changed to more-primitive, silica-poor alkalic basic magmas, with little or no fractionation, possibly in relation to changing regional stress fields (Upton *et al.* 2004). Increasingly, the magmas formed intrusions rather than lavas and tuffs, such as a number of analcime-dolerite sills NW of Edinburgh, dated at 332.3±2.3 to 334.8±2.3 Ma (Monaghan and Pringle 2004).

Asbian and early Brigantian vertebrate faunas

During mining for coal, oil-shale and ironstone in the nineteenth century, tetrapod fossils were collected from Visean strata in the eastern Midland Valley of Scotland (Smithson 1985a; Smithson et al. 2017, fig. 1). Organic mudstones within the Gullane Formation between Granton and Newhaven in Edinburgh contain a vertebrate fauna of actinopterygians and chondrichthyans, along with rare acanthodians, rhizodonts, lungfish and a tetrapod, mostly well preserved in ironstone nodules (Wood 1975). Separate from this, the Granton Shrimp Bed is packed with malacostracan crustaceans along with rare marine orthocone cephalopods, polychaete worms and conodonts, including the conodont animal (Briggs *et al.* 1991, 1983). A similar fauna occurs at Cheese Bay (Fig. 10.9), in East Lothian probably from a similar stratigraphical position (Hesselbo and Trewin 1984).

The oldest Visean tetrapods in the UK are the limbless, snake-like *Lethiscus* at Granton (Anderson *et al.* 2003) and the terrestrially capable, mouse-sized tetrapod *Casineria* at Cheese Bay (Paton *et al.* 1999). These and other taxa from higher in the succession show increasing diversity and innovation in skull and body size during the Visean (Clack 2012). The limbless adelogyrinids occur in the Pumpherston and Dunnet oil-shales and Burdiehouse Limestone within the West Lothian Oil-Shale Formation (Fig. 10.23), and from the Anstruther Formation at Pitcorthie, Fife (Smithson 1985a). An aquatic colosteid has been recorded from the Burdiehouse Limestone and the Gilmerton Ironstone and the earliest spathicephalid is recorded from the Anstruther Formation of East Fife (Smithson *et al.* 2017).

An extraordinary number of terrestrial tetrapod specimens were found during exploration of a quarry from 1984 to 1992 in the East Kirkton Limestone, part of the West Lothian Oil-Shale Formation that is intercalated with the lower part of the Bathgate Volcanic Formation (Rolfe *et al*. 1993; Smith *et al.* 1994). Seven species have been described among the many skeletons that are complete or nearly so and less than 250 mm long (Clack 2017). The fauna includes the earliest known temnospondyl, regarded as a forerunner of modern amphibians, *Westlothiana lizziae,* nicknamed 'Lizzie the lizard'

(Smithson *et al.* 1994) and representatives of the microsaurs and aïstopods (Milner 1993). Abundant isolated bones of larger animals hint at an even greater diversity (Clack 2017).

The tetrapods are accompanied by arthropods, including eurypterids (Jeram and Selden 1993), myriapods (Shear 1993), a scorpion and a solitary specimen of a harvestman spider (Dunlop and Anderson 2005). Book lungs preserved in two specimens of scorpion cuticle testify to a terrestrial habit (Jeram 1993). These and the abundant plant fossils indicate that the animals lived within a richly vegetated volcanic landscape around the carbonate lake now represented by the East Kirkton Limestone (Clarkson *et al.* 1993).

Visean plant communities

The East Kirkton Limestone and Kinghorn Volcanic Formation, near Burntisland in Fife provide evidence of abundant vegetation at this time. The abundant fusain present in both localities indicates burnt vegetation from wildfires (Brown *et al.* 1993; Rex and Scott 1987). The East Kirkton flora includes pteridosperms, progymnosperms, probable true gymnosperms, lycopsids, sphenopsids and ferns (Scott *et al.* 1993). At least four of the gymnospermous plants have been interpreted as arborescent (Galtier and Scott 1993). Distinct ecological communities identified from Fife include a peat swamp flora, dominated by lycopods, the pteridosperm *Heterangium*, the sphenopsid *Archaeocalamites* and some ferns; a zygopterid fern community, possibly representing pioneering vegetation; and a lake-side community of the lycopod *Oxroadia* and gymnosperms (Rex and Scott 1987).

Climatic and eustatic controls

Cyclical sequences influenced by glacio-eustatic sea-level oscillations are recognized from the Asbian Tyne Limestone Formation in the Northumberland–Solway Basin, and in the upper parts of the Strathclyde Group in the MVS (Davies 2008; Fielding and Frank 2015). They mark the progressive climatic change to an icehouse state, coincident with a change to 4^{th} order (10^5 year) cyclicity recognized from about 335–332 Ma (Fielding 2021; Isbell *et al.* 2021; Montañez 2021).

A seasonal tropical climate and vegetation regime is thought to have existed across the MVS during the Asbian and Brigantian (Falcon-Lang 1999b). Many leaves from the Visean flora show xeromorphic features consistent with seasonal water deficiency. The presence of calcretes in the Aberlady and Sandy Craig formations (Andrews and Nabi 1998) and microbial carbonates (Guirdham, 1998) also point to more-arid climatic periods during the Asbian.

Regional development

Western Midland Valley

Extensive subaerial tropical weathering and lateritization of the Clyde Plateau volcanic rocks produced pockets of mainly fine-grained volcaniclastic detritus that comprise the unconformable Kirkwood Formation (Fig. 10.4; 10.20). It is highly variable in thickness, reaching about 30 m in Paisley, and locally passes laterally into the Lawmuir Formation. Rarely, non-volcaniclastic sedimentary rocks and marine beds indicate partial time-equivalence with the Lawmuir Formation (Monro 1999).

The lower parts of the Lawmuir Formation mark the return to fluviatile deposition in the western MVS, with channel, floodplain, lake and coal mire environments, whereas the partly cyclic upper beds contain laterally persistent marine horizons, including limestones (e.g. Hall *et al.* 1998; Ellen et al. 2016). The Lawmuir Formation is up to 300 m thick. Notable features include the non-marine Baldernock Limestone (Whyte 1994), the sulphurous Hurlet Coal, and the Douglas Muir Quartz-Conglomerate. Near Paisley, in one small area influenced by the Paisley Ruck fault-zone, thin coals coalesce locally to form up to 30 m of the Quarrelton Thick Coal.

Central and eastern Midland Valley

In the Lothians, predominantly fluvial, deltaic and lacustrine deposits with rare marine influences dominate the Asbian Gullane Formation; this unit varies in thickness (Table 1) and overlies the Arthur's Seat and Garleton Hills volcanic formations (Fig. 10.4; 10.7). Coals within the Gullane Formation in the Dunbar–Oldhamstocks Basin (Andrews and Nabi 1994) highlight correlation with the Scremerston Member of the Tweed Basin and Scremerston Formation in the Forth Approaches Basin (Fig. 10.8). The latest Asbian–early Brigantian Aberlady Formation (Fig. 10.7; Chisholm *et al.* 1989) consists of a cyclical succession of sandstone, siltstone and mudstone with more marine bands, bioclastic limestones and relatively rich, diverse marine shelf faunas than the underlying Gullane Formation.

Farther west, the West Lothian Oil-Shale Formation is up to 1120 m thick and contains many thin oil-shale beds (Chisholm *et al.* 1989; Fig. 10.23 a, b, c). Proved in deep exploration wells east of Glasgow (Monaghan 2014) and extending across West Lothian, it interfingers with fluvio-deltaic deposits towards Fife and Midlothian (Fig. 10.20). The laterally persistent Burdiehouse Limestone forms a marker horizon.

The lithologically varied strata (Fig. 10.23) were deposited in substantial lakes, 2000–3000 km^2 in area, under a humid climate (Loftus 1985; Loftus and Greensmith 1988). Ten sedimentary and one igneous lithofacies were identified Jones (2005); periods of lake expansion are marked by deposition of marginal lacustrine limestones and desiccation-cracked mudstones, with lake maxima marked by the deposition of deep-water oil-shale facies (Fig. 10.23b, c). The lakes were generally filled with muddy sediment, although minor channels fed sand into them via small, prograding deltas. Units previously described as 'marls' are altered volcaniclastic material (Jones 2005). The lacustrine sediments characteristically contain abundant remains of filamentous, mat-forming, benthonic cyanobacteria (Raymond 1991), with a minor contribution from the non-filamentous planktonic *Botryococcus brauni*. Maddox and Andrews (1987) recognized cryptalgally-laminated dolostones as time markers of basin-wide 'regression'. Guirdham (1998) and Raymond (1991) believed these carbonates were deposited in hydrologically closed, shallow, playa-type lakes, whereas the oil-shales formed in hydrologically open, thermally stratified, deep lakes in which shorelines and water levels were stable over long periods. Switches between the two systems were caused either by climate change, i.e. increased aridity or seasonality within an overall humid sub-tropical environment, or by local tectonism and volcanicity.

Fife

TS3 successions in Fife record a southwesterly prograding fluvio-deltaic sedimentation that passes westward to the lacustrine-dominated succession described above (Figs 10.20, 10.23d,e). Some of the earliest non-marine ostracods are observed in these units in Fife and record the early colonization of terrestrial water bodies (Bennett *et al.* 2012). Palaeontologically distinct marine bands and limestones and varying degrees of marine influence facilitate division of the succession into formations (Browne *et al.* 1999; Fig. 10.7). Subsequently, TC and NM palynological zonations from the Fife Ness section led Owens *et al.* (2005) to suggest this sandstone-dominated unit may be a member of the Pittenweem Formation.

The Asbian Anstruther Formation contains some non-marine limestones and dolostones with oncolites and stromatolites (Kassi *et al.* 1998; Guirdham *et al.* 2003). Much of the succession may be interpreted as upward-coarsening lake–delta cycles, capped by thinner erosive-based, upward-fining fluvial units, but parts seem non-cyclic (Browne *et al.* 1999; Kassi *et al.* 1998). The marine faunas are usually restricted. The abundant but restricted non-marine faunas are dominated by *Naiadites obesus*.

The overlying Pittenweem Formation is distinguished by diverse and abundant marine faunas in mudstone, siltstone and limestone, including the Pittenweem Marine Band (Fig. 10.23e), part of the thin Macgregor Marine Bands. Non-marine fluvial and deltaic sandstone to argillaceous rocks, limestone and dolostone are also present, including Owens *et al.* (2005) proposal to incorporate the 230 m fluvial-lacustrine dominated Fife Ness succession, based on palynological constraints.

The Asbian Sandy Craig Formation (Owens *et al.* 2005) comprises lithologies similar to the other Fife units but with minor proportions of algal-rich oil-shale, coal and multi-storey sandstones (Fig. 10.23d, e). Most of the succession represents upward-coarsening deltaic cycles, capped by thinner upward-fining fluvial units; the estuarine and coastal/alluvial facies of Fielding and Frank (2015). Marine faunas are rare and usually restricted, consisting in one case of only *Lingula*. The abundant but restricted non-marine faunas are dominated by the bivalve *Curvirimula*.

The Brigantian Pathhead Formation (Fig 10.4, 10.7) consists of upward-coarsening marine-deltaic cycles, capped by thinner, upward-fining fluvial units. Marine bands with thin limestones are more common than in the underlying formations and their faunas are usually diverse and abundant. The non-marine faunas are dominated by *Curvirimula*. Marine shelf/deltaic, estuarine and coastal/alluvial/deltaic facies associations are recognized, increasingly interpreted to record sea level excursions in response to glacio-eustatic fluctuations (Fielding and Frank 2015).

Offshore Scotland

Offshore exploration wells and seismic data from the North Sea place the variable TS3 onshore successions in the context of a regional delta system (Kearsey *et al.* 2019a; Figs 10.6b, 10.8). Asbian–Brigantian strata to the east of the Grampian High/Halibut Horst, in the Outer Moray Firth and south Buchan Basin (Quadrants 14, 15, 20, 21; Fig. 10.1) comprise coal-rich intervals within a mudstone-dominated succession, about 200 m thick and representing coal mire environments (Firth Coal Formation; Leeder and Boldy 1990; Cameron, 1993b; Kearsey *et al.* 2019a; Fig. 10.8). A 6 m-thick bed of oil-shale in well 20/10a-3 highlights that organic-rich lacustrine units are present (Quadrant 20 Fig. 10.1). A sand-rich facies, up to 40 m thick, represents fluvial channels and indicates that large-scale, north to south channel systems may have existed across the area; these sediments were deposited behind the apex point of the delta system (Kearsey *et al.* 2019a), with sediment supplied from East Greenland to the north (Morton *et al.* 2001). A minor part of the reservoir in the Claymore and Highlander oil-fields (Fig. 10.1) is within these deltaic sandstones (Harker *et al.* 1991; Whitehead and Pinnock 1991).

Southwestwards, in the Forth Approaches Basin, Visean rocks of the Firth Coal Formation are up to 210 m thick, with thick coals (McLean and Neves 1988; Cameron, 1993b; Kearsey *et al.* 2019a). Broadly coinciding with the onshore Scremerston Coal Member of the Tyne Limestone Formation (Fig. 10.8), this unit represents widespread delta plain and back-swamp mire environments, dominantly terrestrial in the Forth Approaches and terrestrial to deltaic and marine south of the Mid North Sea High in Quadrants 41–42 (Bruce and Stemmerik 2003; Kearsey *et al.* 2019a).

The presence of Asbian–Brigantian strata offshore from western Scotland is uncertain, given the unconformity and thin or absent succession in Ayrshire, Machrihanish and Arran, and lack of well data. In the Firth of Clyde, North Channel and Portpatrick Basin, Pharaoh *et al.* (2018) and Fyfe *et al.* (2020) used the presence of Carboniferous strata in onshore boreholes in Northern Ireland (Penn *et al.* 1983; Mitchell 2004) to interpret a poorly constrained Carboniferous succession from seismic reflection data that could include Visean–Namurian mudstone source-rocks in parts of these offshore areas.

Carboniferous rocks are not understood to be present in the Sea of Hebrides and Minch Basin (Fyfe *et al.* 2021).

Southern Uplands

Whilst the Southern Uplands remained a persistent high (Fig 10.6b), thin Visean successions accumulated in SSE-trending fault-bounded palaeovalleys at Sanquhar and Thornhill (Fig 10.3a; Stone *et al*., 2012). In the east of the Sanquhar Outlier, a 10 m-thick succession of interbedded mudstones, siltstones, sandstones, seat clays and thin argillaceous limestones containing late Visean brachiopods and bivalves rests unconformably on Ordovician strata (Davies 1970). At Thornhill, the upper Asbian–Brigantian Closeburn Limestone Formation comprises 25 m of dolomitic limestone, sandstone, siltstone and mudstone with marine faunas (McMillan 2002).

Northumberland–Solway and Tweed basins

The Asbian and Brigantian strata in this region are assigned to the Tyne Limestone and Alston formations respectively of the Yoredale Group (Fig. 10.7). South of the Southern Uplands, strata from TS3 crop out in Scotland only to the north and NE of Canonbie, and a few kilometres to the north of Berwick-upon-Tweed. The Archerbeck Borehole, drilled north of Canonbie, proved 804 m of Tyne Limestone Formation (Lumsden and Wilson 1961). Farther east, into the basin more than 2000 m are preserved in an ENE-trending graben between the Beckhead-Binky Linn and Antonstown faults (Fig. 10.3; Day 1970). The thickness in the Tweed Basin is about 300 m.

The Tyne Limestone Formation overlies the Fell Sandstone Formation locally disconformably and diachronously (Fig. 10.7). The lower boundary is taken at the base of the sparsely fossiliferous argillaceous limestone of the Clattering Band (Day 1970) or, in a small area around Langholm and Canonbie (Fig. 10.3b), by the Glencartholm Volcanic Member (Dean *et al.* 2011). The volcanic strata lie near the base of the Asbian (TC biozone; Neves *et al.* 1973) and are broadly coeval with the latest part of the Clyde Plateau volcanism (Fig. 10.4). The 150 m-thick volcanic succession consists of basalt overlain by volcaniclastic conglomerate and sandstone, siliciclastic sandstone, dolostone, limestone, mudstone, seatearth and thin coals (Lumsden *et al.* 1967). Richly fossiliferous beds contain shrimps, fish and molluscs (Peach and Horne 1905; Clark *et al.* 2018) and a scorpion bed contains eurypterids, crustaceans and an extensive compression flora of pteridosperms and lycopods (Kidston 1882). The fish beds yielded 35 species, evidence for a major diversification in ray-finned fishes by mid-Visean times (Wood 2018). The large numbers of complete and near complete specimens probably represent mass mortality events in muddy creeks shut off from the open sea.

The uppermost part of the Tyne Limestone Formation exposed near Berwick-upon-Tweed shows a dominantly terrestrial environment, alternating between minor heterolithic and sandy channels, overbank and crevasse splays, gleyed palaeosols and coal mires. The coals are typically up to about 1 m thick, though exceptions reach 3 m. Fluvial sandstone bodies cutting into the succession here include multi-storey units up to 30 m thick with southerly directed channel belts inferred to have been 3–8 km wide (Jones 2007). This succession is termed the Scremerston Coal Member, and is correlated with the eponymous formation offshore (Kearsey *et al*. 2019a).

Southwestwards, in the Solway area, the Tyne Limestone Formation comprises more than 35 cycles, 5–30 m thick, each typically commencing with a marine carbonate and clastic succession capped by a seatearth and coal, representing abandonment and terrestrial conditions (Fig. 10.24a). Most of the coals are only a few centimetres thick. In the middle of the formation, packages of sparsely fossiliferous, calcareous sandstone up to 20 m thick dominate these cycles. There are also four thicker marine packages containing a rich fauna of bryozoa, corals, brachiopods, crinoids, bivalves and foraminifers (Fig. 10.24a). In the Kirkbean outlier (Fig. 10.3b), south of Dumfries, the Arbigland Limestone Member at the base of the Tyne Limestone Formation consists of thick beds of bioturbated calcareous sandstone with plant remains, interbedded with thin sandy ooidal and algal limestones, suggesting a restricted lagoonal environment (Lintern and Floyd 2000). The base of the Asbian lies in the middle of the member (Waters *et al.* 2011) at the first appearance of coral – brachiopod fauna comparable with the Clattering Band.

Sedimentation continued uninterrupted into the Brigantian Alston Formation; from here on the limestones became thicker, ranging up to 13.7 m. The base of the Brigantian Substage and of the formation in the Archerbeck Borehole is taken at the base of the Cornet Limestone; this lies just beneath the Callant Limestone, which is correlated to the basal Brigantian Low Tipalt and Peghorn limestones elsewhere in northern England (Cózar and Somerville 2012; Waters *et al.* 2011).

TS4 Latest Visean–early Namurian (mid Brigantian–Arnsbergian): waning volcanism, deltaic sediments and marine incursions

In TS4, as ice-sheets became more widespread in Gondwana, glacio-eustatically influenced cyclical sedimentation produced sequences that are similar across basins in the Midland Valley (MVS) and southern Scotland. The semi-isolated basins with different lithostratigraphies that had typified the Strathclyde Group of central Scotland were replaced by marine-influenced depositional environments of the Clackmannan Group that extended across the MVS, and southwards into the Borders by the Yoredale Group. Limestones and marine bands can be correlated and formation boundaries approximate to time-lines within the MVS (Browne *et al.* 1999), and between this area and the Northumberland-Solway Basin; for example, the Hurlet Limestone of central Scotland is correlated with the Scar Limestone of northern England (Cózar and Somerville 2021).

At the start of TS4 in the MVS, a widespread marine transgression marked by the Hurlet Limestone (Fig. 10.25) initiated the progressive submergence of most of the Strathclyde Group volcanic palaeotopography. Volcanic influence waned further during these times, though some active volcanic centres remained (Figs 10.4, 10.5) and glacio-eustatic controls on cyclical sedimentation prevailed, with thick coals and limestones deposited in successions volumetrically-dominated by mudstone, siltstone and sandstone (Fig. 10.26).

Deposited in alternating marine, quasi-marine and fluvio-deltaic environments, the Lower Limestone Formation (late Brigantian) contains the strongest marine influences of the Scottish Carboniferous succession. Seven widespread major marine transgressions have been traced throughout the greater part of the MVS (Fig. 10.25; Wilson 1989; Browne *et al.* 1999). The Limestone Coal Formation (early Pendleian) is dominated by fluvio-deltaic cycles containing coals and sideritic ironstones, both of which were formerly mined. Marine influences were less important, but two composite marine bands, the Johnstone Shell-bed and the Black Metals Member (Figs 10.26, 10.27) mark major transgressions (Read 1994). In the Upper Limestone Formation (late Pendleian–early Arnsbergian), marine influences again became significant and laterally persistent limestones are commonly overlain by thick marine mudstones, marking major transgressions (Fig. 10.28). The Orchard Limestone (or equivalents) marks the base of the Arnsbergian Substage. Faunas record marine transgressions from the east within the Lower Limestone Formation (Wilson 1989) and both the west and the east in the Upper Limestone Formation, sometimes resulting in an open marine strait into which new faunal elements migrated from the east (Wilson 1967).

Scottish Caledonian intrusions from north of the Highland Boundary Fault are interpreted to have become the dominant source of sediment brought into the central-eastern MVS during the Pendleian–Arnsbergian interval of TS4, in addition to an East Greenland component (McKenna 2021). This is consistent with the south to SW orientation of channel sand bodies and palaeocurrent measurements in the central MVS (Read 1989a; Hooper 2003; Fig. 10.29).

Abundant data from boreholes, mine workings, seismic studies and geological modelling has facilitated a greater understanding of basin development and geometries during TS4 than for older strata (e.g. Figs 10.10c, 10.21b,d, 10.22b; Underhill *et al.* 2008; Monaghan 2013, 2014). Older studies were summarized by Read *et al.* (2002). Surface coal mines have facilitated detailed studies across the MVS (Hooper 2003), including at Spireslack at the eastern end of the NE-trending Muirkirk syncline in the Ayrshire Coalfield (Fig. 10.26; Leslie *et al.* 2016; Ellen *et al.* 2016), and at Mainshill Wood in the Douglas Basin (Browne and Leslie 2015; Fig. 10.28e).

Structural development

Older publications viewed the Namurian and Westphalian as times of thermal subsidence (e.g. Leeder 1982). Whilst lithofacies in TS4 do not indicate significant tectonic palaeotopography such as fault scarps with alluvial fans, there is evidence of continued syn-depositional faulting and folding in the MVS (Fig 10.10c, 10.29), within a regime of oblique slip tectonics.

In the western MVS, the remnants of the Clyde Plateau volcanic field remained a 'relative' high between Ayrshire and the Central Coalfield. In Ayrshire, deposition was controlled by the differential subsidence of fault blocks on inherited Caledonian trends, separated by the long-lived NE- to ENE-trending Dusk Water, Inchgotrick and Kerse Loch faults (Table 1; Fig. 10.2; 10.10c; 10.29; Mykura *et al.* 1967; Monro 1999; Smith *et al.* 2013). A significantly attenuated succession indicates that a long-lived palaeohigh existed in the footwall block of the Inchgotrick and Kerse Loch faults east and south of Ayr, whereas in the Dalry Basin north of the Dusk Water Fault and in south Ayrshire in the hanging wall of the Kerse Loch Fault, TS4 sedimentary successions are hundreds of metres thick (Table 1; Fig. 10.29). Thickening of the Limestone Coal Formation also occurs into the centre of the synclinal Dailly Coalfield (Figs. 10.3; 10.29) on a releasing bend of the Kerse Loch Fault (Smith *et al*. 2013).

The synclinal Douglas Basin also developed adjacent to a large NE-trending fault on the southern side of the MVS (Figs. 10.3; 10.29). Here, TS4 strata thicken into both the syncline centre and the Kennox Fault, as well as thinning onto a growing, NNE-trending, intrabasinal anticline (Lumsden 1964).

In the Central Coalfield, south of the West and East Campsie faults, the ENE-trending Kilsyth Trough was the locus of maximum subsidence (Table 1; Fig. 10.3, 10.10c, 10.29) possibly related to a deep Caledonide lineament influencing structures from the Paisley Ruck in the west across to the East Ochil Fault (Read 1989a). The successions and number of workable coals thin southwards, over the east–west-orientated Wilsontown Fault, and the Limestone Coal Formation thins onto the rising NE-trending Riggin Anticline (Read 1988; Fig. 10.3b). The structural grain changes in northern and eastern parts of the Central Coalfield to be dominated by growth of the *c.* N–S Clackmannan Syncline (Fig. 10.3, 10.10c, 10.29; Hooper 2003). The thickest onshore occurrences of the Limestone Coal and Upper Limestone formations occur at the northern end of the syncline in the Kincardine Basin (Table 1; Fig. 10.27c). Isopach maps in this area show syn-depositional synclinal growth (Fig. 10.22d; Rippon *et al.* 1996). The Clackmannan Syncline is cut by numerous post-depositional east–west faults; however, two syn-depositional faults defined a narrow 'Forth Graben' (Hooper 2003), an extension of the Kilsyth Trough.

In the eastern MVS, structural development was dominated by the growing, NNE-trending Midlothian–Leven Syncline and flanking Burntisland Anticline (Figs 10.3, 10.10c, 10.22b, 10.27a, b, 10.29; Browne and Woodhall 2000; Ritchie *et al.* 2003; Underhill *et al.* 2008). Faults on east–west and ENE–WSW orientations at the northern and southern ends of the structures exerted control, for example with significant thickening across the East Ochil and Roslin-Vogrie faults (Table 1: Fig. 10.10c, 10.29).

Detailed structural analyses at the Spireslack section have documented a sinistral oblique-slip (transpression) generated network of kinematically-linked folds and faults (Leslie *et al.* 2016), with a superimposed dextrally transpressive linked network of fold, fault and fracture structures (Andrews *et al.* 2020); both networks post-date deposition of the Upper Limestone Formation. This is a conundrum to be further investigated because previous authors have interpreted the range of MVS structures such as NNE-trending folds and ENE-trending extensional faults in TS4 to be related to dextral oblique-slip (Read 1989a; Rippon *et al.* 1996; Ritchie *et al.* 2003; Underhill *et al.* 2008; Fig. 10.10c, h).

Igneous activity

Eruption of the Bathgate Hills Volcanic Formation had commenced contemporaneously with deposition of the later parts of the West Lothian Oil-Shale Formation, and interfingering with limestones marking marine transgressions in the Lower Limestone, Limestone Coal and Upper Limestone formations (Smith *et al.* 1994; Fig. 10.4, 10.16). The volcanic succession, about 600 m at its thickest in the Bathgate Hills, comprises basaltic lavas with subordinate tuffs and re-deposited volcanic detritus. They form an elongate, north–south lava-field along a 'Bo'ness line' (Read *et al.* 2002) at the eastern margin of the Clackmannan Syncline (Fig. 10.16). In the Rashiehill Borehole 12 km WNW of Bathgate, the base of the formation is taken at a change to more mafic olivine-basalts compared with the underlying Clyde Plateau Volcanic Formation (Anderson 1951).

Thick tuffs, volcaniclastic sedimentary rocks and rare basalt lavas also occur in the Limestone Coal and Upper Limestone formations around the Saline Hills, 25 km NNE of Bathgate (Cameron and Stephenson 1985; Fig. 10.16). Farther east in Fife, bedded tuffs provide evidence of phreatomagmatic activity at numerous volcanic centres including complex necks and vents, such as Largo Law. In North Ayrshire, explosive volcanic activity is recorded with tuffs interbedded with Limestone Coal Formation strata in the Dalry area (Monro 1999; Fig. 10.4).

Clusters of analcime-bearing olivine-dolerite sills that comprise an estimated volume of 7.25 km^3 were emplaced during early Namurian times, in an area of about 750 km^2 in west and central Fife between the East Ochil and Rosyth faults. Numerous associated plugs and necks of similar composition are thought to have fed the sills which were emplaced at shallow structural levels (Francis and Walker 1987). The advancing ends of the sills commonly pass into peperitic breccias, formed through the explosive disintegration of magma and disruption of, and mixing with sediment as the sill advanced through water-saturated sediment (see also Stephenson *et al.* 2003, p. 179). The dolerite is typically altered to 'white trap' and where the sills intruded coal seams, the coal is either replaced or coked. 'White trap' is composed of quartz, illite, kaolinite, muscovite, rutile, anatase and carbonate and results from the interaction of circulating external fluids and volatiles with the rock.

Vertebrate fauna

Two important vertebrate faunas are known from different palaeoenvironments in the Pendleian of the MVS. These are from the Bearsden Fish Bed in strata approximately equivalent to the Top Hosie Limestone, north of Glasgow (Wood 1982) and the Dora Bone Bed (Figs 10.9, 10.27b), in the upper part of the Limestone Coal Formation exposed during operation of the former surface coal mine near Cowdenbeath in Fife (Fig. 10.3b; Andrews *et al.* 1977).

The Bearsden fauna includes the famous Bearsden Shark with its peculiar dorsal keel-like spine and brush organ which was initially referred to *Stethacanthus* but is now renamed as *Akmonistion zangleri* (Coates and Sequeira 2001). The actinopterygian fish species include juveniles and small fusiform species as well as larger, rhombic bodied forms (Coates 1998). The Bearsden fauna apparently bears no relationship to any other known Carboniferous assemblage in the world.

The Dora Bone Bed is part of the seatearth which underlies a thin coal seam between the Little Splint Coal and the Lochgelly Blackband Ironstone (Fig. 10.27b; Andrews *et al.* 1977). The tetrapods include a possible filter-feeder, a baphetoid and anthracosaurs (Smithson 1985b). Among the last group and up to 1.5 m long, *Proterogyrinus* was well adapted for terrestrial locomotion and may have been a crocodile-like predator (Smithson 1986). The bone bed fauna also includes acanthodians, actinopterygians, dipnoans, rhizodonts and several other, probably aquatic, tetrapods.

Some of the tetrapods at Dora are also common to the Gilmerton Ironstone within the Lower Limestone Formation, the Burghlee/Rumbles Ironstone in the Limestone Coal Formation at the former Ramsay and Burghlee collieries in Loanhead, and from the Upper Limestone Formation in the former Niddrie colliery, Edinburgh. Other species from Ramsay colliery include a probable temnospondyl and a baphetoid. Attributed with some uncertainty to the Burghlee Ironstone at Ramsey colliery, Loanhead is the limbless *Acherontiscus* (Clack *et al.* 2019b).

The high level of diversity among Tournaisian lungfish continued through the late Mississippian (Smithson *et al.* 2016). At least five taxa have been recognized from the Burghlee or Rumbles Ironstone (Smithson *et al.* 2019). Namurian lungfish are also known from the Dora Bone Bed, Powgree Burn, in

Ayrshire and from the Upper Limestone Formation at the former Niddrie colliery. The crushing dentition of all these is taken to indicate a probable diet of bivalves, ostracods and crustaceans.

Invertebrate palaeontology

Biofacies studies in the MVS have provided understanding of the extent, salinity, substrate and turbidity of marine and marginal marine environments. Marine and marginal straits extended across the region during the early Namurian (Wilson 1967, 1989). For example, reduced salinity environments commonly contain the brachiopod *Lingula* and the bivalve *Streblopteria*, muddy near-shore zones were dominated by bivalves, and during marine transgressions clearer waters supported limestone belts with firm substrates and dominantly epifaunal assemblages of colonial corals, brachiopods, crinoids and echinoids. The limestones were more common in the SE of the MVS where the water was less turbid and more saline. More detailed palaeoecological variations have illuminated a fault-controlled embayment adjacent to the Kerse Loch Fault in Ayrshire (Dean *et al.* 2010) and a possible palaeo-estuary spanning from north Ayrshire to Glasgow (Brand 1998).

Lingula bands are commonly succeeded by claystones containing the mainly non-marine bivalves such as *Paracarbonicola*, *Naiadites* and *Curvirimula*, which had evolved from marine ancestors, possibly in estuarine settings, and progressively adapted to lower salinities (Eagar 1977; Brand 1998; Amler and Silantiev 2021).

Climatic and eustatic controls

The northward migration of Scotland into the 'everwet' equatorial climatic zone allowed land vegetation to colonize new environments. During TS4, the region became part of the Euramerican floral province and lay in the 'coal belt', dominated by heterosporous lycopod trees. These formed a primitive type of rain forest (Phillips and Peppers 1984) in which thick domed equatorial peats accumulated, ultimately giving rise to thick coals (Clymo 1987). The peats were generally underlain by marshy waterlogged palaeosols (gleys) riddled with *Stigmaria*, the roots of lycopods, which ultimately became seatearths. The Namurian 'Fossil Grove' in Victoria Park, Glasgow provides a good example of this environment (Gastaldo 1986).

Glacio-eustatic controls that commenced in TS3 became prevalent into TS4. During the Namurian, the first extensive Southern Hemisphere glaciogenic deposits coincide with extensive peat mires developed in Scotland, incised fluvial systems and marine bands that are interpreted as eustatically controlled (Davies 2008). The lithofacies represented by the cyclical sequences of the Clackmannan Group and the Yoredale Group in the Northumberland–Solway Basin indicate repeated and widespread changes in sea level on a slowly subsiding platform, under limited accommodation and limited sediment supply (e.g. Read 1995; Fielding 2021).

Sea-level oscillations controlled by obliquity or short eccentricity Milankovitch cyclicity (or orbital forcing), have been identified in distal fluvio-deltaic environments of the Limestone Coal Formation in the central MVS, using spectral analysis (Weedon and Read 1995). Cycles of 400 ka (obliquity) have been recognized in the late Brigantian (Kassi *et al.* 2004). As well as large-scale changes in sea level, sedimentary processes such as building out and abandonment of local delta lobes, the avulsion of fluvial channel belts, and the migration of meander belts controlled more localized cyclicity (Read and Forsyth 1989). Tidal ranges are thought to have been less than a metre; tidal rhythmites being only seen locally (Wells *et al.* 2005).

Regional development

Midland Valley

The Lower Limestone, Limestone Coal and Upper Limestone formations are present across the MVS from Ayrshire to Fife, with the base of the Lower Limestone Formation buried at about -3.5 km in the Midlothian–Leven Syncline and about -1.5 km in the Kincardine Basin (Fig. 10.21b).

Repeated progradation and abandonment of deltaic complexes and the interaction of tectonic uplifts to parts of the waterlogged delta plain can be recognized in the sedimentological record. For example, in the Lower Limestone Formation close to the Ardross Fault in Fife (Fig. 10.3), Fielding *et al.* (1988) interpreted (1) laminated claystones and marine bioclastic limestones, deposited in prodelta and marine-shelf environments (e.g. Fig. 10.25d limestone beds), (2) crudely coarsening-upward sandstone units as delta front deposits of fluvially dominated though wave-influenced, shallow-water deltas (e.g. Fig. 10.25d 40–50 m), and (3) interbedded clastic sedimentary rocks and coals, deposited in delta-plain environments, best developed in a fault-bounded enhanced subsidence zone (e.g. Figure 10.25d, Largoward Black Coal interval).

The Lower Limestone Formation is more sandstone- and coal-dominated in east Fife (Fig. 10.25d), where palaeocurrents and channel bodies indicate continued fluvio-deltaic influence from the NNE. Units are more limestone-dominated in the SE of the MVS and more argillaceous in the west (Fig. 10.25b; Goodlet 1957; Wilson 1989). In general, limestones are thickest in low subsidence areas; e.g. Pickard (1992, 1994) described build-ups in the locally thickened Blackhall (Charlestown Main) Limestone caused by increased carbonate productivity in clear shallow water on the flanks of the slowly subsiding Burntisland Anticline.

In the Limestone Coal Formation, sand channels have been mapped from abundant subsurface data in and around the Kincardine Basin. They entered the basin from the NW and NE and exited to the SW, prograding westwards along the Kilsyth Trough (Figs 10.27d, 10.29; Read 1989a; Rippon *et al.* 1996). Proximal and transitional facies with fluvial sandstone, splitting and composite coal seams are dominant on the eastern side of the basin, with more distal, regularly cyclic, coal-bearing facies to the west (Read 1995). Similar palaeocurrent directions from the NE are observed in south Ayrshire (Mykura *et al.* 1967); however, sand and pebbles derived from the Southern Uplands entered locally from the south (Stedman 1988).

In the Upper Limestone Formation stacked fluvial sandstones are notable (Fig. 10.30) and might represent fluvial deposition during glacio-eustatic lowstands. Examples include up to 58 m of 'Barrhead Grit' in the Kilsyth Trough (Forsyth 1982; Hall *et al.* 1998) and the Spireslack Sandstone in Ayrshire, where a lower channel-set appears to be confined to erosional palaeovalleys of limited lateral extent and relief, whereas an upper channel-set is laterally extensive with greater lateral accretion (Ellen *et al.* 2019; Figs. 10.26, 10.28d). Small-scale coal-bearing cycles are also common in the Upper Limestone Formation (Fig. 10.28e). Coals are generally thin except below the Calmy Limestone where the Upper Hirst Coal (Fig. 10.28a,c) locally exceeds 2.5 m. Siliciclastic sediment continued to enter the MVS from the north and NE, consequently limestones tend to thicken to the south and SW in environments distal to the sediment source. The Castlecary Limestone at the top of the Upper Limestone Formation (Fig. 10.28a) is an exception, tending to be thickest in the east. It was subaerially exposed locally and was eroded shortly after deposition, a prelude to events in TS5.

Offshore eastern Scotland

Mid Brigantian–Pendleian (TS4) fluvio-deltaic, coal-bearing sedimentary successions form part of the Firth Coal Formation proved in exploration wells from the Outer Moray Firth (Quadrants 14 and 15) and mapped on seismic data in surrounding faulted basins (Arsenikos *et al.* 2018; Fig. 10.1). Similar strata in the south Buchan Basin (Quadrant 20 and 21) span the mid-Brigantian to Kinderscoutian interval (Andrews *et al.* 1990; Leeder and Boldy 1990; Kearsey *et al.* 2019a; Fig. 10.8). The Brigantian–Pendleian part of the formation is less than 200 m thick. The mudstone-dominated succession contains numerous coals up to 3 m thick, alternating with sandstone, siltstone and thin limestone (Whitbread and Kearsey 2016). Abrupt facies changes are observed with sand-rich facies up to 40 m thick interpreted as channel fill. These fluvial facies and feeder channels have been interpreted as the riparian zone of a major deltaic system that occupied the North Sea region at that time, passing southwards to delta-front and marine settings (Kearsey *et al.* 2019a).

Western Scotland and offshore

In western Scotland and islands, attenuated Clackmannan Group successions are exposed on Arran and in Machrihanish and are interpreted in the offshore Rathlin Trough through to the Ballycastle Coalfield in Northern Ireland (Fig. 10.1). With thicknesses of 280 m on Arran and 202 m at Machrihanish the onshore successions have similarities to that around Ayr (Waters *et al.* 2011).

Southern Uplands

During the Namurian, provenance, faunal and sedimentological studies indicate that the Southern Uplands High remained an effective barrier between the MVS and southern Scotland, and was a sediment source area for southern Ayrshire (Stedman 1988; Fig. 10.29) and northern England (Tyrrell *et al*., 2006). In the Thornhill Basin, up to 25 m of the Enterkin Mudstone Formation contains marine fauna of Brigantian and possibly Pendleian age (McMillan 2002).

Northumberland–Solway Basin

Thermal subsidence in this basin during the Brigantian to Arnsbergian interval resulted in more-uniform patterns of sedimentation with *c.* 600 m near Canonbie, thickening to *c.* 1100 m in the NE-trending Solway Syncline (Fig. 10.3) and in eastern Northumberland (Chadwick *et al.* 1995; Frost and Holliday 1980; Waters *et al.* 2014). Yoredale-type marine to terrestrial cycles continued apparently uninterrupted during this time and thickness differences are due largely to compaction and the accumulation of greater volumes of clastic detritus in the basin centre. However, the limestone component of each cycle is remarkable in its almost ubiquitous presence and similar thickness across the basin. In the early Namurian, shallow water depths and a more prolific benthic marine fauna in the east of the basin were noted by Brand (2011).

North of the Scottish border, rocks of this time interval crop out only near Annan and around Canonbie (Fig. 10.3b) and are assigned to the upper part of the Alston and the overlying Stainmore formations (Fig. 10.7). This succession is best known from the Archerbeck (Lumsden and Wilson 1961), Rowanburnhead and Woodhouselees boreholes (Waters *et al*. 2014).

The sedimentary cycles in the Alston Formation are better developed than in the underlying Tyne Limestone Formation and are typically 10–25 m thick in the Archerbeck Borehole (Fig. 10.24b). The limestones are rich in corals, crinoids, brachiopods, bivalves and foraminifers and vary from 3.5 to 13.7 m thick, except for the uppermost Great Limestone which is 22.5 thick. The succession above each limestone typically coarsens upwards with the uppermost part containing plant debris, roots and coal (Lumsden *et al.* 1967).

The clastic rocks overlying the Great Limestone and the succeeding Little Limestone cycle at the base of the Stainmore Formation resemble those of the Alston Formation (Fig. 10.24c). However, the limestone beds in the upper part of the formation are less than 2 m thick and commonly sandy. The Penton Coals comprise a dominantly terrestrial unit, about 43 m thick (Fig. 10.24c). Rising sea levels within the Penton Coals are indicated by the sparse fauna of *Lingula* and fish fragments. A sandstone unit, 14 m thick, beneath the Penton Coals might represent fluvial channel deposits. With this exception, the Solway succession seems to have been affected by fewer Pendleian and Arnsbergian fluvial channel systems than the eastern part of the Northumberland–Solway Basin (Waters *et al.* 2014, fig. 12a).

TS5 Mid Namurian to earliest Westphalian (mid Arnsbergian–early Langsettian): fluvial influx and incision

Uplift and erosion in east Greenland resulted in a major fluvial influx of coarse-grained sandstone across the North Sea and northern Britain during the Kinderscoutian (Millstone Grit; Morton and Whitham 2002; Lancaster *et al.* 2017; Fig. 10.6c). Together with a global eustatic lowstand at the Mississippian–Pennsylvanian 'mid Carboniferous break' (Fig. 10.5, mega T-R trends column) this resulted in fluvial influx, incision and local unconformities in Scotland. In the Midland Valley (MVS), Passage Formation strata deposited during TS5 are dominated by fluvial sandstones and subordinate marine incursions. A relatively thin succession (0–350 m) deposited during 6 million years contains several unconformities recognized by locally absent marine bands and limestones (Fig. 10.4). Channel belts carry assemblages of heavy minerals derived from different parts of the Highlands (Muir 1963) and record southerly to south-westerly palaeocurrents (Read 1989b; Hooper 2003). Although the depositional environment was predominantly fluvial, a stratigraphical framework is provided by sporadic marine bands. Very rare ammonoids, together with spores from coals closely associated with the marine bands have enabled the succession to be subdivided at regional substage level (Neves *et al.* 1965; Fig. 10.4). During this time, fluvial sandstones, overbank claystones and coals indicate that the climate may have been monsoonal with intense seasonal rainfall and fluctuating river flows and water tables (Read 1989b).

Cyclic, marine-influenced sedimentation continued in the Solway area (Stainmore Formation), whilst farther east in Northumberland coarse fluvial sandstones of the Millstone Grit Group were deposited on a sandy braidplain (Waters *et al.* 2014; Fig. 10.6c). This major fluvial system seems not to have reached the Solway region.

Structural development

Sedimentary and volcanic rocks from the MVS provide evidence for dextral transpression becoming the increasingly dominant structural control during TS5, with both local inversions and synclinal basin development. For example, structures in the coal-bearing Namurian–earliest Langsettian Passage Formation of the Westfield Basin of Fife (Fig. 10.3a) provide spectacular evidence of syn-sedimentary, NE-trending growth folding in the hanging wall of the East Ochil Fault (Underhill *et al.* 2008; Fig. 10.22a). Over a distance of about 250 m, strata thicken from 28 m on its flanks to 130 m in the core of the syncline (Brand *et al.* 1980). Farther east along the East Ochil Fault, the Earl's Seat Anticline developed by inversion of an earlier basin (Read 1988; Ritchie *et al.* 2003; Underhill *et al.* 2008). Similar, large-scale seismic geometries are observed offshore in the Midlothian–Leven Syncline and Forth Anticline (Fig. 10.22b). In the Central Coalfield, the NNW-trending Salsburgh Anticline developed following deposition of the No. 2 Marine Band (Arnsbergian), and dividing the Uddingston Syncline in the Lanarkshire Basin and southern parts of the Clackmannan syncline (Fig. 10.3; Read 1989b). The resultant N–S-orientated fabric represents a change in dominance in the tectonic pattern of the Central Coalfield that continued through the Coal Measures, from the former NE- to ENE-trends that had influenced earlier sedimentation in the Lanarkshire Basin and Kilsyth Trough.

At the regional scale, preserved thicknesses of 0–350 m for the Passage Formation are dominantly found in the approximate N–S coalfield basins (Read 1988). In several areas, thickness variations and structural development continued similar to TS4, for example an attenuated succession in central and northern Ayrshire, excepting the basaltic lavas of the Troon Volcanic Member, and control by NE- to ENE-orientated fault blocks (Monro 1999; Smith *et al.* 2013; Table 1; Fig. 10.4). In the central MVS, relatively complete sections occur in the centre of the Kincardine Basin Fig. 10.22d; Forsyth *et al.* 1996; Read *et al.* 2002) along with continued deposition in and around the Midlothian–Leven Syncline in Fife and the Lothians.

Arnsbergian marine bands and the Castlecary Limestone, the top of which marks the regional base of the Passage Formation, are missing near the growing Salsburgh Anticline and the succession is significantly attenuated south of the Wilsontown Fault (Read 1988; Fig. 10.3b for structural features). Deep incision of the Castlecary Limestone by fluvial channel systems trending west-southwestwards also occurred in the south of the Kincardine Basin (Read 1989b, fig 4b). Farther south in the Douglas Basin, Lumsden (1967b) described angular unconformities in the Kennox Fault footwall, and at the local base and the top of the Passage Formation in the fault hanging wall. The intervening succession is up to 225 m thick, with four unusually thick Manson Coal seams (each 1.4–2.5 m) suggesting active localized subsidence (Browne and Leslie 2015).

In late Namurian times, the continued patterns of subsidence and growth folds in the MVS together with unconformities appears consistent with regional dextral transpression, as illustrated in the 'late Carboniferous' model of Coward (1993; Fig. 10.1b). In contrast, the Northumberland–Solway Basin appears relatively quiescent, with continued thermal subsidence.

Igneous activity

Basaltic volcanism continued locally through TS5 (Figs. 10.4, 10.5). In Ayrshire, the Troon Volcanic Member comprises olivine-basalt lavas with intercalations of tuff and sandstone. Sedimentary intercalations have yielded spores of Kinderscoutian to Marsdenian age (Monro 1999). Subsequent subaerial weathering and erosion of the lavas, followed by the transportation of some of the resulting volcanic detritus, produced the high-alumina Ayrshire Bauxitic Clay Member worked for the chemical industry (Monro *et al.* 1983; Monro 1999; Browne *et al.* 1999). Namurian lavas also occur on Arran and at Machrihanish and Loch Ryan (Fig. 10.16). In the Westfield Basin, Fife, highly decomposed olivine-basalt lavas up to 38 m thick are overlain by mottled clayrock. Largely explosive volcanism continued throughout the deposition of the Passage Formation in the Largo Law area in east Fife (Fig. 10.4).

Regional development

Midland Valley

At the start of TS5, the Castlecary Limestone was subaerially weathered and dolomitized locally, or eroded by deeply incised fluvial channels filled with coarse-grained pebbly sandstones of the Passage Formation (Cameron *et al.* 1998, Read 1988; Fig. 10.4). In the Central Coalfield, deposition continued with three persistent late Arnsbergian marine bands, Nos 0, 1 and 2, each mainly containing a limestone and underlain by a thin coal (Fig. 10.32b). Each of these bands is eroded locally by the base of the overlying sandstone. Above the No. 2 Marine Band, a meandering-river environment is interpreted producing thick, leached, overbank mudstones with mature palaeosol profiles. These Glenboig Lower Fireclays were formerly extensively worked as high-alumina refractories. Above the Lower Fireclays a cluster of four closely-spaced marine bands, underlain by thin coals, and collectively termed the Netherwood or No. 3 Marine Band group (Fig 10.32b), are known to be Kinderscoutian. The Chokierian and Alportian substages are not recognized and it seems probable that the Mississippian–Pennsylvanian break identified in North America, lies at the base of, or within, this interval (Read 1989b; Fig. 10.5). Above the No. 3 Marine Band group (Fig. 10.31), a braided river depositional environment is interpreted. This dominantly sandstone succession is interrupted by two impersistent marine bands, the No. 5 and No. 6 Marine Band groups (Fig 10.32a; Read 1989b; Cameron *et al.* 1998). The sparse marine fauna indicates that all but the topmost band of No. 6 group probably belong to the Marsdenian. The topmost band may represent the Subcrenatum Marine Band at the base of the Westphalian (Neves *et al.* 1965). Another cluster of clayey palaeosols, formerly worked as refractories and collectively known as the Bonnybridge Upper Fireclay, interrupts the sandy basal Langsettian succession between No. 6 Marine Band group and the base of the Scottish Coal Measures Group. These palaeosols are associated with the thick but impersistent Bowhousebog Coal.

In the Midlothian–Leven basins, fluvial facies dominate, with northerly and easterly sourced sediment (Muir 1963). The Castlecary Limestone has generally been preserved intact and most of the marine bands are represented, with the exception of Midlothian where the No. 5 group is locally reduced to a single marine band and No. 6 group is missing.

Southern Uplands

Whilst the Southern Uplands continued to form a barrier between the MVS and the Northumberland–Solway Basin, limited deposition occurred in the Sanquhar and Thornhill outliers (Fig. 10.3a). At Sanquhar, a mudstone containing a marine band allows possible correlation with the Passage Formation. At Thornhill, the Passage Formation is represented by about 40 m of pebbly sandstone and siltstone disconformably overlying Brigantian strata (McMillan 2002).

Offshore Scotland

The Firth Coal Formation in Quadrants 20 and 21 contains palynological evidence for strata as young as Kinderscoutian, indicating the long-lived persistence of a Carboniferous fluvial–coal mire depositional environment described in TS4. The Firth Coal Formation lacks evidence of marine incursions suggesting in this area the apex point of the deltas system has been passed and the sediments were deposited on the riparian strip (Kearsey *et al.* 2019a). In the Forth Approaches Basin (Fig. 10.1), 126 m of sandstone in exploration well 26/08-1 are correlated tentatively with the Passage Formation in the MVS and to the Millstone Grit Formation that is widely recognized on the southern side of the Mid North Sea High (Kearsey *et al.* 2019a; Fig. 10.8).

Northumberland–Solway Basin

Thermal subsidence of the basin continued through late Namurian times, with cyclic Yoredale-type sediments of the Stainmore Formation accumulating in the Solway region. In the lowest part of the Woodhouselees Borehole are several units of shelly mudstone and thin limestone. Waters *et al.* (2014) interpreted the lowest two of these as the Thornbrough and Newton Limestone of early-Arnsbergian age (E_{2a} and E_{2b} zones respectively) and the uppermost group of beds, lying about 37 m above these as the Dipton Foot Shell Beds at the base of the Kinderscoutian (Brand 2011). However, palaeontological evidence for the presence of the late Arnsbergian, Chokierian and Alportian substages is elusive. The reason for such a thin succession at this time – seen throughout northern England – is not understood fully, but it may represent a condensed sequence or may contain unrecognized unconformities such as an incised valley.

TS6 Westphalian: rivers, deltas and coal mires

The Scottish and Pennine Coal Measures groups are dominated by repeated, generally upward-coarsening, fluvio-deltaic cycles of mudstone, siltstone, sandstone, commonly capped by seatearth palaeosol and coal (Fig. 10.32c,d). These indicate that during the Westphalian (TS6), the Midland Valley (MVS) and Northumberland–Solway Basins were on the northern edge of a vast, flat, alluvial delta plain which covered much of NW Europe (Opluštil and Cleal 2007). Deltaic, fluvial and poorly-drained floodplain facies associations (Hooper 2003) represent the lateral switching of rivers, delta lobes and the establishment of coal mires within a tropical equatorial climate.

Carboniferous basins in England and Wales record a change in sediment provenance in the Westphalian with the appearance of heavy mineral populations and detrital zircon ages switching from a northern provenance to a source from the west and subsequently from the uplifting Variscan mountain front to the south (Hallsworth *et al.* 2000). In contrast, in the MVS the rivers were still inferred to be from a Paleozoic Caledonian (Highlands) source located to the NW and a north-easterly (Greenland) source, combined with intrabasinal sediment recycling (McKenna 2021). Fluvio-deltaic complexes typically show southwestwards progradation in Fife and Midlothian, with palaeocurrent data indicating a switch to southerly direction in the central and western MVS (Read 1988; Hooper 2003). Together with the Coal Measures succession in the Sanquhar Basin in the Southern Uplands, these palaeocurrent directions suggest that the Southern Uplands high may have been breached.

The thickest and most complete Coal Measures successions have been preserved within the MVS (Table 1). Notable successions are also present at Sanquhar and in the Canonbie Coalfield, in the Solway area. Coal seams are well developed in the Scottish Lower and Middle Coal Measures, and up to 20 seams have been worked extensively (Cameron and Stephenson 1985).

The Scottish Upper Coal Measures lack significant coals due to a shift in facies to a less waterlogged, fluvially-dominated environment. Some well drained palaeosols containing nodular pedogenic carbonate are present (Dean *et al.* 2011). A similar change to primary red-beds (Oxisols) in the Asturian–Stephanian Warwickshire Group succession of the Solway region (Fig. 10.7) has been taken (e.g. Jones *et al*. 2011) to represent a major shift to a drier and more-seasonal climate.

Structural development

Whilst repeated alluvial plain lithofacies and a reduced variability in thickness indicate widespread subsidence of a low-lying palaeotopography between the Highlands and Southern Uplands highs in TS6, syn-depositional growth of NNE-trending synclines and anticlines (central and eastern MVS, Solway) and across NE-trending fault blocks (western MVS) accompanied basin subsidence (Fig. 10.10d). Examples include thickening into the Midlothian–Leven Syncline (Fig. 10.22b) and post-Namurian formation of the smaller Earl's Seat Anticline and Thornton–Balgonie Syncline (Underhill *et al.* 2008; Fig. 10.3b). In the Central Coalfield, thinning of strata on to the growing Salsburgh Anticline continued through to the Bolsovian (Hooper 2003), dividing the southern Clackmannan Syncline from the Lanarkshire Basin. In contrast, in the western MVS, sedimentation in a half-graben and a horst block bounded by active east- to NE-trending structures continued, such as south of the Kerse Loch Fault in the Littlemill Basin (Mykura *et al.* 1967; Figs 10.21c, 10.22c).

In the MVS, tightening of NNE-trending folds and the creation of other north- and NW-trending folds occurred during later parts of the Westphalian (Mykura *et al.* 1967; Rippon *et al.* 1996; Fig. 10.10d), together with development of a late Westphalian to Stephanian unconformity, discussed further in TS8 below. During this time, volcanism was largely absent, except in the Leven Basin where tuffs are interbedded with the Scottish Lower and Middle Coal Measures formations (Fig 10.4).

The MVS pattern of growth folds and faults active at the same time is consistent with dextral transpressional tectonics (Ritchie *et al.* 2003; Underhill *et al.* 2008). Regionally, this accords with re-insertion of the Baltica continental block (Coward, 1993) and to compressional stress fields during the peak of the Variscan Orogeny (Corfield *et al.* 1996; Howell *et al.* 2021), discussed further in TS8.

To the south of the Southern Uplands in the Northumberland–Solway Basin, strata thicken into the NNE-trending Solway Syncline; ENE-folds and three separate unconformities have been recognized and related to NE–SW-directed transpression in the Variscan Foreland (Howell *et al.* 2021).

Climatic controls and faunal changes

During TS6, Scotland lay in the 'everwet' equatorial climatic belt of the Euramerican floral province (Fig. 10.5; Opluštil and Cleal 2007). Plant communities have been linked to specific depositional environments using macrofloral and spore evidence, mostly from the Duckmantian (Scott 1977, 1979). Peat mires in coal swamps were dominated by lycopods, especially *Lepidodendron* and *Sigillaria*. Drier environments away from coal swamps were dominated by seed ferns along with *Cordaites*, lycopods, sphenopsids and true ferns (Scott and Galtier 1985). A varied floodplain flora was dominated by seed ferns, with some sphenopsids and lycopods, whilst seed ferns also grew on the better drained channel levees. *Calamites*, which had a creeping rootstock, was able to colonize unstable environments such as river point bars and lakesides.

It has been suggested that during the later Westphalian and the succeeding Stephanian stages, Scotland moved from the 'everwet' equatorial climatic belt into a markedly seasonal regime, and towards the end of the Carboniferous, into a semi-arid zone. Previously, this was thought to be a rain-shadow effect caused by the rising Variscan mountains to the south (Maynard *et al.* 1997; Warr 2000). However, more recent studies (Tabor and Poulsen 2008; Tabor *et al.* 2008; DiMichele *et al.* 2009) have suggested that the climatic change was driven by global factors, including changes in ocean circulation, falling concentrations of atmospheric carbon dioxide and glaciation in Gondwana. This led to the collapse of the lycopod ecosystem which dominated the coal mires (DiMichele *et al.* 2009) and occurred at a time that approximated to the Scottish Middle to Upper Coal Measures formation boundary. Tree ferns like *Psaronius* appeared in the Westphalian and became abundant in the Stephanian. *Cordaites*, which is thought to be closely related to conifers, continued into the Stephanian.

An extensive coal-swamp vertebrate fauna has been recorded from the Scottish Coal Measures (Clack 2012). This includes many actinopterygian fish species along with chondrichthyans and acanthodians, particularly from north Lanarkshire (Elliott 2018). The fauna also includes lungfish (Sharp and Clack 2013; Beeby *et al*. 2020) and tetrapods. With one exception, none of the pre-Westphalian tetrapod genera are present (Smithson 1985). Diversification among the tetrapods had intensified by Westphalian time with representatives of most of the major groups seen here recorded from across Europe and North America (Clack 2012).

Regional development

Midland Valley

The three constituent formations of the Scottish Coal Measures Group are separated by marine bands and are of variable thickness (Table 1; Fig. 10.32c). Cyclical fluvio-deltaic deposits of the Scottish Lower Coal Measures Formation succeeded the sandy braided river deposits of the topmost Passage Formation. The earliest cyclical deposits include sporadic marine incursions and erosively based fluvial sandstones, the latter most common in the Midlothian–Leven areas. Locally, over 4 m-thick coals occur just below and above the base of the Scottish Coal Measures Group around Musselburgh and Kirkcaldy (Browne and Woodhall 2000). Later deposits tend to be more clay rich and contain *c.* 1.5 m-thick coals but no marine bands. Many individual coals can be traced from Glasgow eastwards to Falkirk and westwards into Ayrshire (Forsyth and Brand 1986; Waters *et al*. 2011, p. 101; McLean 2018).

The base of the Scottish Middle Coal Measures Formation is marked by the base of the Vanderbeckei Marine Band. It represents an extensive marine transgression and contains a varied fauna, locally including ammonoids. Many *c.* 0.5–2 m-thick coals have been mined in the cyclical fluvio-deltaic succession. In the Central Coalfield, thick coals dominate the lower part of the formation, with marine and *Lingula* bands, siltstones and claystones interpreted as tidal bay, lagoon and flat deposits, distributary mouth bar sandstones, and thick, erosive-based, channel sandstones (Fig. 10.32c,d), including the prominent Shettleston Sandstone in upper parts (Forsyth *et al.* 1996). The *Lingula* bands are notable as the shells are normally graded, flow aligned and occasionally show imbrication. This suggests they were deposited by a flow event, or events, which may have carried the shells a considerable distance. The thickest coals have a well-developed seatearth below them and thus are considered to be Histosols (Kearsey *et al.* 2019b). Minor marine incursions culminated in the major transgression of the Aegiranum Marine Band, the base of which marks the base of the overlying formation.

The Scottish Upper Coal Measures Formation is preserved in the centre of synclinal basins. The Uddingston Syncline, Lanarkshire Basin succession is typical, with 80 m of cyclical fluvio-deltaic deposits with thin coals and thick channel sandstones underlying the Shafton (Bothwell Bridge) Marine Band. Succeeding strata are mostly reddened, include cyclical intervals, erosive-based sandstones and poorly bedded mudstones. Reddening may be primary, related to periods of lowered water table and pedogenesis during deposition, and/or secondary relating to oxidation beneath the Variscan unconformity (Mykura *et al.*, 1967). Thicker successions are preserved in the Douglas and Midlothian–Leven synclines (Table 1). Non-marine bivalve assemblages of the *Anthraconauta phillipsi* Zone and part of the *Anthraconauta tenuis* Zone have been identified in SW Ayrshire (Mykura *et al.* 1967) placing these strata in the Asturian Substage with possible partial equivalence to the Warwickshire Group (Waters *et al.* 2011).

Western Scotland and offshore

Coal Measures are present in the Firth of Clyde (McLean and Deegan 1978) and surrounding areas. At Machrihanish, coals in the Scottish Lower and Middle Coal Measures formations are locally of workable thickness and both the Vanderbeckei and Aegiranum marine bands are present. On Arran, Scottish Lower and Middle Coal Measures formations are dominated by multi-storey channel bodies and overbank deposits containing crevasse splays and Vertisols; these represent a basin marginal sequence (Kirk 1989). Other small Carboniferous outliers to the NW of the Highland Boundary Fault, such as at Ininmore Bay on the Sound of Mull (Fig. 10.2; Love and Neves 1963), mostly belong to the later Carboniferous .

Offshore eastern Scotland, *c.* 180 m of Westphalian Coal Measures-type strata occur in exploration well 26/08-1 in the Forth Approaches Basin (Kearsey *et al.* 2015). No Westphalian strata are preserved in wells beneath the Permian unconformity in the Outer Moray Firth–south Buchan Basin (Whitbread and Kearsey 2016); farther afield in Quadrants 31 and 39, the Flora Sandstone has been ascribed a Bolsovian–Asturian age (Martin *et al*. 2002). Provenance data suggest some sediment at this time was sourced from East Greenland, and it seems likely that rivers continued to flow through that area.

Southern Uplands

Isolated Westphalian outliers aligned on NW-trending lineaments preserve relicts of what might formerly have been a more extensive, albeit attenuated, succession in the Southern Uplands. In the Sanquhar Coalfield just south of the Southern Upland Fault (Fig. 10.3), more than 600 m of Coal Measures, representing depositional environments closely similar to those in the MVS have been preserved. Worked coals are present in the Scottish Lower and Middle Coal Measures but most of the Upper Coal Measures is reddened (Stone *et al.* 2012). At Thornhill, the reddened Scottish Lower, Middle and Upper Coal Measures are *c*. 160 m thick. The basin is attributed to dextral strike-slip on NE-trending faults (McMillan and Brand 1995). The poorly exposed Coal Measures strata in the Loch Ryan Outlier (Fig. 10.16) also include basaltic lava.

Northumberland–Solway Basin

More than 1600 m of strata assigned to the Pennine Coal Measures and Warwickshire groups are preserved within the NNE-trending Solway Syncline and between the NE–SW-orientated Gilnockie and Hilltop faults (Figs. 10.3, 10.7). The Canonbie Coalfield, which was worked until early in the twentieth century, is exposed at the north end of the structure, becoming concealed beneath Permo-Triassic rocks to the SW.

The Subcrenatum Marine Band, defining the base of the Pennine Coal Measures Group in England, is absent from the coalfield, probably because of non-deposition. However, evidence supporting disconformity at this junction, additional to absence is equivocal. The markedly divergent dips exposed in the River Esk at Gilnockie Bridge cited by Lumsden *et al.* (1967), were alternatively interpreted by Jones and Holliday (2016) as multiple phases of localized, syn-sedimentary fluvial channel-bank collapse within Coal Measures strata. A second explanation, by Picken (1988), interpreted borehole and seismic reflection data to show the progressive overstep of Coal Measure strata on to Stainmore Formation. However, Picken's cross-section is drawn sub-parallel to the Gilnockie Fault, and Howell *et al.* (2021) concluded that the apparent unconformity surface is the subsurface intersection of that fault.

The Pennine Lower Coal Measures Formation is 30 to more than 50 m thick (Howell *et al.* 2021). The lower part is mostly sandstone, overlain by mudstones with two thin coals. The Vanderbeckei Marine Band, the base of which marks the base of the Pennine Middle Coal Measures Formation is represented by a *Lingula* band containing fragments of fish. Higher in the succession the Aegiranum Marine Band denoting the base of the Bolsovian Substage contains *Lingula*, *Orbiculoidea*, conodonts and abundant foraminifera (Lumsden *et al.* 1967). The Middle Coal Measures contains 11 coals, each 0.6 to 1.7 m thick, but with compound units up to 4.3 m thick of coals with interbedded seatearths.

The base of the Pennine Upper Coal Measures Formation is taken at the top of the Cambriense Marine Band, which is 58–73 m above the Aegiranum Marine Band, the base of the Scottish Upper Coal Measures Formation in the MVS. The Pennine Upper Coal Measures Formation consists mainly of grey mudstone with thin sandstones, some coals, *Spirorbis* limestones and conchostracan (‘*Estheria*’)-rich mudstones (Jones *et al.* 2011). The coals and gley-type palaeosols indicate a dominantly waterlogged environment. Non-marine bivalves characteristic of the *Anthraconauta tenuis* Zone have also been recorded from the upper part of the formation, indicating that these strata are Asturian (Lumsden *et al.* 1967).

Both the Pennine Middle and Upper Coal Measures thicken generally SE toward the Hilltop Fault, though both are thickest in the axial region of the syncline. Thicknesses of the Middle Coal Measures are from about 150 m to more than 300 m and from less than 50 m to more than 300 m for the Upper Coal Measures (Howell *et al.* 2021). Seismic reflection data indicate that these thickness changes are related to a Duckmantian episode of NE–SW-directed transpression resulting in unconformity. This caused mild northwestwards inversion of the western limb of the Solway Syncline above the Gilnockie Fault at 1–2 km depth and contemporaneous growth of low amplitude ENE-trending syn-depositional folds. Strong reflectors indicate the presence of the unconformity with the northeasterly overstep of Middle Coal Measures strata that lie above the Archerbeck Coal and the succeeding lower part of the Upper Coal Measures, such that the upper part of the Upper Coal Measures rests on Middle Coal Measures at about the level of the Archerbeck Coal (Howell *et al.* 2021; Waters *et al*. 2011, fig. 42).

The Warwickshire Group (Fig. 10.7) is known from boreholes and a section in the River Esk (Jones *et al.* 2011). The succession is 530 m thick in the Becklees Borehole beneath Permo-Triassic strata, but up to 1000 m may be preserved in the axial region of the Solway Syncline. Mudstones from the lowest strata at outcrop contain a non-marine bivalve fauna indicative of an Asturian age (Barrett and Richey 1945), but biostratigraphical control on higher parts of the group is lacking and these may be significantly younger (Howell *et al.* 2021). The defining characteristic of the group is the presence of red palaeosols containing pedogenic carbonate, as distinct from strata that were secondarily oxidized beneath the unconformity (Jones *et al.* 2011).

Three formations were defined by Jones *et al.* (2011). The lowest is the Eskbank Wood Formation, 145–175 m of dominantly grey lacustrine mudstone, some thin coals, along with Oxisols and gley-type palaeosols and a few calcretes. Thin limestones suggest areas of shallow, well oxygenated fresh-water lakes. There are a few minor channel sandbodies, overbank and thin crevasse splay deposits. The environments represent complex alternations of wetland and well drained alluvial plain.

Coarse-grained lithic arenite sandstone interbedded with alluvial mudstone, Oxisols and a few Vertisols and calcrete palaeosols characterize the overlying 131–168 m thick Canonbie Bridge Sandstone Formation. Some sandstone units form multi-storey sandbodies up to 50 m thick and palaeocurrent data indicate that the rivers flowed towards the NNW (Jones *et al.* 2011). Heavy-mineral compositional analyses and the age population of zircons from the sandstone are similar to those in the coeval Halesowen Formation in the West Midlands (Morton *et al.* 2010; Jones *et al.* 2011). These data indicate that sediment was derived from the Variscides of central or western Europe and the formation represents the farthest north that such sediment is known to have reached.

An unconformity separates the Canonbie Bridge Sandstone from the overlying Becklees Sandstone Formation which is described in TS7.

TS7 Stephanian: Variscan unconformity to post-orogenic extension

A widespread latest Carboniferous unconformity exists above folded Upper Coal Measures formations. Fold tightening and fault inversion (Rippon *et al.* 1996; Underhill *et al.* 2008) occurred in response to peak Variscan orogenic events and re-insertion of the Baltica continental fragment causing dextral transpression across Scotland (Coward 1993; Fig. 10.1b). Late Carboniferous regional dextral movement is also recognized in northern Scotland with wrench and contractional domains related to the Walls Boundary Fault (Armitage *et al.* 2021) and Great Glen and related faults (Speight and Mitchell 1979; Underhill and Brodie 1993; Kemp *et al.* 2019; Dichiarante *et al.* 2016).

In the Canonbie coalfield to the south of the Southern Uplands, deposition of the Warwickshire Group, folding and inversion persisted into the Stephanian (Fig. 10.10e), interpreted as a response to dextral oblique slip and compression in the Variscan foreland (Chadwick *et al.* 1995; De Paola *et al.* 2005; Howell *et al.* 2021).

Subsequently in the Midland Valley (MVS) and offshore eastern Scotland, ENE-trending tholeiitic dykes and extensional faults cut across tightened and inverted Carboniferous basins (Fig. 10.10e; Cameron and Stephenson 1985; Rippon *et al.* 1996). MVS tholeiitic dykes and sills were emplaced along east-trending fault planes and are also offset by them (Browne and Woodhall 2000; Stephenson *et al.*

2003), consistent with intrusion and extension occurring at the same time during the first stages of post-Variscan extension.

Across NW Europe, Stephanian to early Permian post-orogenic extension occurred in response to the gravitational collapse of the Variscan Orogen and far-field extensional stress between the Gondwana and Laurentian plates (Ziegler 1990; Timmerman 2004). The approximately east–west-orientated structures in Scotland associated with a tholeiitic magmatic phase are approximately perpendicular to the trend of the regionally extensive NW- to NE-trending rift systems that followed in TS8 (e.g. Oslo Graben; Coward 1995; Neumann *et al.* 2004).

Midland Valley structural development

The major synclinal structures shown on the depth map to the base of the Scottish Coal Measures Group (Fig. 10.21c) highlight the syn- and post-depositional folding that affected these strata. Evidence of post-depositional fault inversion includes the northwesterly dipping, steep, reverse Pentland Fault, with Carboniferous strata on its southeastern side tilted to vertical or locally overturned (British Geological Survey 2003; Underhill *et al.* 2008). Post-depositional folding examples also include the Forth Anticline in the Firth of Forth, and the D'Arcy-Cousland Anticline in Midlothian (Fig. 10.3b, 10.10e; Hallett *et al.* 1985; Ritchie *et al.* 2003; Underhill *et al.* 2008). Isopach maps in the Midlothian Syncline show the Carboniferous depositional axis oblique to the fold structure (Tulloch and Walton 1958), and the axial traces of some anticlinal folds become curved to the NE towards their northern termination at east-trending faults (e.g. Earl's Seat Anticline). In Fife, NNE-trending folding affects upper Visean- and lower Namurian rocks adjacent to the steep, NE-trending Ardross Fault (Fig. 10.3) consistent with dextral transpression (McCoss 1988). The transpressional phase must have ended by Stephanian to Permian times because volcanic vents of this age along the faults cut the folded strata (Forsyth and Rundle 1978).

Structural geometries show these late Carboniferous folds are transected by E–W-striking dykes and extensional faults (Fig. 10.10e). Structures such as the Roslin–Vogrie Fault in Midlothian, Leven Fault in Fife, and Abbey Craig Fault in Clackmannan offset folded Scottish Middle and Upper Coal Measures strata (British Geological Survey 1974, 1999, 2003). The E–W-trending faults are steeply dipping and, in some cases, the downthrown side changes along the fault length.

The thermal maturity of organic material in coals and carbonaceous mudstones in Carboniferous rocks of central Scotland, and their compaction, indicates that 1.7–1.9 km of strata have been removed (Raymond 1991; Vincent *et al.* 2010; Monaghan 2014). Until recently, the timing of maximum burial, uplift and erosion had been speculative because, with the exception of the Mauchline Basin Permian strata, the post-Carboniferous depositional record onshore is missing. However, a recent study using apatite fission-track techniques has shown that the maximum depth of burial was attained in latest Carboniferous–early Permian times (McKenna 2021). Thus, TS7 is a turning point from basin formation and burial, to uplift and erosion from the Permian onwards, consistent with post-Variscan extensional basins developing offshore. Values of post-Carboniferous denudation were estimated at 1.2–2 km dependent on location using the apatite fission-track method (McKenna 2021).

Magmatism: late Carboniferous tholeiitic sills and dykes

The dominant alkaline basic magmatism was interrupted in late Carboniferous times by a brief period in which silica-oversaturated tholeiitic magmas were emplaced (Stephenson *et al.* 2003, p. 27; Fig. 10.5). Voluminous high-level intrusions form the Midland Valley Sill-swarm (Fig. 10.33), which is associated with one of the major dyke swarms of NW Europe, extending from the Outer Hebrides eastwards at least as far as the Central Graben of the North Sea (Smythe 1994). This episode may be related to the earliest lavas of the late Carboniferous–early Permian rift of the Oslo region and other tholeiitic rocks of similar age in southern Sweden (Smythe *et al.* 1995; Kirstein *et al.* 2006).

In Scotland the tholeiitic dykes cut rocks ranging from Archaean to the Scottish Upper Coal Measures and the sills intruded Upper Devonian to Scottish Middle Coal Measures strata. Blocks of quartz-dolerite occur in subvolcanic necks in east Fife, which are considered to be early Permian in age, and in the western Highlands camptonite dykes cut quartz-dolerites. The U–Pb radiometric date of 307.6±4.8 Ma (Monaghan and Parrish 2006) indicates intrusion during late Westphalian to early Stephanian times.

The dyke swarm occurs across a 200 km-wide zone that stretches for over 300 km from Barra in the Outer Hebrides and Kintyre in the west, to the east coast between Peterhead and Dunbar. Regionally the swarm is arcuate, trending 110° on the west coast, east–west in the central MVS, and 070° along the NE coast (Fig. 10.33). Locally some dykes are deflected to a NE trend along the Highland Boundary Fault. Individual dykes average 30 m in width but may reach up to 75 m, and may be traced as *en echelon* offsets for up to 130 km. In the MVS, the dykes were emplaced partially along active or recently active east–west faults (Read 1959). An intimate relationship between faulting, multiphase dyke emplacement and mineralization has been demonstrated in the Bathgate Hills (Stephenson 1983) and elsewhere. In the Westfield Basin, intrusion of quartz-dolerite pre-dated east–west faulting. In contrast, to the east of Edinburgh east–west quartz-dolerite dykes cut across and thus post-date east–west-striking faults (British Geological Survey 2003).

The Midland Valley Sill-swarm

These sills underlie an area of about 1920 km^2 around the inner Firth of Forth and have an estimated volume of over 125 km^3 (Fig. 10.33; Stephenson *et al.* 2003, p. 217). In places, the composite thickness is about 200 m, commonly consisting of several leaves, 25 to 100 m thick and linked by transgressive dyke-like intrusions along pre-existing fault planes (Francis 1982). The sills form many prominent landmarks, such as the Lomond Hills and Benarty Hill in Fife, Cockleroy Hill and Carribber Hill in the Bathgate Hills, and the Castle Rock and Abbey Craig at Stirling.

The thicker sills increase in grain size from the chilled margins to the centre and a pegmatitic zone may be developed about one third of the way down from the top. Patches and veins of pink, fine-grained quartzo-feldspathic material are also common. Veins of fine-grained basalt from later pulses of magma occur in both sills and dykes. Sharp and sometimes uneven contacts of the sills and dykes with their host sedimentary rocks provide evidence that the sediments were lithified prior to intrusion (Fig. 10.34) Thermal aureoles of up to 500 m have been shown by the marked effect on organic maturation in adjacent lithologies (Murchison and Raymond 1989; Raymond and Murchison 1991).

Field and geochemical evidence (Macdonald *et al.* 1981), strongly suggests that the Midland Valley Sill-swarm was fed by the associated dykes. This relationship was explained by Francis (1982) and developed by Goulty (2005), who suggested that the sills were emplaced into the sedimentary basins at a lower structural level than the upper limit of dyke emplacement. Analysis of the variation in sill thickness with intrusion depth led Goulty (2005) to estimate that the hydrostatic head of magma was about 100 m below the ground surface on completion of the intrusion and argued that sill emplacement was probably accompanied by flood basalt effusion, all traces of which have been removed by erosion.

Like the alkaline basic intrusions, the tholeiitic sills and dykes have been altered, locally forming zones of 'white trap'. In the Bathgate Hills, where dykes have passed through oil-shale-bearing strata, sticky black hydrocarbon deposits occur in calcite veins and as a coating to joints (Parnell 1984). In the Ochils, the Bathgate Hills and the Renfrewshire Hills, dykes have acted as both a heat source and a channel for the circulation of metalliferous brines, and some have mineral veins of former economic significance on their margins (Stephenson 1983; Francis *et al.* 1970; Hall *et al.* 1982; Stephenson and Coats 1983: see also Ch. 16).

Northumberland–Solway Basin

Jones *et al.* (2011) noted that polygonal cracks at the top of the Canonbie Bridge Sandstone (Warwickshire Group; Fig. 10.7) are filled with sand from the overlying Becklees Sandstone Formation. They inferred that this marked lithification of the former and that time may have elapsed before deposition of the latter. An unconformity was confirmed at this horizon by Howell *et al.* (2021) from seismic reflection data where, on the western limb of the syncline, the Becklees Sandstone laps onto the Canonbie Sandstone and reflectors just below the junction appear to be truncated along the higher parts of the limb, suggesting erosion had taken place. They invoked NW-directed thrusting along the Gilnockie Fault (Fig 10.3b), causing folding, steepening and some erosion of the western limb of the syncline. Contemporaneous reverse reactivation of the Hilltop Fault formed the Carlisle Anticline in the hanging wall to the SE and probably prevented uplift of the eastern limb of the Solway Syncline. Howell *et al.* (2021) concluded that these events resulted in a NW–SE-orientated shortening of 10 percent.

This inversion event appears to have shifted the depocentre of the syncline southeastwards to accommodate deposition of at least 200 m, and possibly as much as 700 m of the Becklees Sandstone Formation in the centre of the syncline (Chadwick *et al.* 1995; Howell *et al.* 2021). The sandstone contains a smaller proportion of lithic clasts and more rounded grains than the Canonbie Bridge Sandstone. Sharp-based units of sandstone up to 30 m thick are interbedded with Oxisols, some Vertisols and calcretes. Within the Becklees Formation, Howell *et al.* (2021) identified a further unconformity which cuts down into older strata, truncating bedding beneath the discontinuity. The fluvial character of the sediments and the broad u-shape of this unconformity in cross-section suggest that it probably represents the erosive base of a major fluvial channel system.

TS8 Latest Carboniferous–earliest Permian: post-Variscan extension and alkaline magmatism

A phase of post-Variscan extension and magmatism, distinct from TS7, marks the continued transition from Carboniferous plate accretion events to continental extension that characterizes the Permo-Triassic. Widespread NE- to NW-trending rifts and regional magmatism began to develop across NW Europe in the very latest Carboniferous and early Permian, accompanied by basaltic magmatism from 305–290 Ma (Coward 1995: Neumann *et al.* 2004; Timmerman *et al.* 2004; Fig. 10.10f). In the Midland Valley (MVS), alkaline basaltic sills, vents and dykes and one preserved lava succession (Figs. 10.4, 10.16) had an extension-related petrogenesis (Wallis 1989) and appear to be related to NE- to NW-trending post-Carboniferous extensional fault systems (Anderson *et al.* 1995; Upton *et al.* 2004). This phase appears to be distinct from later NW–SE-orientated extension documented in the Highlands (*c.* 267 Ma; Dichiarante *et al.* 2016) and the development of the North Sea northern and southern Permian (Glennie and Underhill 1998).

The MVS alkaline magmatism (e.g. 305.2±2.1 to 294.8 ±2.1 Ma; Monaghan and Pringle 2004) overlaps in age with emplacement of the tholeiitic Whin Sill-swarm and related dykes in Northumberland

(297.4±0.4 Ma, Hamilton and Pearson 2011) and latest Carboniferous–early Permian dextral transtension (Fig. 10.10f; De Paola *et al.* 2005), suggesting the locus of that tectono-magmatic event had migrated southwards.

Northwesterly trending post-Variscan basins are most notable on the western side of the MVS and across the Southern Uplands. For example, the NE Arran Trough in the Firth of Clyde (McLean and Deegan 1978; Caldwell and Young 2013), NW-trending faults defining the location of the Mauchline Basin (Smith *et al.* 2013) and the Dumfries–Thornhill–Sanquhar and Stranraer–Loch Ryan basins crossing the Southern Uplands (Figs 10.2, 10.3). At Mauchline, Sanquhar and Thornhill, the early Permian succession includes amygdaloidal basaltic lavas, breccias, fluvial and aeolian red sandstones (Mykura *et al.* 1967; McMillan 2002; Smith *et al.* 2013). The Mauchline succession includes plant faunas which have been variably interpreted as Stephanian (latest Carboniferous) or early Permian (Wagner 1983). The ^{40}Ar–^{39}Ar date on the Mauchline lavas (291.7±5.3 Ma, Monaghan and Browne 2010) and re-assessment of the plant faunas has given a consensus for an early Permian age (Besly and Cleal 2021).

Late Stephanian–early Permian magmatism

Lavas, vents, necks, sills, minor intrusions and dykes of alkali-basaltic and related highly undersaturated compositions occur in small volumes in various centres from Orkney to the western and southwestern Highlands (Fig. 10.1), Ayrshire and Fife (Fig. 10.16). Many are thought to be early Permian (e.g. Wallis 1989; Monaghan and Browne 2010), though some are known to be associated with the Namurian sills of similar composition; the Orkney Dyke-swarm is late Permian. A large range of mineralogy and textures are represented (Stephenson *et al.* 2003, p. 175; Upton *et al.* 2004): (a) mildly silica-undersaturated olivine-dolerite, basalt and basanite, without modal nepheline and little analcime; (b) more-strongly silica-undersaturated basic rocks with modal nepheline and/or analcime, including analcime-dolerite/gabbro, nepheline-dolerite/gabbro and nepheline-monzogabbro, together with olivine-rich (picritic) variants; (c) strongly silica-undersaturated, highly alkaline, feldspar-poor or feldspar-free rocks, mostly fine-grained basanite, foidites and alkaline lamprophyres (all formerly classified as 'monchiquitic' types).

In common with the tholeiitic intrusive rocks, the alkaline rocks may be altered, rendering their classification difficult. Alteration may be particularly intense forming zones of 'white trap' close to fault planes and adjacent to sedimentary rocks that were probably saturated with water at the time of intrusion.

The volcanic necks and dykes, in particular, contain xenoliths and xenocrysts of upper mantle and lower crustal origin (Upton *et al.* 1983, 1998). Four broad groups are recognized: probable mantle peridotites and garnet pyroxenites; shallow mantle or deep-crustal garnet pyroxenites; lower crustal granulite-facies meta-igneous rocks; and megacrysts (Upton *et al.* 2004). These xenoliths and xenocrysts have been recorded from some 70 localities across all of the Scottish tectonic terranes and provide information on magma genesis and reflect the heterogeneity of the lower crust and lithospheric mantle across the region (Upton *et al.* 2011). Dating of zircons from within metatonalite and metadiorite xenoliths from Ayrshire and East Lothian shows that these materials were derived from mid- to late-Ordovician arc protoliths and 'Newer' granites (Badenszki *et al*. 2019).

East Fife volcanoes

More than one hundred alkali-basaltic diatremes, volcanic necks and associated intrusions in Fife represent the remnants of a volcanic field of early Permian tuff-rings and maar volcanoes (Fig. 10.16; Forsyth and Chisholm 1977; Gernon *et al.* 2013). Some basanitic and foiditic intrusions in East Lothian are probably of similar age (Stephenson *et al.* 2003, p. 153). Some of the volcanoes lie along the NE-trending dextral strike-slip Ardross Fault, which allowed magma originating from depths of *c.* 60 km to reach the surface (Gernon *et al.* 2016). The morphology of these volcanoes has been studied in detail, allowing rare insights into pyroclastic processes and the deeper levels of the plumbing system (summary by Stephenson *et al.* 2003, p.158).

Various stages in the evolution of the volcanoes are preserved. Initial updoming with associated radial and concentric fracturing was followed by gas-fluxioning and wall-rock stoping. Intrusive tuffisites were commonly injected along the fractures and small 'cryptovolcanic' structures, representative of this stage, are particularly common. Larger necks have the form of funnel-shaped tuff pipes, containing masses of proximal pyroclastic rocks, which incorporated blocks and comminuted debris of sedimentary wall-rock, all with dominant inward dips. Included plant fragments accumulated on the surface and were entombed by post-eruptive collapse into the vent along ring-faults. At Elie Ness (Gernon *et al.* 2013), early eruptions were dominated by highly vesicular scoria from the explosive degassing of volatile-rich magma, whilst the lithologies, textures and bedding characteristics of the later-formed pyroclastic rocks represent phreatomagmatic eruptions that generated pyroclastic fall-out and density currents through the explosive interaction of magma with wet sediment or groundwater.

Highlands and Islands

In the Sound of Islay between Islay and Jura an early Permian (285±5 Ma, K–Ar) subaerial volcano was located on a NNW-trending fracture, associated with a narrow half-graben within the Dalradian metasedimentary basement (Upton *et al.* 1987). Remnants of this structure now crop out on Glas Eilean and the Black Rock skerries (Fig. 10.1) where alkali olivine-basalt lavas and intercalated sedimentary rocks form a succession that is *c.* 120 m thick. Farther NNW along the same lineament on Colonsay and Mull are sub-silicic alkaline dykes (Upton *et al.* 1998).

Numerous subvolcanic necks and plugs of silica-poor basic rocks and NW–SE dykes of alkaline lamprophyre (camptonite and monchiquite), with subordinate foidite, basanite and basalt are present in the western and northwestern Highlands and Islands (Rock 1983; Fig. 10.1). Most of the dykes have early Permian K–Ar radiometric dates of *c.* 290 Ma (Baxter and Mitchell 1984), though a NNW-trending dyke on Mull has yielded an Ar–Ar age of 268±2 Ma (Upton *et al.* 1998) and the WSW–ENE Orkney Swarm is late Permian (*c.* 250 Ma). These dykes are the most silica-undersaturated, and the most primitive suite of basic igneous rocks recorded anywhere in Britain. The necks and dykes are among the most prolific sources of suites of lower crustal and mantle xenoliths (Upton *et al.* 2011).

Western Midland Valley

The most-extensive lava field of this time slice crops out around the south of the Mauchline Basin, where up to 238 m of highly silica-undersaturated basanite and olivine nephelinite lavas of the Mauchline Volcanic Formation overlie Scottish Upper Coal Measures unconformably (Fig. 10.16; Stephenson *et al.* 2003, pp. 166-169). This volcanic field might have originally extended to the SE, to include the Carron Valley Basalt Formation in the Thornhill Basin. Basaltic lavas and tuffs are also present locally at the base of the Permian succession on Arran.

In Ayrshire, strongly silica-undersaturated dolerite, basanite and foidite intrude Coal Measures strata, but none cuts the early Permian Mauchline Sandstone Formation. An ^{40}Ar–^{39}Ar age of 288±6 Ma from the Lugar Sill (Henderson *et al.* 1987) and palaeomagnetic data on some of the sills support an association with early Permian volcanism (Armstrong 1957). The composite sills at Saltcoats and Lugar (Fig. 10.16) are internationally recognized for their contribution to our understanding of igneous processes, including multiple magma injections, post-injection differentiation aided by gravitational crystal settling and residual liquid and volatile enrichment (Stephenson *et al.* 2003, pp. 190-202). Four analcime-dolerite sills in the Glasgow–Paisley area, along with two plug-like intrusions of augite-phyric nepheline-monzogabbro close to the West Campsie Fault at Lennoxtown, may have been emplaced during this volcanic event (Hall *et al.* 1998).

Southern Uplands

The thin sills of analcime-dolerite and a few NW-trending dykes of monchiquite and alkali dolerite that cut Scottish Coal Measures in the Sanquhar Basin, and the sporadic dykes of monchiquite and nepheline-gabbro within Lower Paleozoic rocks are all assumed to be latest Carboniferous or Early Permian (Read *et al.* 2002).

Concluding remarks

Following Read *et al*. (2002), our knowledge of the Carboniferous geology of Scotland has continued to expand; subsequent citations comprise about 40 per cent of the references used in this chapter. In concluding this review, we take stock of progress, summarise some of the gaps in our understanding, and tentatively suggest future avenues of research.

A robust lithostratigraphical and chronological framework provides the basis for detailed sedimentological, structural and petrogenetic studies. The fluvio-deltaic, shallow-marine and volcanic environments within Scottish Carboniferous basins preserve a record of the profound and irreversible changes in the Earth's bio- and geosphere that were witnessed during this period. The appearance of novel traits in land plants allowed the global spread of forests (Beerling 2017). These forests created new terrestrial, freshwater, and near-shore environments that are thought to have opened ecological opportunities for many biotic groups (Gibling and Davies 2012). This facilitated key evolutionary innovations such as tetrapods stepping out on to land (Clack *et al.* 2016), and with exceptionally preserved fish and plant remains, the Carboniferous of Scotland surely has many more important finds that will continue to contribute to the understanding of the evolution of life on Earth.

Movement of continental fragments in the foreland of the Variscan Orogen controlled early Carboniferous sinistral transtension and mid to late Carboniferous dextral transpression in the Highlands (Armitage *et al.* 2021; Dichiarante *et al.* 2016), Midland Valley of Scotland (Rippon *et al.* 1996; Read 1988; Underhill *et al.* 2008) and northern England (Chadwick et al. 1995; Howell et al. 2021). Development of the sedimentary basins and magmatic history accords broadly with the regional plate-tectonic model of Coward (1993), in which 'expulsion' of the Baltica fragment is followed by 'reinsertion' along with Variscan compression from the south. Whilst late Carboniferous deformation is increasingly well understood, the variety of structural orientations and overprinting by younger events result in a continuing debate on the kinematics of early to mid-Carboniferous basins, to understand better the timing of the change from sinistral to dextral oblique-slip tectonics in northern Britain. The apparently contradictory, contemporaneous patterns and timings of faulting and folding north and south of the Southern Uplands, and also within basins, are partially resolved within a partitioned oblique-slip deformation model (as in De Paola *et al.* 2005) involving re-activation of NE- to ENE-trending inherited Caledonide fractures. Integrating local studies in the time-slice framework has future potential to further unravel the evolution of the oblique-slip dominated, lozenge-shaped Midland Valley of Scotland with syn-depositional basins across *c*. ENE faults and NNE-trending folds; its linkage to major faults in the Highlands; and significant differences in tectonic style and magmatism observed south of the Southern Uplands.

Magmatism is an integral part of the Carboniferous basin evolution in Scotland. South of the Southern Uplands, short pulses of basaltic magma were erupted during Late Devonian and early Carboniferous extension on ENE-trending faults in the Northumberland–Solway Basin. During Visean times major volcanic edifices were constructed of mildly alkaline intraplate magmas in the Midland Valley. A change then occurred in the Midland Valley in late Visean times to more-primitive, silica-poor, alkalic basic magmas and these continued to be emplaced through into Permian times, except for a brief interruption during late Carboniferous post-orogenic extension by the intrusion of voluminous tholeiitic basalt as sills and dykes in both Scotland and northern England. The magmas have been extensively characterized and their petrogenesis explained in terms of differing mantle melt proportions and depths of generation (Stephenson *et al*. 2003; Upton *et al*. 2004). However, less well understood is what caused the changes in magma type in the late Visean and Stephanian, and why the locus of tholeiitic magmatism moved southwards into northern England during early Permian times.

New tectono-magmatic studies using an improved chronological framework is likely to constrain evolution of these basins more tightly in the history of the Variscan orogenic foreland, through the welding of Pangaea to the start of its break-up.

Table

Table 1: *Summary of either approximate maximum thickness or measured section/borehole specific structural locations, in metres, of Strathclyde, Clackmannan and Scottish Coal Measures group strata by area. Examples are given to illustrate thickness variations across faults and folds. F= Fault, FW= footwall, HW=hangingwall. Data from BGS maps, memoirs, boreholes, Browne et al. (1999) and Waters et al. (2011).*

Stratigraphic unit	Ayrshire	Glasgow - Lanarkshire	Douglas	Clackmannan	Westfield West Lothian	Edinburgh, Mid and East Lothian	Central - East Fife
Upper Coal Measures	Central 460	300	270	85	Westfield <10	60	Onshore 250 Offshore 1500
Middle Coal Measures	280	260	330	200	Westfield 180	340	Leven 350
Lower Coal Measures	200	230		160	Westfield 128	190	Leven 240
Passage Fm	North, central < 50. Volcanic 166	40 – 200	225	Kincardine 370	Westfield 210	200-300	200 – 300
Upper Limestone Fm	HW Dusk Water F 100 FW Inchgotrick and Kerse Loch F, Ayr 0 –20 HW Kerse Loch F 210	Kilsyth Trough > 400 Thins southwards	230	Kincardine 600	West Lothian 385	300	480
Limestone Coal Fm	HW Dusk Water F 200 HW Inchgotrick F 15 FW Inchgotrick F, Ayr absent FW Kerse Loch F 30 HW Kerse Loch F 85	315	175	Kincardine 550	West Lothian 290	FW Roslin – Vogrie Fault 119 HW Roslin – Vogrie Fault 236	FW East Ochil 69 HW East Ochil 286 Burntisland anticline 221 Kirkcaldy (Leven syncline) 286
Lower Limestone Fm	FW Inchgotrick F absent HW Inchgotrick F thickens 20 – 60	Kilsyth Trough 200 Thins southwards	60	Stirling 70	West Lothian 180	200	240
Strathclyde Group (sedimentary units only)	North Ayrshire < 10m South Ayrshire Lawmuir Fm 20 – 160	Lawmuir Fm 300	Lawmuir Fm 120	Stirling <50	West Lothian Oil-Shale Fm 1120	Aberlady Fm 140 Gullane Fm 130 – 860	Pathhead Fm 220 Sandy Craig Fm 670 Pittenweem Fm 260 Anstruther Fm 810

Figure captions

Fig. 10.1: Plate tectonic reconstructions modifed after Coward (1993, figs 8, 11) and palaeolatitudes from Edel *et al*. (2018) for Greenland and Europe during (a) early Carboniferous, with the addition of microplates names, present on the southern margin of the Laurussian plate and (b) Stephanian–Autunian (latest Carboniferous–earliest Permian), suggesting expulsion and later re-insertion of the Baltica indentor affecting the UK, including conjunction with Varsican orogenic events.

Fig. 10.2: Regional overview of Carboniferous basins and main faults thought to have been active during Carboniferous times. Onshore data from mapping, boreholes and seismic data. Offshore data from limited numbers of exploration wells and seismic mapping. Incorporating numerous data sources including BGS Geology 625K Data © UKRI and Arsenikos *et al.* (2018), plus Andrews *et al.* (1990); Brackenridge *et al.* (2020); British Geological Survey (1996a); Bruce and Stemmerik (2003); Chadwick *et al.* (1995); Fyfe *et al.* (2020, 2021); Howell *et al.* (2021); Kearsey *et al.* (2019a); Milton-Worssell *et al.* (2010); Monaghan (2013); Ritchie *et al.* (2003, 2011); Underhill *et al.* (2008); Whitbread and Kearsey (2016). Plug and vent locations are shown north of the Highland Boundary Fault only; see Fig. 10.16 for igneous intrusions south of the fault. At this scale, the Highlander Field plots at the same location as the Claymore Field. Offshore quadrants in orange. Hillshading using NEXTMap Britain elevation data from Intermap Technologies. BGS © UKRI 2023.

Fig. 10.3a: Summary geological map of Carboniferous basins of Scotland and the Northumberland–Solway basin showing major faults, folds and basins. Simplified from BGS Geology 625K and BGS Geology 50K Data © UKRI; Arsenikos *et al.* (2018); Chadwick *et al.* (1995); Day (1970); Read *et al.* (2002). See Fig 10.16 for volcanic vent locations. Cross-section modified after BGS UK3D v2015 regional cross-sections, 3.5 times vertical exaggeration. Inverclyde Group is taken from BGS Geology 625K Data © UKRI; note this includes Kinnesswood Formation now assigned to the Devonian. Hillshading using NEXTMap Britain elevation data from Intermap Technologies. BGS © UKRI 2023

Fig. 10.3b: Summary structural and location map of Carboniferous basins of Scotland and the Northumberland–Solway basin showing major faults, folds and places named included in the text. Simplified from BGS Geology 625K and BGS Geology 50K Data © UKRI; Arsenikos *et al.* (2018); Chadwick *et al.* (1995); Day (1970); Read *et al.* (2002). BGS © UKRI 2023Fig. 10.4: Volcanic-stratigraphic summary chart for the Midland Valley of Scotland, significantly modified after Cameron and Stephenson's (1985) concept to incorporate ^{40}Ar–^{39}Ar and U-Pb ID TIMS ages and improved biostratigraphical constraints, modified after Browne *et al.* (1999); Waters *et al.* (2011), Dean *et al.* (2011) including Ballagan Formation from Marshall *et al.* (2019); Visean volcanic formations from

Monaghan and Parrish (2006) and Monaghan *et al.* (2014), including previous dates recalculated to the same decay constant); Fife formations as in Owens *et al.* (2005). Timescale from IUGS 2020. Miospore zones as used in Waters *et al.* (2011, p. 16). Numbered time slices (TS 1-8) in the right-hand column. Timescale from ICS (2020). Modified from concept in Cameron and Stephenson (1985) and Read et al. (2002). BGS © UKRI 2023.

Fig. 10.5: Summary of time slices 1–8 used to describe the Carboniferous geology of Scotland in this chapter. With indication of igneous activity; global sea-level changes plotted as transgressive-regressive cycles (T=transgression in blue to the left, R=regression); number of genera per stage for plants, arthropods and tetrapods globally, a=earliest coal forest wetland biomes, b=collapse of wetland biomes, c=earliest giant millipedes, d=earliest winged insects, e=modern tetrapod origins, f=increased tooth shape diversity. Contains timescale from ICS (2020)/Timescale Creator 8.0, including T-R cycles from Haq and Schutter (2008); number of genera per stage from Paleobiology Database by Marcello Ruta, with permission. BGS © UKRI 2023.

Fig. 10.6: Regional palaeoenvironmental summary maps for (a) Tournaisian (Time Slice 1), (b) late Asbian (Time Slice 3) and (c) Kinderscoutian (Time Slice 5). Right-hand side showing sedimentary environment interpretations, left-hand side showing reconstruction of palaeolandscapes as they evolve through the Carboniferous. Left side palaeolandscapes created using real-world physics engine GIS software by T. Kearsey; right side based upon Kearsey *et al.* (2015), Whitbread and Kearsey (2016), Kearsey *et al.* (2019a). BGS © UKRI 2023.

Fig. 10.7: Correlation of the Carboniferous successions in the Midland Valley, Tweed and Northumberland–Solway basins, modified after Browne *et al.* (1999); Waters *et al.* (2011), Dean *et al.* (2011). Ballagan Formation from Marshall *et al.* (2019); Visean volcanic formations from Monaghan and Parrish (2006) and Monaghan *et al.* (2014, including previous dates recalculated to the same decay constant); palynological constraints as Owens *et al.* (2005) leading to omission of the Fife Ness Formation; Warwickshire Group after Jones *et al.* (2011) and Howell *et al.* (2021). Darker grey are inter-formational unconformities, lighter grey are intra-formational unconformities in the Passage Formation. Broken lines represent locally missing correlative marker horizons. BGS © UKRI 2023.

Fig. 10.8: Offshore summary stratigraphy for the Carboniferous of the central North Sea and its relationship to onshore stratigraphy in the Tweed and Northumberland–Solway basins, modified after Kearsey *et al.* (2015, 2019a). BGS © UKRI 2023.

Fig. 10.9: Locations of tetrapod, other vertebrate, plant and arthropod fossil sites in the Carboniferous of Scotland. LHB=Loch Humphrey Burn, GR=Granton, PC=Pettycur, NI=Niddrie, GI=Gilmerton, CB=Cheese Bay. Contains data extracted from Joint Nature Conservation Committee's Geological Conservation Review database https://hub.jncc.gov.uk/assets/b0f53582-f93d-4e70-8ff9-0f16b660e4ad and Namurian and Westphalian tetrapod sites included in Smithson (1985a). BGS © UKRI 2023.

Topic box:

Fig.: (a) *Pederpes finneyae* Clack 2002, a nearly complete tetrapod fossil from the Ballagan Formation at Auchenreoch Glen, near Dumbarton. Photograph © Sarah M. Wallace-Johnson; specimen GLAHM: 100815 in the collections of The Hunterian, University of Glasgow. (b) Drawing of reconstructed *Pederpes* from '*Pederpes finneyae*, an articulated tetrapod from the Tournaisian of Western Scotland', Clack and Finney (2005), Journal of Systematic Palaeontology, copyright © The Natural History Museum, reprinted by permission of Taylor & Francis Ltd, http://www.tandfonline.com on behalf of The Natural History Museum.

Fig. 10.10: Summary of the main tectono-magmatic events and active tectonic structures affecting the Midland Valley of Scotland and the Northumberland–Solway Basin for six of the time slices described in this chapter. Tectonic elements for the Midland Valley are incorporated from many sources including Read *et al.* (2002), Millward *et al.* (2019), Underhill *et al.* (2008); for the Northumberland–Solway Basin incorporated from Chadwick *et al.* (1995), De Paola *et al.* (2005), Fraser and Gawthorpe (2003), Hamilton and Pearson (2011). Dykes offshore from Smythe *et al.* (1995), (b) (e) and (f) modified after Monaghan and Parrish (2006). Strain ellipses orientated (g) after Ritchie et al. (2003) for sinistral strike slip and (h) after Underhill *et al.* (2008) for dextral strike-slip, reflecting idealized structures developed under oblique slip regional stress fields. Blue areas indicate Carboniferous strata as shown on Figs 10.2, 10.3. BGS © UKRI 2023.

Fig. 10.11: Tournaisian (TS1) palaeogeography of the Midland Valley, and Tweed and Northumberland–Solway basins. The map includes a selection of sedimentary environments throughout the 13 million years duration and is not a snapshot in time. Locations of borehole logs and section on Fig. 10.13 are shown. Redrafted from Millward *et al.* (2019), reproduced with permission.

Fig. 10.12: Ballagan Formation in the Tweed Basin: fluvial channel cut and fill into interbedded siltstone, fine-grained sandstone and dolostone alongside the Whiteadder Water at Edington Mill [3894 6548]. Photograph ©D Millward

Fig. 10.13a: Selected logs illustrating the sedimentary facies of the Ballagan Formation across the Midland Valley and Tweed Basin, locations shown on Fig. 10.11. The grain sizes of the dolostones and sandy siltstones are exaggerated for clarity. A short section at the base of the Clyde Sandstone Formation is shown from the Knocknairshill Borehole. The borehole logs are measured downwards in metres below ground level. The Burnmouth section commences 280 m above the base of the Ballagan Formation and is measured upwards. Original log of the Blairmulloch Borehole (BGS number NS52NE21 [25605 62820) by S K Monro with additional information from Williams *et al.* (2006). Knocknairshill Borehole (BGS number NS37SW10 [23056 67438]) log by I B Paterson. East Linton Borehole (NT57NE2 [35966 67709) log by A D McAdam. Burnmouth log by C E Bennett (University of Leicester), with additional information from Clack *et al.* (2016 and supplementary data, 2019a, Otoo *et al.* (2019) and Ross *et al.* (2018). Additional invertebrate fossil data from Brand (2018). BGS©UKRI 2023.

Continued Fig. 10.13b: Composite key for all the sedimentary logs in Chapter 10. BGS © UKRI 2023.

Fig. 10.14: Reconstruction of the Ballagan Formation vertebrate and related faunas illustrating the approximate size relationships. From left to right: rhizodont (R), gyracanth (G), tetrapod (T), actinopterygian (A), myriapod (M), and eurypterid (E). The Tournaisian rhizodonts attained lengths up to 3 m (Clack *et al*. 2019a). Artwork by Yasmin Yonan reproduced from Otoo *et al.* (2019) under the CC BY 4.0 licence.

Fig. 10.15: A reconstruction of the Ballagan Formation marshland palaeoenvironment, upper diagram in ‘dry’ conditions when palaeosols and evaporitic pools and lakes are dominant, and in ‘wet’ conditions when large bodies of standing water dominate. Topographically higher areas of Vertisols are less affected by flooding. Adapted from Kearsey *et al.* (2016) BGS © UKRI 2023..

Fig. 10.16: Map showing Late Devonian, Carboniferous and early Permian distribution of extrusive and intrusive magmatism of the Midland Valley and southern Scotland, excepting the Midland Valley tholeiitic sill- and dyke-swarms. Thin CPV (Clyde Plateau Volcanic Formation) and PGP (Passage Formation) on Arran indicate units too small to be shown at this scale. Extracted from BGS Geology 625K data © UKRI . Radiometric dates from Monaghan and Pringle (2004), Monaghan and Parrish (2006), Monaghan and Browne (2010) and Monaghan *et al.* (2014) with ^{40}Ar–^{39}Ar dates all recalculated to the decay constant and standard value of Renne *et al.* (2011). Lugar Sill date from Henderson *et al*. (1987). A spreadsheet of recalculated dates is provided in supplementary information. Hillshading using NEXTMap Britain elevation data from Intermap Technologies. Modified from concept in Cameron and Stephenson (1985) and Read et al. (2002). BGS © UKRI 2023.

Fig. 10.17: Map of the Kilpatrick Hills and Campsie Fells, showing outcrops of the Clyde Plateau Volcanic Formation and volcano-tectonic lineaments (linear vent systems) defined by plugs, necks and proximal volcaniclastic beds. Based on BGS 1: 50 000 sheets 30W (Greenock, 1990), 30E (Glasgow, 1993) and 31W (Airdrie, 1992). AG, Auchenreoch Glen; Ga, Glenarbuck; GNSV, Greenside Volcaniclastic Member; LHB, Loch Humphrey Burn; LVS, Linear Vent System from Forsyth et al. (1996). BGS © UKRI 2023.

Fig. 10.18: Marine Villa tuff, Garleton Hills Volcanic Formation, Marine Villa, East Lothian. Bedded and cross-laminated trachytic tuff and lapilli tuff emplaced by pyroclastic fall-out and pyroclastic density currents. Photographer: D Millward. BGS image P1019702 © UKRI.

Fig. 10.19: Oblique aerial view from the north of Arthur's Seat Volcano and Salisbury Crags, Edinburgh and geological cross-section E–W after Mitchell and Mykura (1962). The volcanic necks of the Lion's Head and Lion's Haunch form the rugged highest ground in the centre of the photograph. The analcime-dolerite sill of Salisbury Crags forms the prominent line of cliffs at the right. BGS image P001316 © UKRI (source: BGS GeoScenic).

Fig. 10.20: Palaeogeographic map for the late Asbian (*c*. 333 Ma, TS3) showing variations in sedimentary environments that developed east of the remnant Clyde Plateau volcanic high and syn-depositional fault and fold structures. Abbreviations as Fig. 10.3b. Original concept from Loftus and Greensmith (1988) revised by Monaghan (2014) incorporating deep exploration well data and further updated here for the western Midland Valley. © DECC, reproduced under the Open Government Licence v3.0.

Fig. 10.21: Contoured faulted depth maps in kilometres relative to Ordnance Datum, based on borehole, well, seismic, mining and outcrop data. Syn-depositional faults and folds shown, name abbreviations as Fig. 10.3b. (a) base West Lothian Oil-Shale–Pittenweem–Aberlady formations, data from Monaghan (2014) © DECC reproduced under the Open Government Licence v3.0) (b) base Lower Limestone Formation data from Monaghan (2013) BGS © UKRI and Monaghan (2014) © DECC reproduced under the Open Government Licence v3.0) (c) base Coal Measures data from Monaghan (2013) BGS © UKRI. Hillshading using NEXTMap Britain elevation data from Intermap Technologies.

Fig. 10.22: Examples of various styles of syn-depositional fault and fold growth in Carboniferous Midland Valley strata. (a) BGS photograph and annotated photograph of the Westfield surface coal mine site showing field evidence for spectacular thickening into the syncline during deposition of the Passage Formation. (b) Interpreted 14 km long seismic line across the Midlothian–Leven Syncline in

the Firth of Forth highlighting the open asymmetric fold geometry and stratal growth into the centre of the syncline from Strathclyde Group strata onwards. (a) and (b) reproduced from Underhill *et al.* (2008) with permission from Elsevier. (c) Cross-section of the Middle Coal Measures showing thickening across the Kerse Loch Fault (KLF), as constrained by borehole and mining data, simplified from Mykura *et al.* (1967) BGS © UKRI (d) Isopach maps of Namurian strata in the Kincardine Basin, constrained by borehole and mining data redrawn from Rippon *et al.* (1996).

Fig. 10.23: Summary and detailed logs of the Asbian–Brigantian Strathclyde Group sedimentary strata of the Midland Valley highlighting lateral facies variability from west to east. (a) Summary West Lothian Oil-Shale Formation log from Jones (2005) BGS © UKRI, blue bars indicate the stratigraphical position of the detailed logs, stratigraphical names in capital italics to show equivalence of Fife terminology; (b) [307819 667392] and (c) [307902 667156] Detailed logs of the West Lothian Oil-Shale Formation from the Linhouse Water, West Lothian from Jones (2005) BGS © UKRI; (d) Log of the Rosyth Borehole core (BGS borehole NT08SE9641) [30934 68217], West Fife from Guirdham *et al.* (2003) reproduced with permission of Scottish Journal of Geology; Pittenweem Formation up to the Burdiehouse Limestone, Sandy Craig Formation above; (e) Generalized log of the Pittenweem and Sandy Craig formations from East Fife boreholes from Read *et al.* (2002). The borehole logs are measured downwards in metres below ground level, and the section is measured in metres upwards from the base. See Fig. 10.13b for key to logs.

Fig. 10.24: Selected sections from the Archerbeck Borehole (BGS borehole NY47NW1) [34160 57820] near Canonbie, Dumfriesshire. Sedimentary logs illustrating the (a) Tyne Limestone, (b) Alston and (c) Stainmore formations. Redrawn from Lumsden and Wilson (1961). The borehole logs are measured downwards in metres below ground level. See Fig. 10.13b for key to logs. BGS©UKRI 2023.

Fig. 10.25: Summary and detailed logs of the late Brigantian, Lower Limestone Formation. (a) generalized vertical section from West Fife, from Read *et al.* (2002); (b) condensed succession from the Kirkwood Borehole (BGS borehole NS 34NE11) [23885 64716] in Ayrshire; (c) upper part of the formation from the Annfield Borehole (BGS borehole NT18NW205) [3142 6865] (Forsyth 1970) BGS © UKRI, West Fife as in Read *et al.* (2002); (d) log of the St. Monans coastal section on the east limb of the St Monans Syncline, from Kassi *et al.* (2004), reproduced with permission. The borehole logs are measured downwards in metres below ground level, and the section is measured upwards in metres from the base. See Fig. 10.13b for key to logs.

Fig. 10.26. Section through strata of the Limestone Coal Formation from the Spireslack Surface Coal Mine Area D [27462 63068], East Ayrshire. Cyclic sedimentation from below the Black Metals Member

to the lowermost Upper Limestone Formation (above the base Index Limestone). BGS image P849584 © UKRI.

Fig. 10.27: Summary and detailed logs of the Pendleian Limestone Coal Formation. (a) condensed section in the Lomond Hills Block, in the foot-wall of the East Ochil Fault and (b) thin succession on the Burntisland Arch from Browne and Woodhall (1999) BGS © UKRI); (c) generalized vertical section from the Central Coalfield/Kilsyth Trough from Read *et al.* (2002); (d) detailed log of repeated fluvio-deltaic and coal mire cycles from the Gartcosh No. 1 Borehole (BGS borehole NS76NW224) [2707 6684] from Read *et al.* (2002). The sections are measured upwards in metres from the base. See Fig. 10.13b for key to logs.

Fig. 10.28: Summary and detailed logs of the Arnsbergian Upper Limestone Formation (a) generalized vertical section as fully developed in the Kincardine Basin, blue bars show stratigraphical range of detailed logs; (b) Plean No. 1 Limestone overlain by coal-bearing cycles in Maggie Duncan's Hill Borehole (BGS borehole NS99SW227) [2942 6905]; (c) thick multistorey sandstone, Upper Hirst Coal and Calmy Limestone from Headswood No. 1 Water Borehole (BGS borehole NS88SW208) [2829 6825], all from Read *et al.* (2002); (d) Log of the Spireslack Sandstone, east Ayrshire [27450 63020], from Ellen *et al.* (2019); (e) Log of the formation in the Douglas Basin, from the Mainshill Wood surface coal mine preserved section by M.A.E. Browne, E. Callaghan, R. Ellen [28518 63165] BGS © UKRI. The sections are measured upwards in metres from the base. See Fig. 10.13b for key to logs.

Fig. 10.29. Palaeoenvironmental, thickness and active structures map for the Pendleian (*c*. 329 Ma) Limestone Coal Formation (TS4), above the Black Metals Member showing syn-depositional fault and fold structures and sediment supply/palaeocurrent indicators. Abbreviations used for fault names are given on Fig. 10.3b. Based on Hooper (2003); McKenna (2021); Monaghan (2014); Mykura *et al.* (1967); Read (1989a, 2002). BGS © UKRI 2023.

Fig. 10.30: Roslin Glen, Hare Craig, East bank cliff, River North Esk, Midlothian; Upper Limestone Formation [32665 66212]; 10 m-thick stacked fluvial sandstone with multiple channel bases eroded into 3 m thick unbedded, rootleted palaeosol, on 6 m of upward-coarsening mudstone, siltstone and sandstone. Photographer: M Browne. BGS image P738516 © UKRI.

Fig. 10.31: Burrowine Moor Quarry, Devilla, west Fife, west view [29611 69015]; Passage Formation, 4 m-thick fluvial sandstone with channel base eroding into 1.4 m thick shelly mudstone of the No. 3 Marine Band group. Daysack, at foot of face, about 50 cm. Photographer: M Browne. BGS image P740508 © UKRI.

Fig. 10.32: Logs of (a) Passage Formation representative section from the IGS South Kersie (BGS borehole NS88NE7) [2867 6898] included in Read et al. (2002) showing stacked, erosive-based channel fills overlying a coal-bearing cycle and marine band; (b) Passage Formation composite section from the River Avon gorge between [29599 67911] and [29691 67853] showing marine bands above the Castlecary Limestone, after McAdam and Clarkson (1996, p201, reproduced with permission of the Edinburgh Geological Society; (c) Summary of Scottish Coal Measures Group section, adapted from BGS 1: 50 000 sheet 31W (Airdrie, 1992;). Standard UK marine band names are used with local names in brackets, correlation from Waters *et al*. (2011); (d) Detail of the Coal Measures succession in eastern Glasgow and fluvio-deltaic depositional environments, from the UK Geoenergy Observatories borehole GGC01 (BGS borehole NS66SW3754) [260915 663109], a thinner succession than that shown in log (c). (c) and (d) BGS © UKRI. The borehole logs are measured downwards in metres below ground level, and the sections are measured upwards in metres from the base. See Fig. 10.13b for key to logs.

Fig. 10.33: Map showing the distribution of latest Carboniferous tholeiitic basic intrusions of the Midland Valley Sill- and Dyke-swarm. Modified fromCameron and Stephenson (1985), contains BGS Geology 625K data ©UKRI. Hillshading using NEXTMap Britain elevation data from Intermap Technologies. BGS © UKRI 2023.

Fig. 10.34: Cowdenhill Quarry, Banknock, Falkirk, east face [27692 67982]; top of a quartz-gabbro sill of the Midland Valley Sill-swarm in irregular contact with the overlying Lower Limestone Formation mudstone, siltstone and sandstone. Photographer: M Browne. BGS image P740330 © UKRI.

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1 Figures - Carboniferous chapter

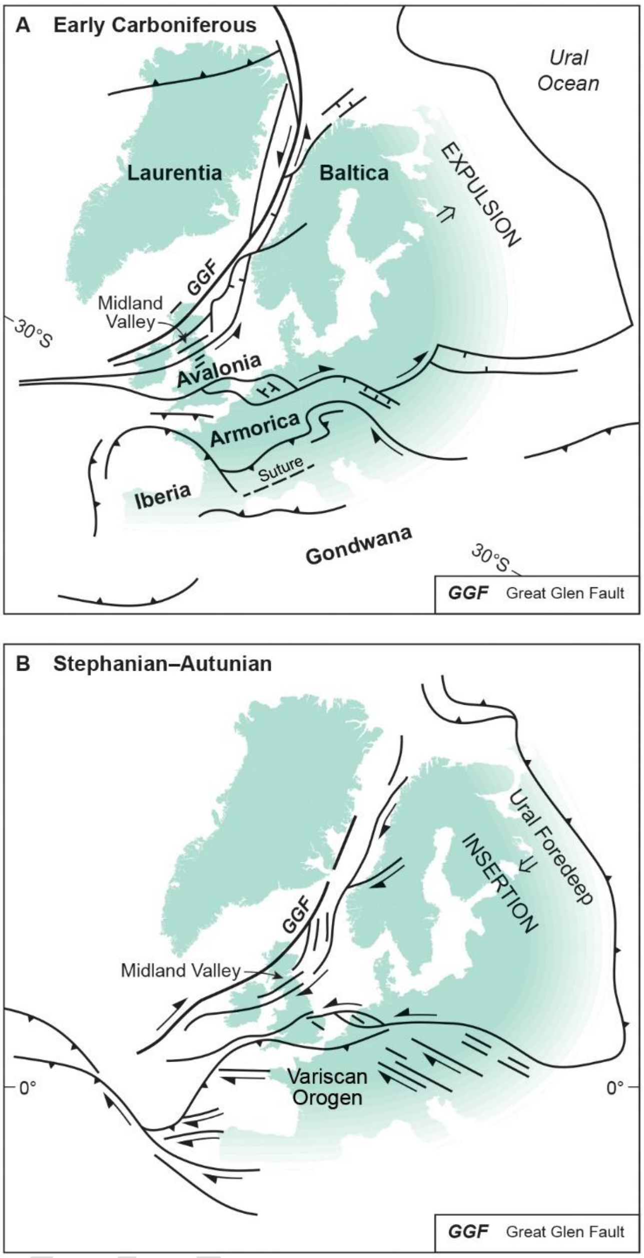
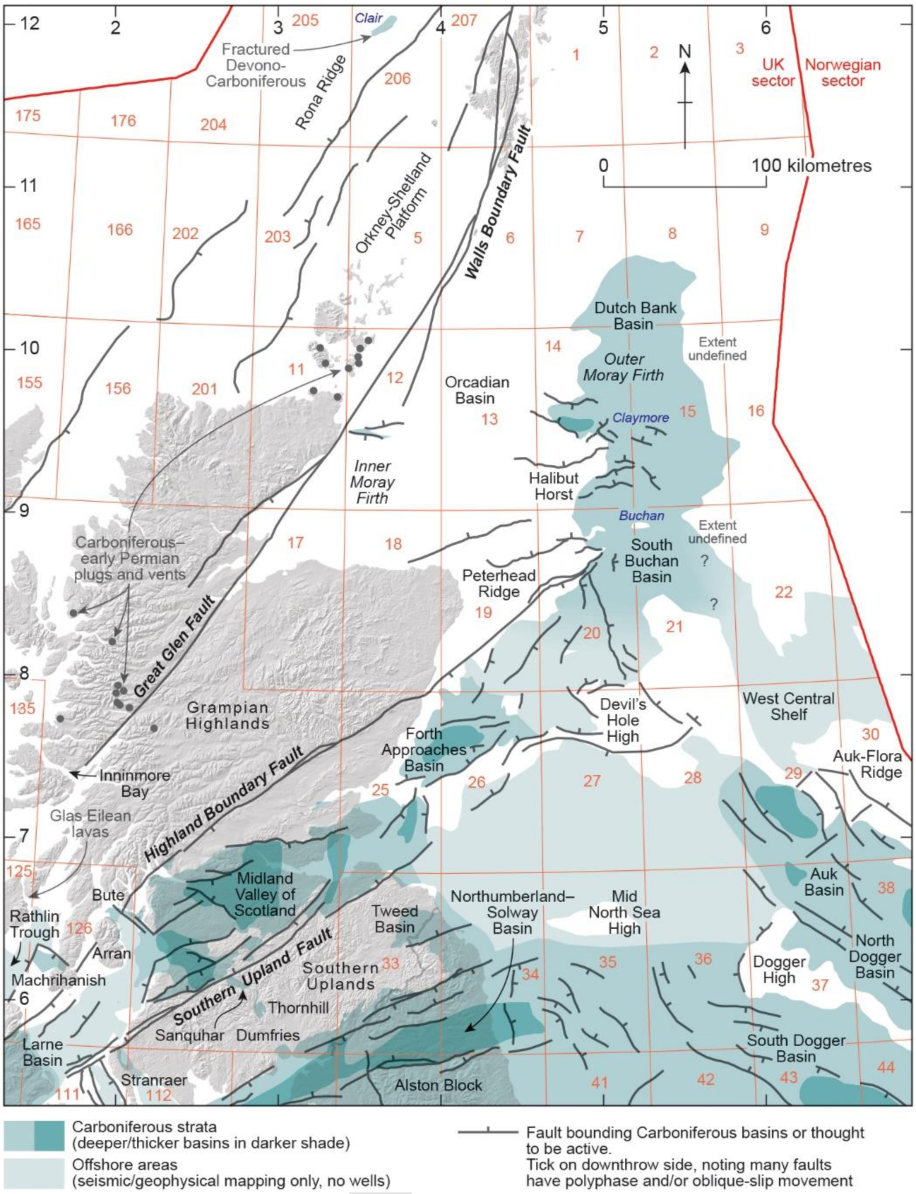


Fig. 10.1



Fractured Devono-Carboniferous
Clair
Rona Ridge
Orkney-Shetland Platform
Walls Boundary Fault
UK sector
Norwegian sector
N
0
100 kilometres
Dutch Bank Basin
Outer Moray Firth
Extent undefined
Orcadian Basin
Claymore
Inner Moray Firth
Halibut Horst
Buchan
South Buchan Basin
Peterhead Ridge
Carboniferous–early Permian plugs and vents
Great Glen Fault
Grampian Highlands
West Central Shelf
Devil's Hole High
Forth Approaches Basin
Auk-Flora Ridge
Inninmore Bay
Glas Eilean lavas
Highland Boundary Fault
Midland Valley of Scotland
Auk Basin
Bute
Rathlin Trough
Arran
Machrihanish
Tweed Basin
Northumberland–Solway Basin
Mid North Sea High
North Dogger Basin
Southern Upland Fault
Southern Uplands
Thornhill
Dogger High
Sanquhar
Dumfries
South Dogger Basin
Larne Basin
Stranraer
Alston Block
Carboniferous strata (deeper/thicker basins in darker shade)
Offshore areas (seismic/geophysical mapping only, no wells)
Fault bounding Carboniferous basins or thought to be active.
Tick on downthrow side, noting many faults have polyphase and/or oblique-slip movement

Fig. 10.2

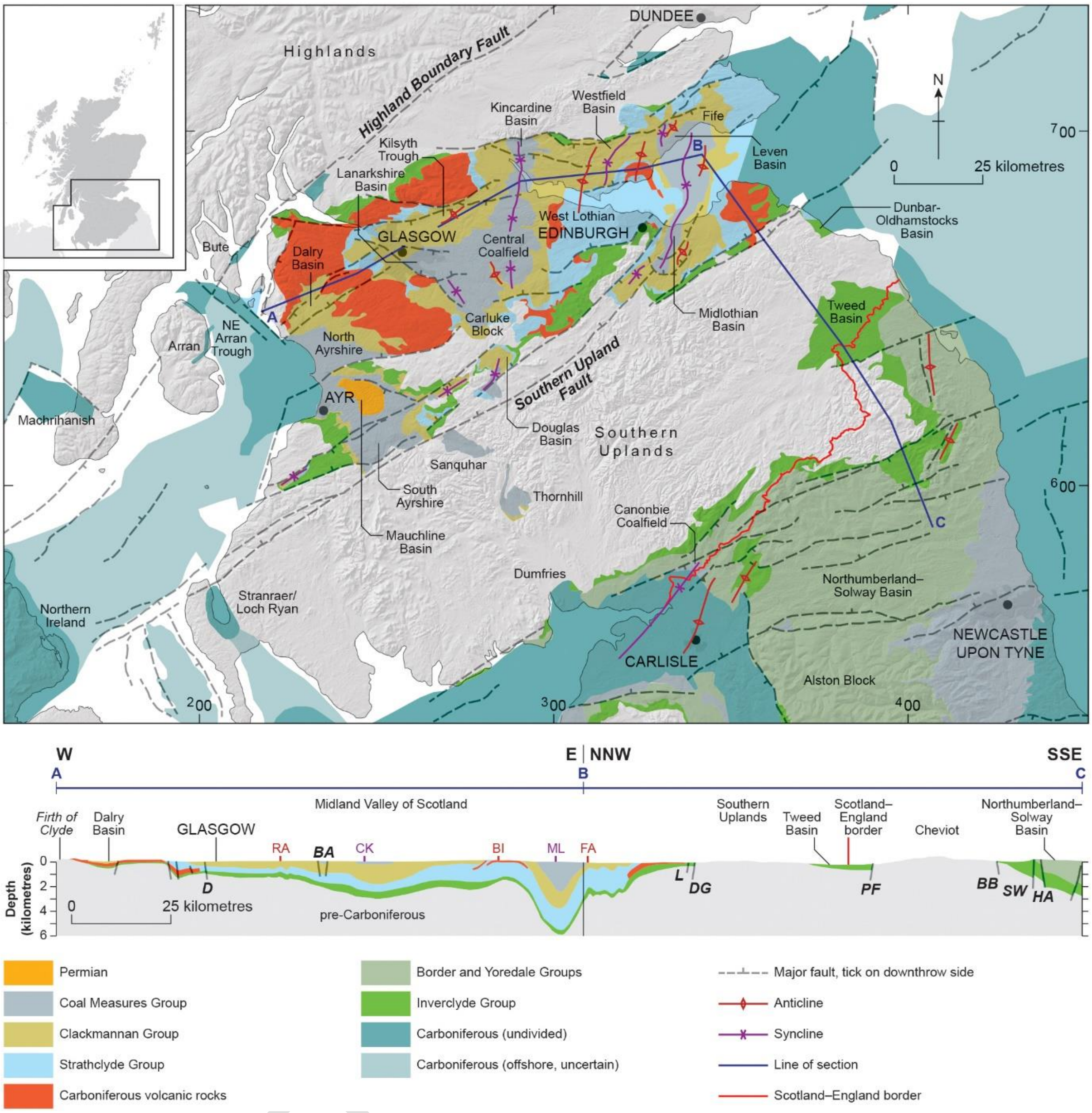


Fig. 10.3a (put on opposing page with 10.3b)

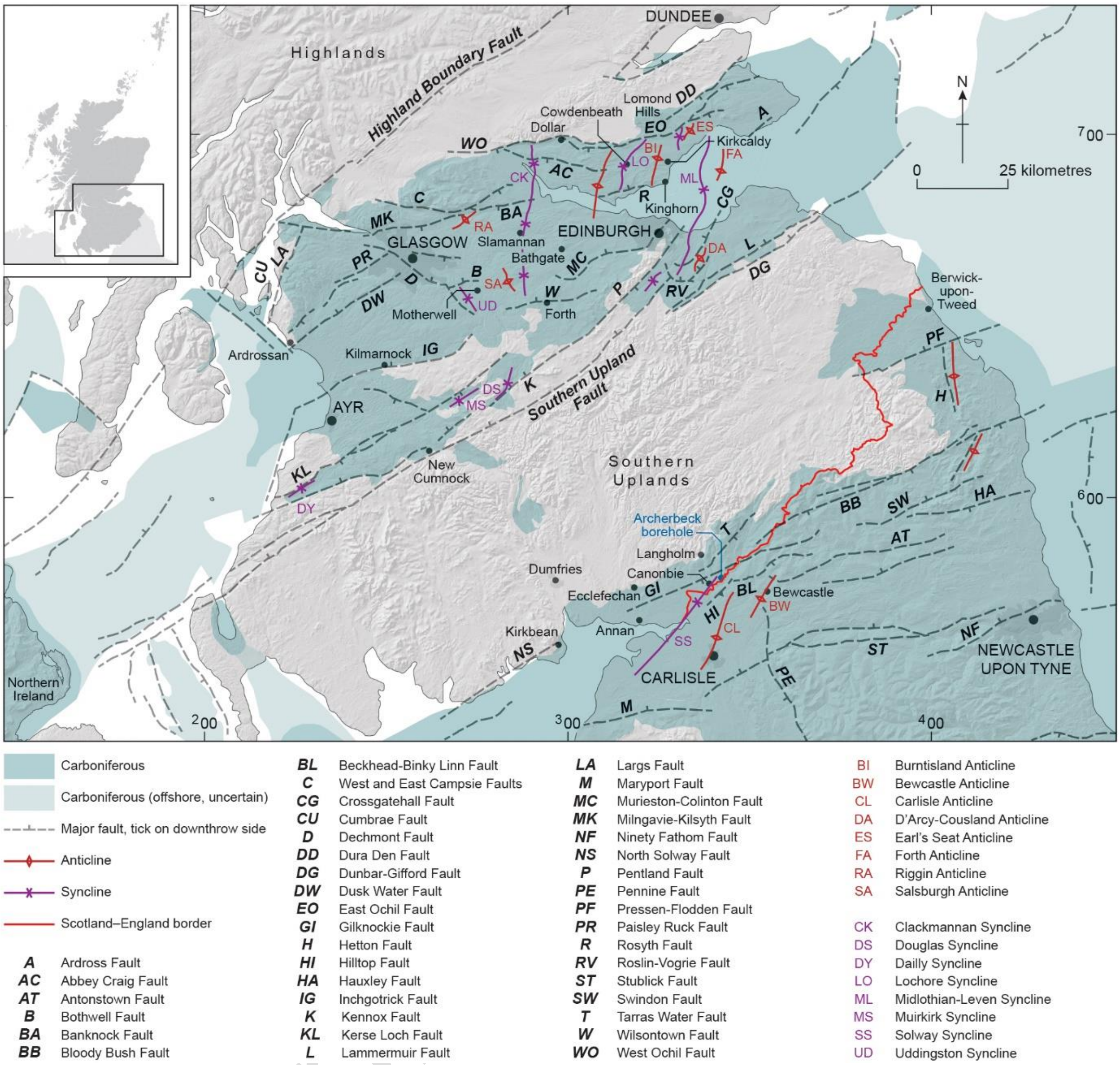
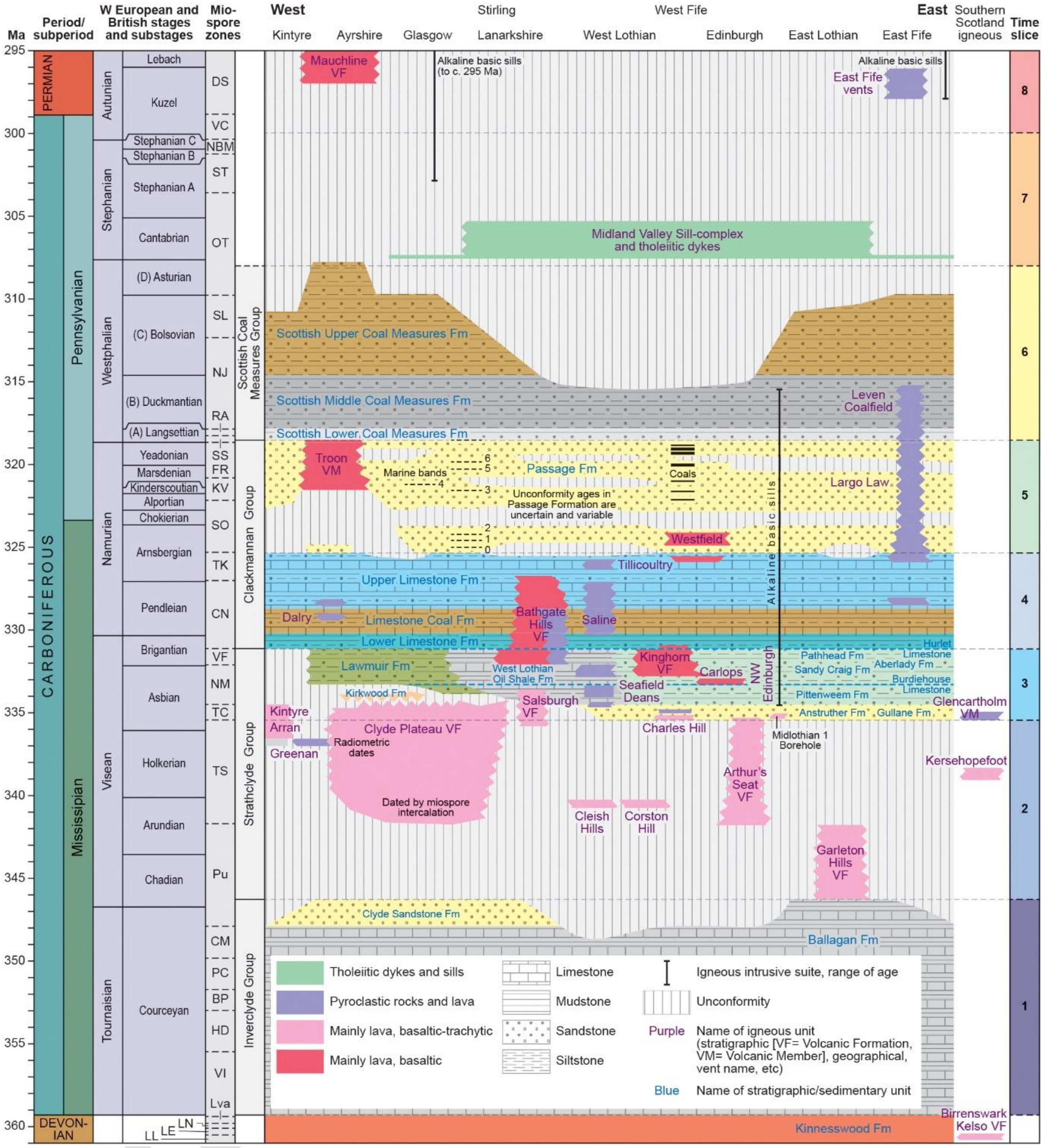
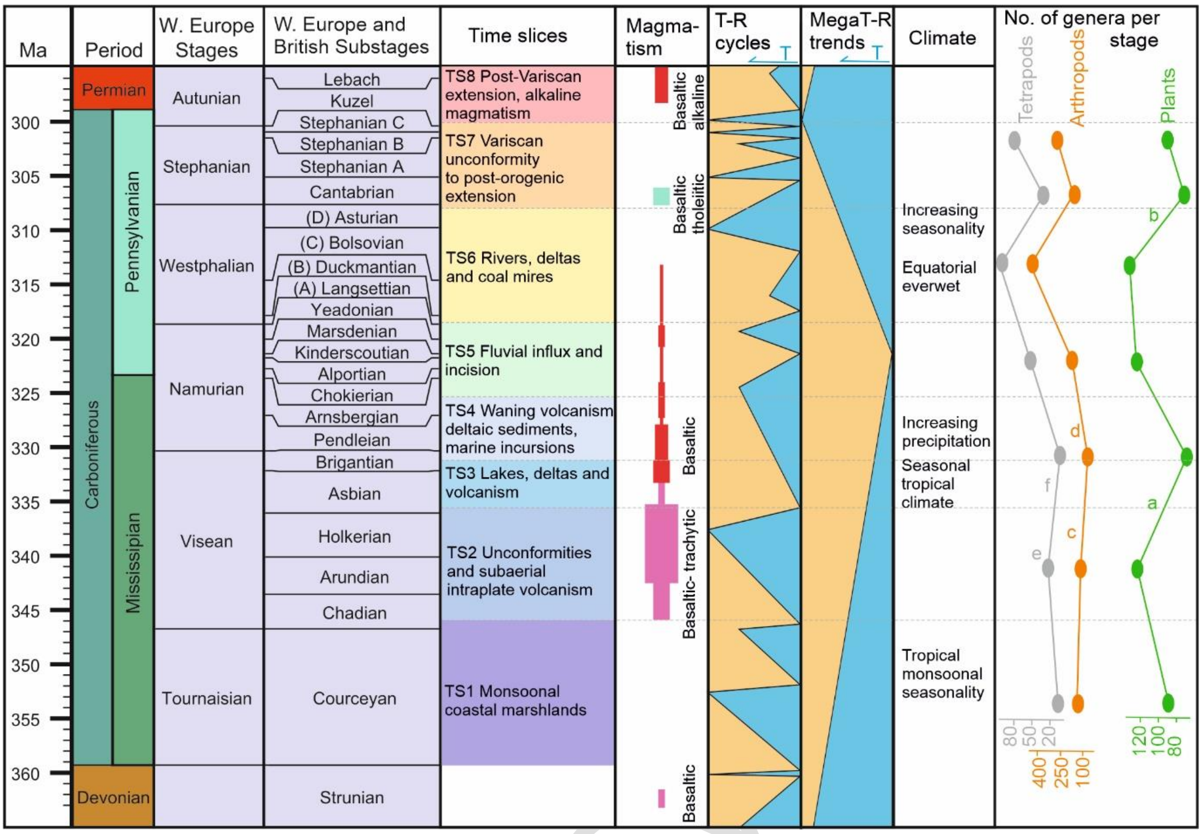


Fig 10.3b (put on opposing page with 10.3a)



Ma
Period/ subperiod
W European and British stages and substages
Mio-spore zones
West
Kintyre
Ayrshire
Glasgow
Stirling
Lanarkshire
West Fife
West Lothian
Edinburgh
East Lothian
East
East Fife
Southern Scotland igneous
Time slice
PERMIAN
CARBONIFEROUS
Pennsylvanian
Mississipian
DEVON-IAN
Autunian
Stephanian
Westphalian
Namurian
Visean
Tournaisian
Lebach
Kuzel
Stephanian C
Stephanian B
Stephanian A
Cantabrian
(D) Asturian
(C) Bolsovian
(B) Duckmantian
(A) Langsettian
Yeadonian
Marsdenian
Kinderscoutian
Alportian
Chokierian
Arnsbergian
Pendleian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Courceyan
DS
VC
NBM
ST
OT
SL
NJ
RA
SS
FR
KV
SO
TK
CN
VF
NM
TC
TS
Pu
CM
PC
BP
HD
VI
Lva
LL LE LN
Scottish Coal Measures Group
Clackmannan Group
Strathclyde Group
Inverclyde Group
Mauchline VF
Alkaline basic sills (to c. 295 Ma)
Alkaline basic sills
East Fife vents
Midland Valley Sill-complex and tholeiitic dykes
Scottish Upper Coal Measures Fm
Scottish Middle Coal Measures Fm
Scottish Lower Coal Measures Fm
Leven Coalfield
Troon VM
Marine bands
Passage Fm
Coals
Unconformity ages in Passage Formation are uncertain and variable
Largo Law
Westfield
Tillicoultry
Upper Limestone Fm
Dalry
Limestone Coal Fm
Bathgate Hills VF
Saline
Lower Limestone Fm
Alkaline basic sills
Hurlet
Lawmuir Fm
West Lothian Oil Shale Fm
Kinghorn VF
Carlops
NW Edinburgh
Pathhead Fm
Limestone
Aberlady Fm
Sandy Craig Fm
Burdiehouse Limestone
Seafield Deans
Pittenweem Fm
Glencartholm VM
Kirkwood Fm
Salsburgh VF
Kintyre
Arran
Clyde Plateau VF
Charles Hill
Anstruther Fm
Gullane Fm
Greenan
Radiometric dates
Midlothian 1 Borehole
Kersehopefoot
Arthur's Seat VF
Dated by miospore intercalation
Cleish Hills
Corston Hill
Garleton Hills VF
Clyde Sandstone Fm
Ballagan Fm
Tholeiitic dykes and sills
Pyroclastic rocks and lava
Mainly lava, basaltic-trachytic
Mainly lava, basaltic
Limestone
Mudstone
Sandstone
Siltstone
Igneous intrusive suite, range of age
Unconformity
Purple
Name of igneous unit (stratigraphic [VF= Volcanic Formation, VM= Volcanic Member], geographical, vent name, etc)
Blue
Name of stratigraphic/sedimentary unit
Birrenswark Kelso VF
Kinnesswood Fm

Fig 10.4



Ma
Period
W. Europe Stages
W. Europe and British Substages
Time slices
Magma-tism
T-R cycles
MegaT-R trends
Climate
No. of genera per stage
Tetrapods
Arthropods
Plants
Permian
Carboniferous
Pennsylvanian
Mississipian
Devonian
Autunian
Stephanian
Westphalian
Namurian
Visean
Tournaisian
Lebach
Kuzel
Stephanian C
Stephanian B
Stephanian A
Cantabrian
(D) Asturian
(C) Bolsovian
(B) Duckmantian
(A) Langsettian
Yeadonian
Marsdenian
Kinderscoutian
Alportian
Chokierian
Arnsbergian
Pendleian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Courceyan
Strunian
TS8 Post-Variscan extension, alkaline magmatism
TS7 Variscan unconformity to post-orogenic extension
TS6 Rivers, deltas and coal mires
TS5 Fluvial influx and incision
TS4 Waning volcanism deltaic sediments, marine incursions
TS3 Lakes, deltas and volcanism
TS2 Unconformities and subaerial intraplate volcanism
TS1 Monsoonal coastal marshlands
Basaltic alkaline
Basaltic tholeiitic
Basaltic
Basaltic- trachytic
Basaltic
Increasing seasonality
Equatorial everwet
Increasing precipitation
Seasonal tropical climate
Tropical monsoonal seasonality
300
305
310
315
320
325
330
335
340
345
350
355
360
80
50
20
400
250
100
120
100
80
a
b
c
d
e
f

Fig 10.5

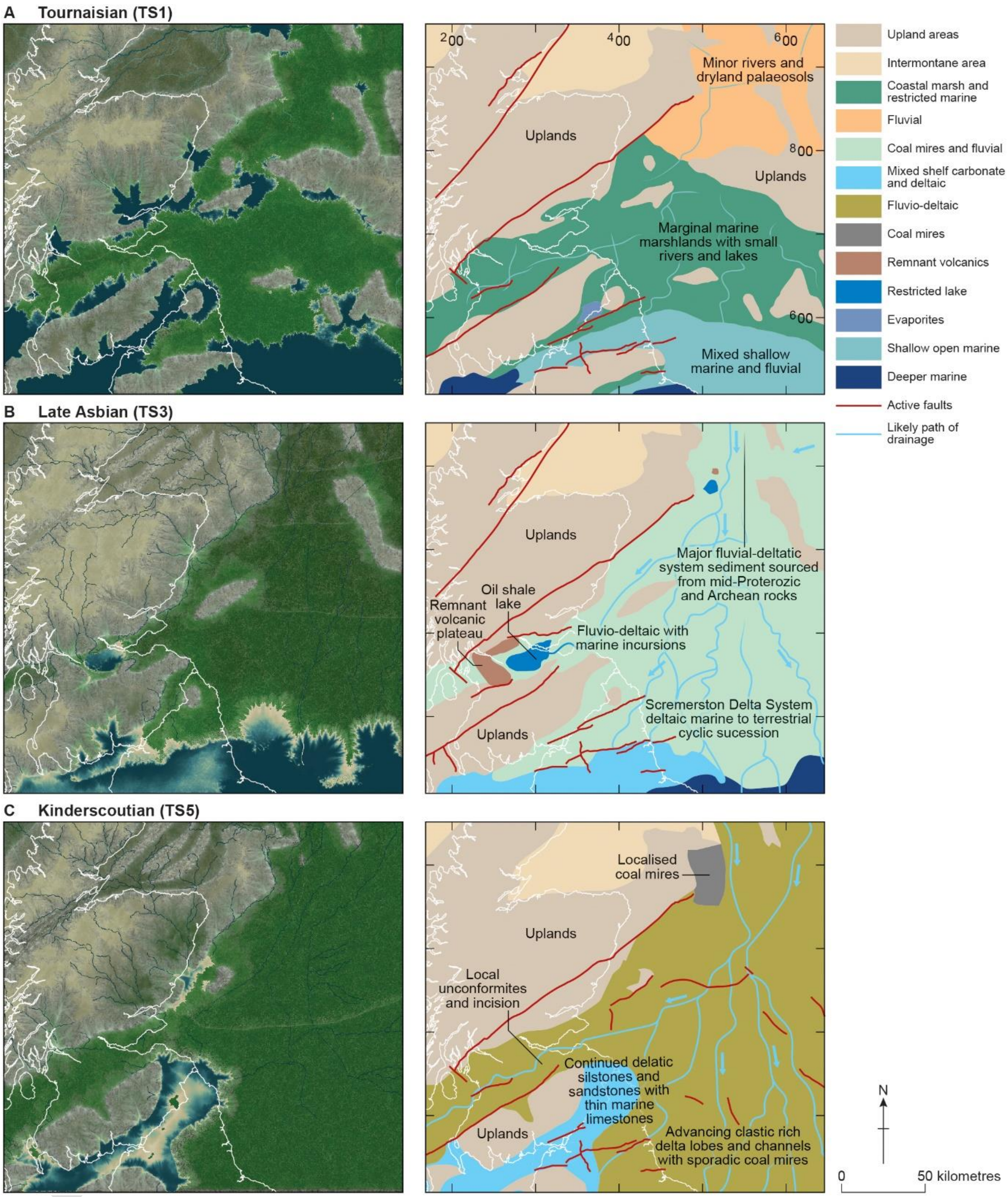
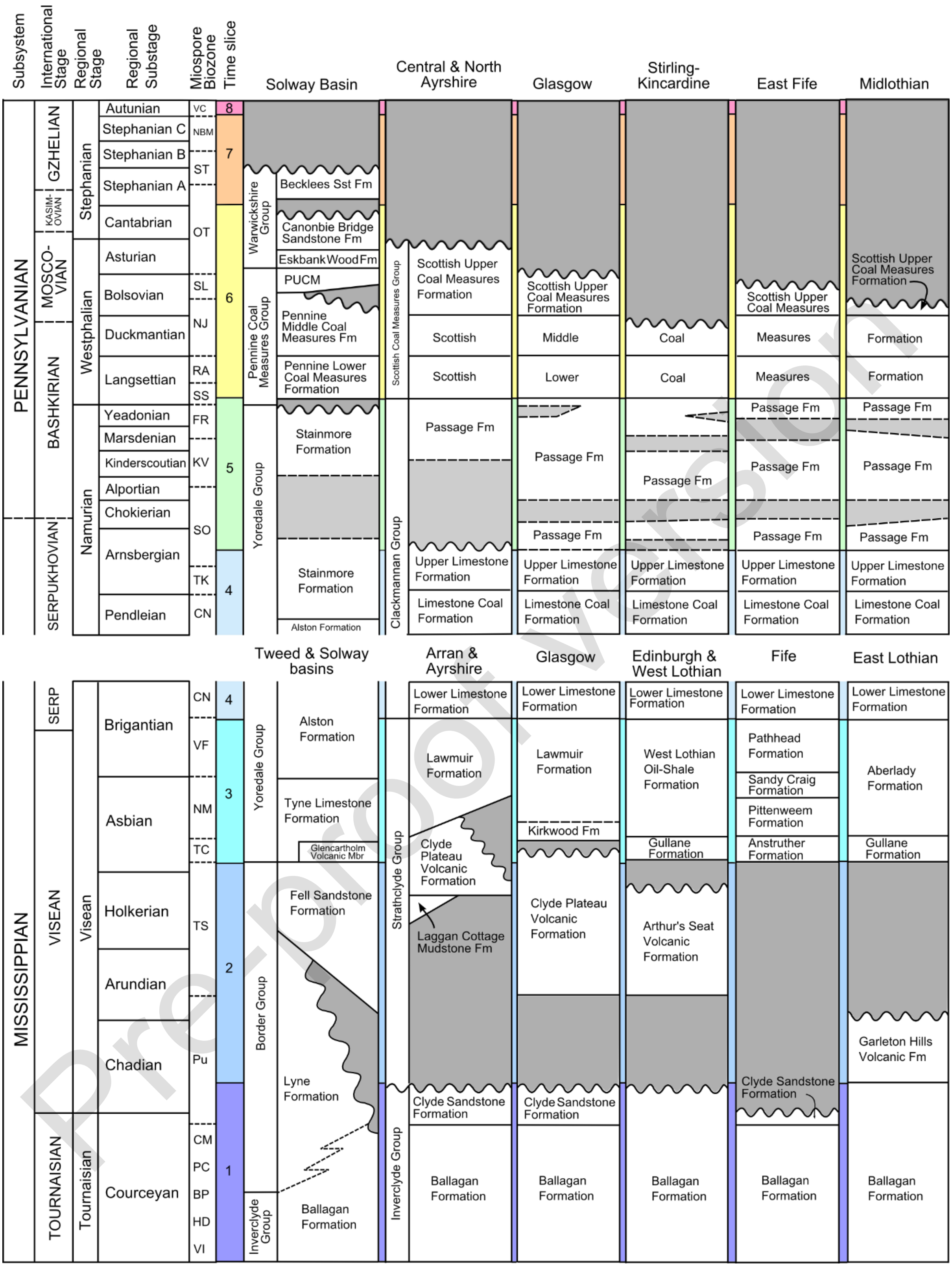

A Tournaisian (TS1)
B Late Asbian (TS3)
C Kinderscoutian (TS5)
200
400
600
800
600
Minor rivers and dryland palaeosols
Uplands
Uplands
Marginal marine marshlands with small rivers and lakes
Mixed shallow marine and fluvial
Uplands
Major fluvial-deltatic system sediment sourced from mid-Proterozic and Archean rocks
Oil shale lake
Remnant volcanic plateau
Fluvio-deltaic with marine incursions
Scremerston Delta System deltaic marine to terrestrial cyclic sucession
Uplands
Localised coal mires
Uplands
Local unconformites and incision
Continued delatic silstones and sandstones with thin marine limestones
Uplands
Advancing clastic rich delta lobes and channels with sporadic coal mires
Upland areas
Intermontane area
Coastal marsh and restricted marine
Fluvial
Coal mires and fluvial
Mixed shelf carbonate and deltaic
Fluvio-deltaic
Coal mires
Remnant volcanics
Restricted lake
Evaporites
Shallow open marine
Deeper marine
Active faults
Likely path of drainage
N
0
50 kilometres

Fig 10.6



Subsystem
International Stage
Regional Stage
Regional Substage
Miospore Biozone
Time slice
Solway Basin
Central & North Ayrshire
Glasgow
Stirling-Kincardine
East Fife
Midlothian
PENNSYLVANIAN
GZHELIAN
KASIM-OVIAN
MOSCO-VIAN
BASHKIRIAN
SERPUKHOVIAN
Stephanian
Westphalian
Namurian
Autunian
Stephanian C
Stephanian B
Stephanian A
Cantabrian
Asturian
Bolsovian
Duckmantian
Langsettian
Yeadonian
Marsdenian
Kinderscoutian
Alportian
Chokierian
Arnsbergian
Pendleian
VC
NBM
ST
OT
SL
NJ
RA
SS
FR
KV
SO
TK
CN
8
7
6
5
4
Warwickshire Group
Becklees Sst Fm
Canonbie Bridge Sandstone Fm
EskbankWoodFm
Pennine Coal Measures Group
PUCM
Pennine Middle Coal Measures Fm
Pennine Lower Coal Measures Formation
Yoredale Group
Stainmore Formation
Stainmore Formation
Alston Formation
Scottish Coal Measures Group
Clackmannan Group
Scottish Upper Coal Measures Formation
Scottish
Scottish
Passage Fm
Upper Limestone Formation
Limestone Coal Formation
Scottish Upper Coal Measures Formation
Middle
Lower
Passage Fm
Passage Fm
Upper Limestone Formation
Limestone Coal Formation
Coal
Coal
Passage Fm
Upper Limestone Formation
Limestone Coal Formation
Scottish Upper Coal Measures
Measures
Measures
Passage Fm
Passage Fm
Passage Fm
Upper Limestone Formation
Limestone Coal Formation
Scottish Upper Coal Measures Formation
Formation
Formation
Passage Fm
Passage Fm
Passage Fm
Upper Limestone Formation
Limestone Coal Formation
Tweed & Solway basins
Arran & Ayrshire
Glasgow
Edinburgh & West Lothian
Fife
East Lothian
MISSISSIPPIAN
SERP
VISEAN
TOURNAISIAN
Visean
Tournaisian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Courceyan
CN
VF
NM
TC
TS
Pu
CM
PC
BP
HD
VI
4
3
2
1
Yoredale Group
Border Group
Inverclyde Group
Alston Formation
Tyne Limestone Formation
Glencartholm Volcanic Mbr
Fell Sandstone Formation
Lyne Formation
Ballagan Formation
Strathclyde Group
Inverclyde Group
Lower Limestone Formation
Lawmuir Formation
Clyde Plateau Volcanic Formation
Laggan Cottage Mudstone Fm
Clyde Sandstone Formation
Ballagan Formation
Lower Limestone Formation
Lawmuir Formation
Kirkwood Fm
Clyde Plateau Volcanic Formation
Clyde Sandstone Formation
Ballagan Formation
Lower Limestone Formation
West Lothian Oil-Shale Formation
Gullane Formation
Arthur's Seat Volcanic Formation
Ballagan Formation
Lower Limestone Formation
Pathhead Formation
Sandy Craig Formation
Pittenweem Formation
Anstruther Formation
Clyde Sandstone Formation
Ballagan Formation
Lower Limestone Formation
Aberlady Formation
Gullane Formation
Garleton Hills Volcanic Fm
Ballagan Formation

Fig. 10.7

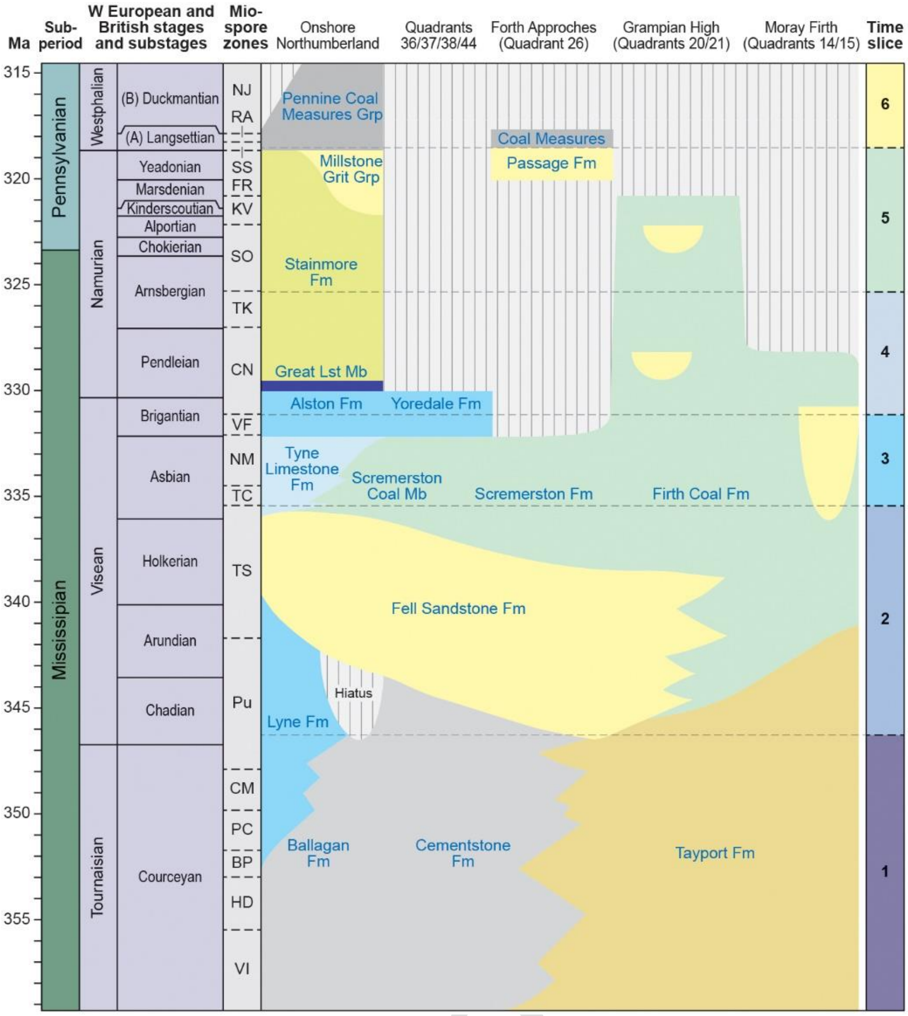


Fig 10.8

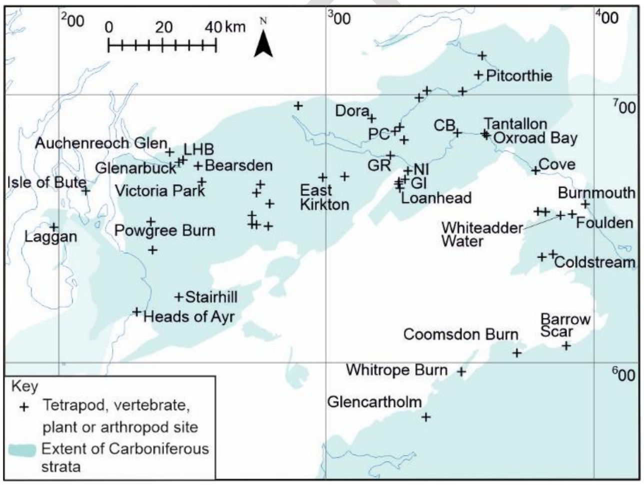
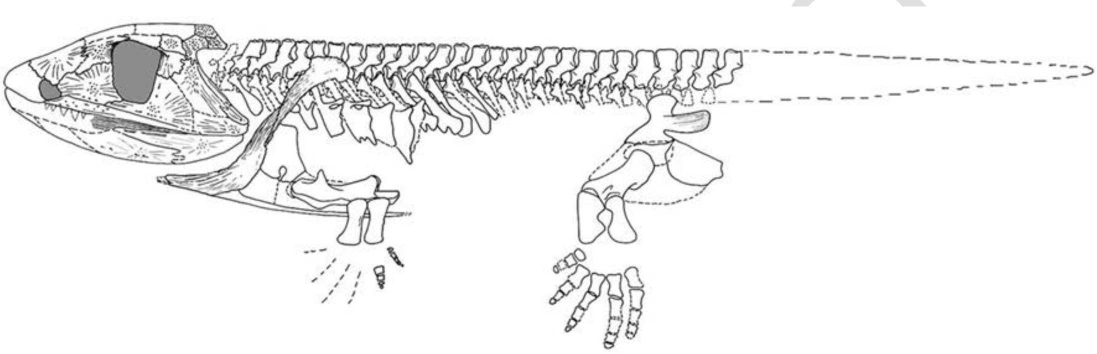


Fig 10.9



Topic box figures

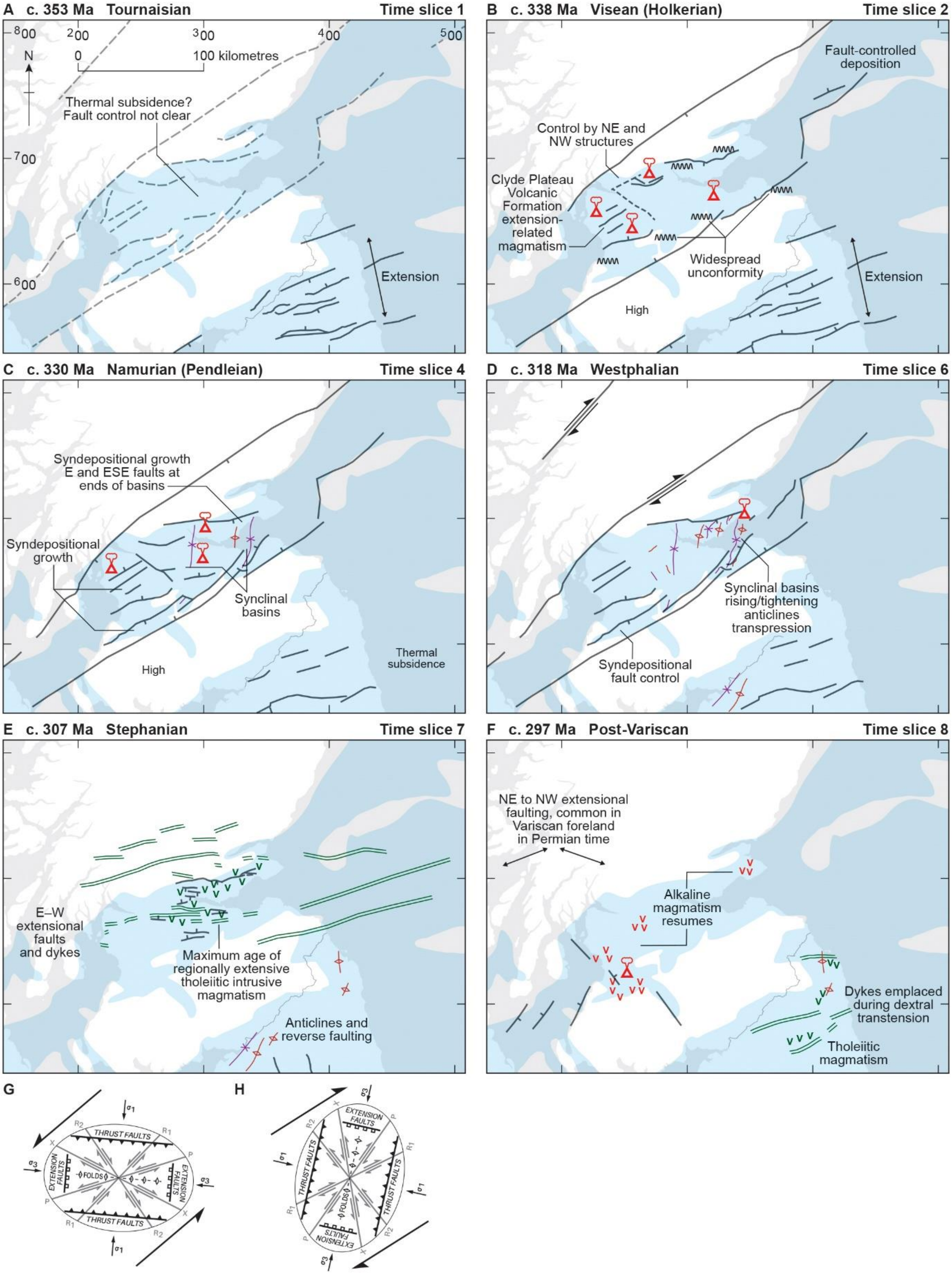

A c. 353 Ma Tournaisian
Time slice 1
800
200
300
400
500
700
600
N
0
100 kilometres
Thermal subsidence? Fault control not clear
Extension
B c. 338 Ma Visean (Holkerian)
Time slice 2
Fault-controlled deposition
Control by NE and NW structures
Clyde Plateau Volcanic Formation extension-related magmatism
Widespread unconformity
High
Extension
C c. 330 Ma Namurian (Pendleian)
Time slice 4
Syndepositional growth E and ESE faults at ends of basins
Syndepositional growth
Synclinal basins
High
Thermal subsidence
D c. 318 Ma Westphalian
Time slice 6
Synclinal basins rising/tightening anticlines transpression
Syndepositional fault control
E c. 307 Ma Stephanian
Time slice 7
E–W extensional faults and dykes
Maximum age of regionally extensive tholeiitic intrusive magmatism
Anticlines and reverse faulting
F c. 297 Ma Post-Variscan
Time slice 8
NE to NW extensional faulting, common in Variscan foreland in Permian time
Alkaline magmatism resumes
Dykes emplaced during dextral transtension
Tholeiitic magmatism
G
THRUST FAULTS
EXTENSION FAULTS
FOLDS
H
EXTENSION FAULTS
THRUST FAULTS
FOLDS

Fig. 10.10

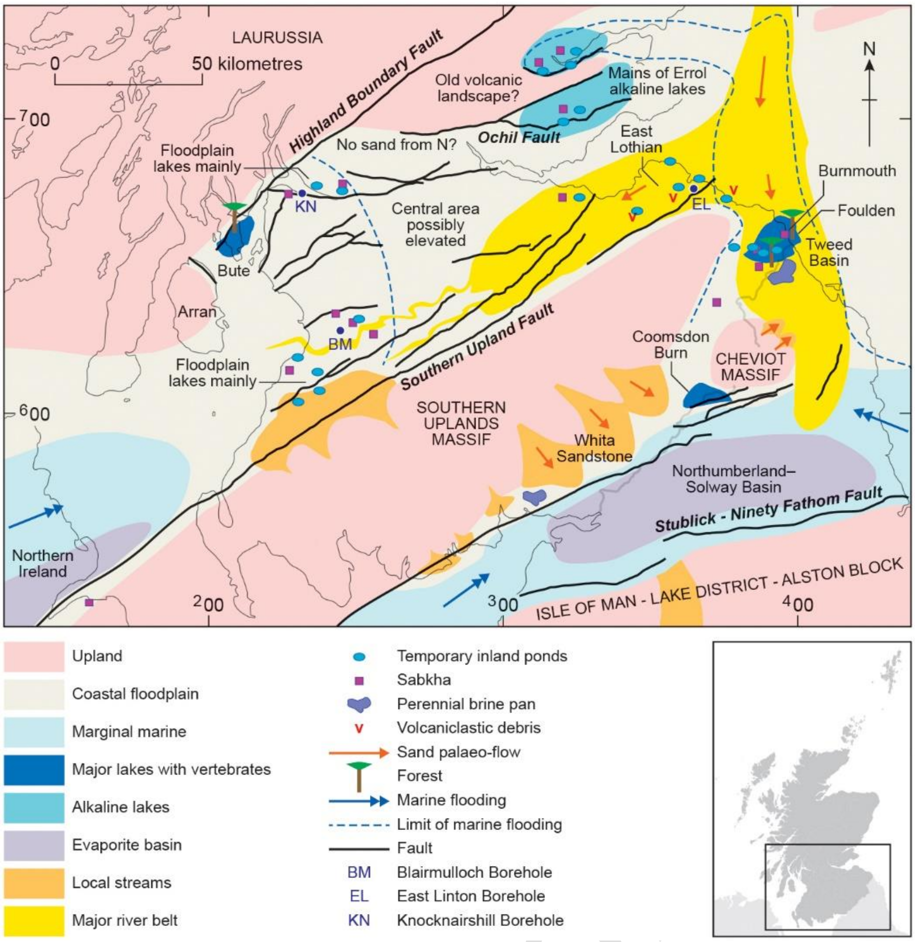


Fig 10.11

Fig 10.12

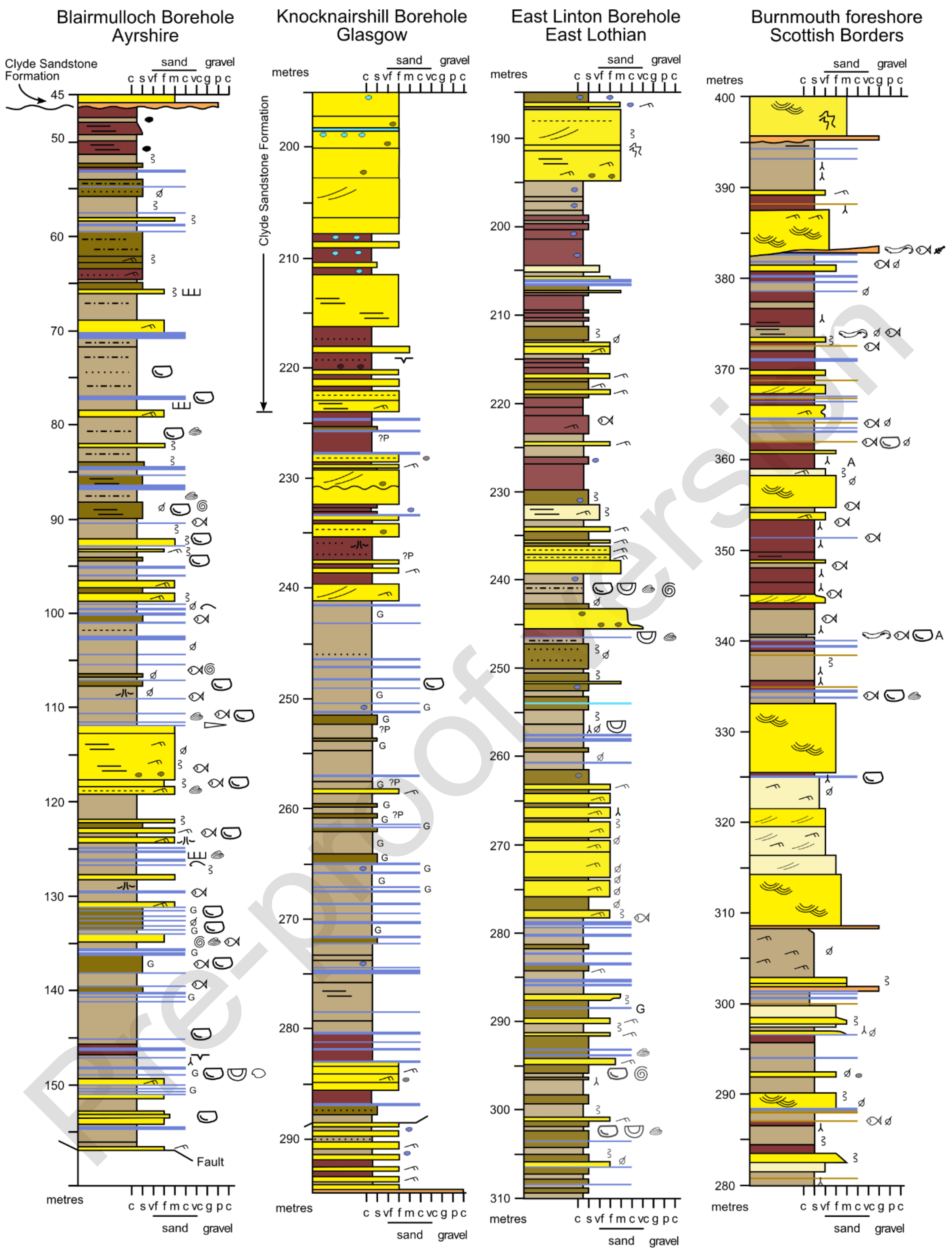

Blairmulloch Borehole
Ayrshire
Clyde Sandstone Formation
Knocknairshill Borehole
Glasgow
Clyde Sandstone Formation
East Linton Borehole
East Lothian
Burnmouth foreshore
Scottish Borders
metres
sand
gravel
c s vf f m c vc g p c
Fault

Fig. 10.13a

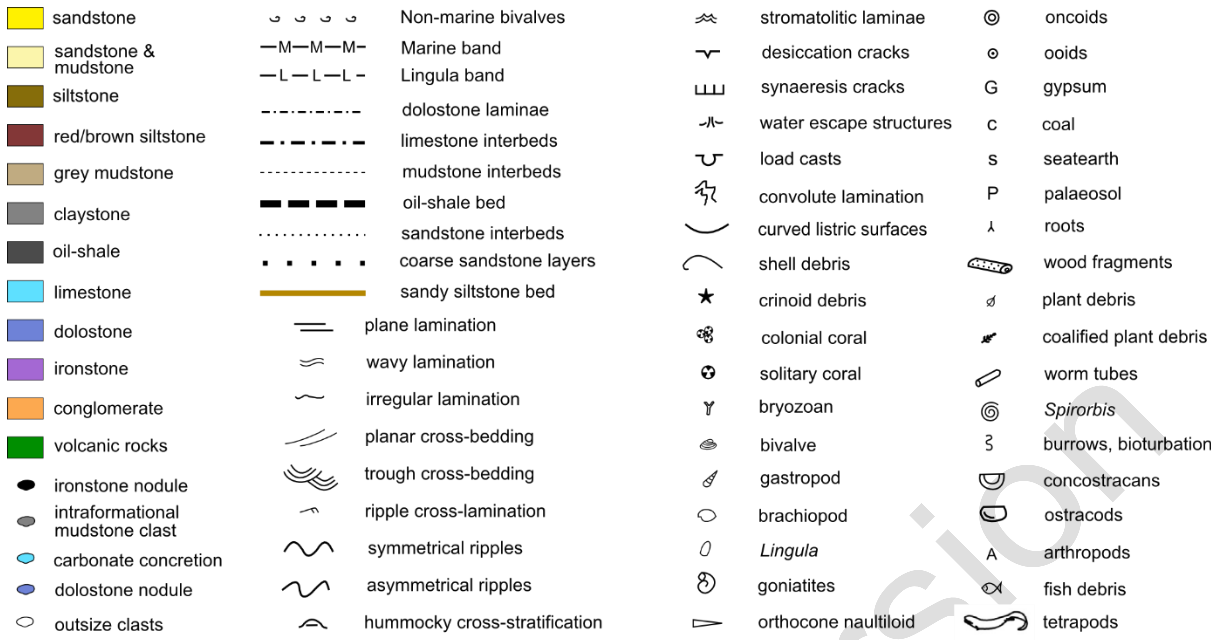


Fig 10.13 b (key)

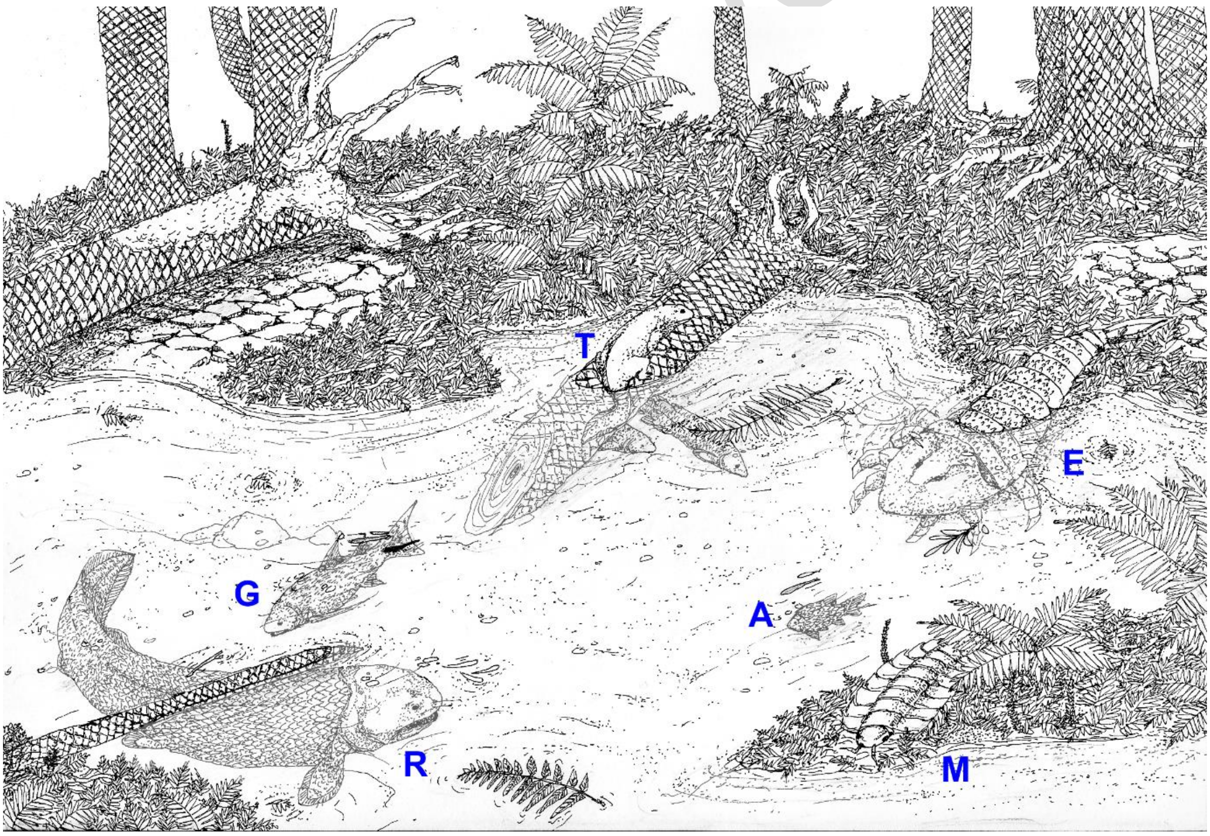


Fig. 10.14

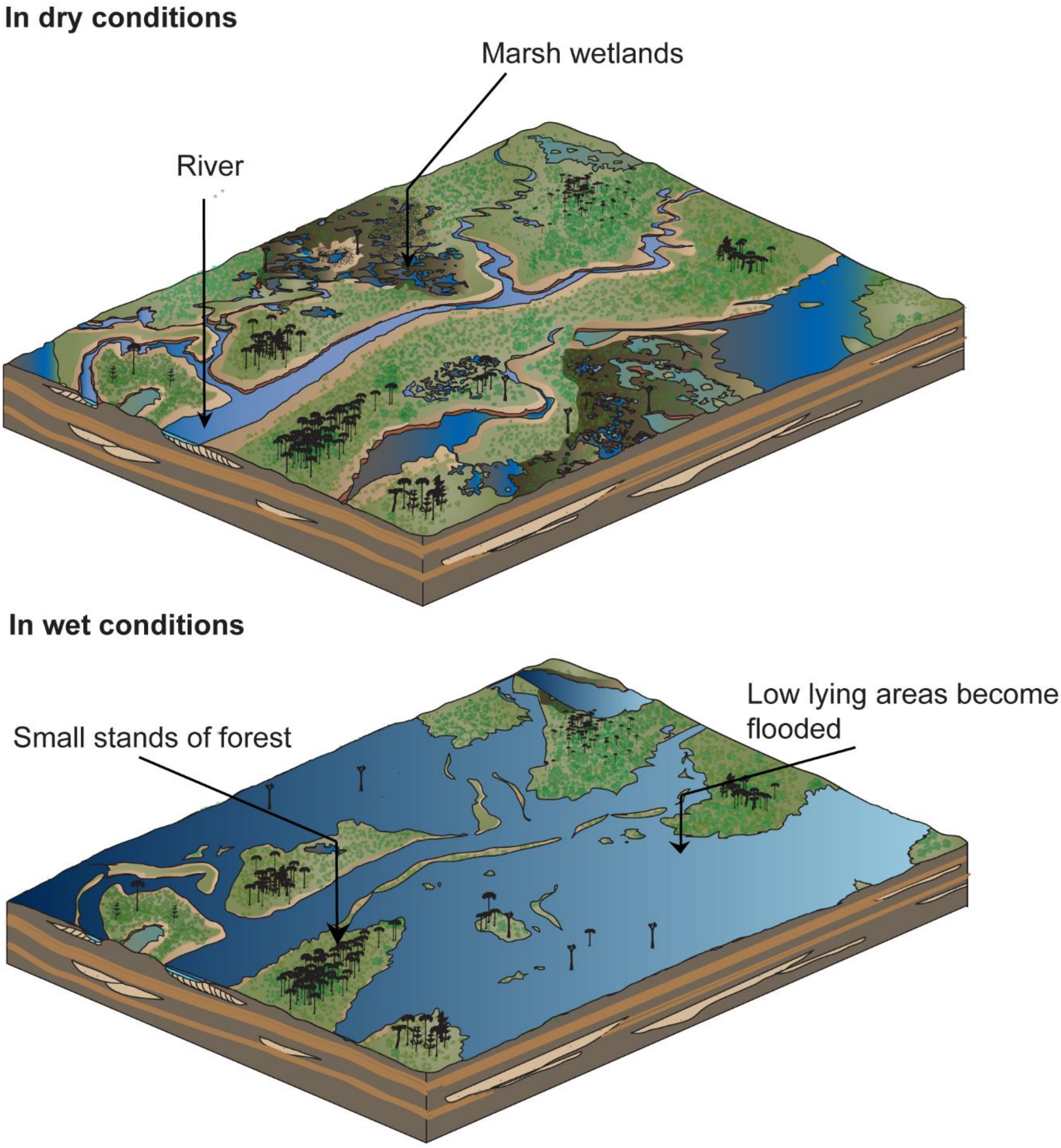

In dry conditions
Marsh wetlands
River
In wet conditions
Small stands of forest
Low lying areas become flooded

Fig 10.15

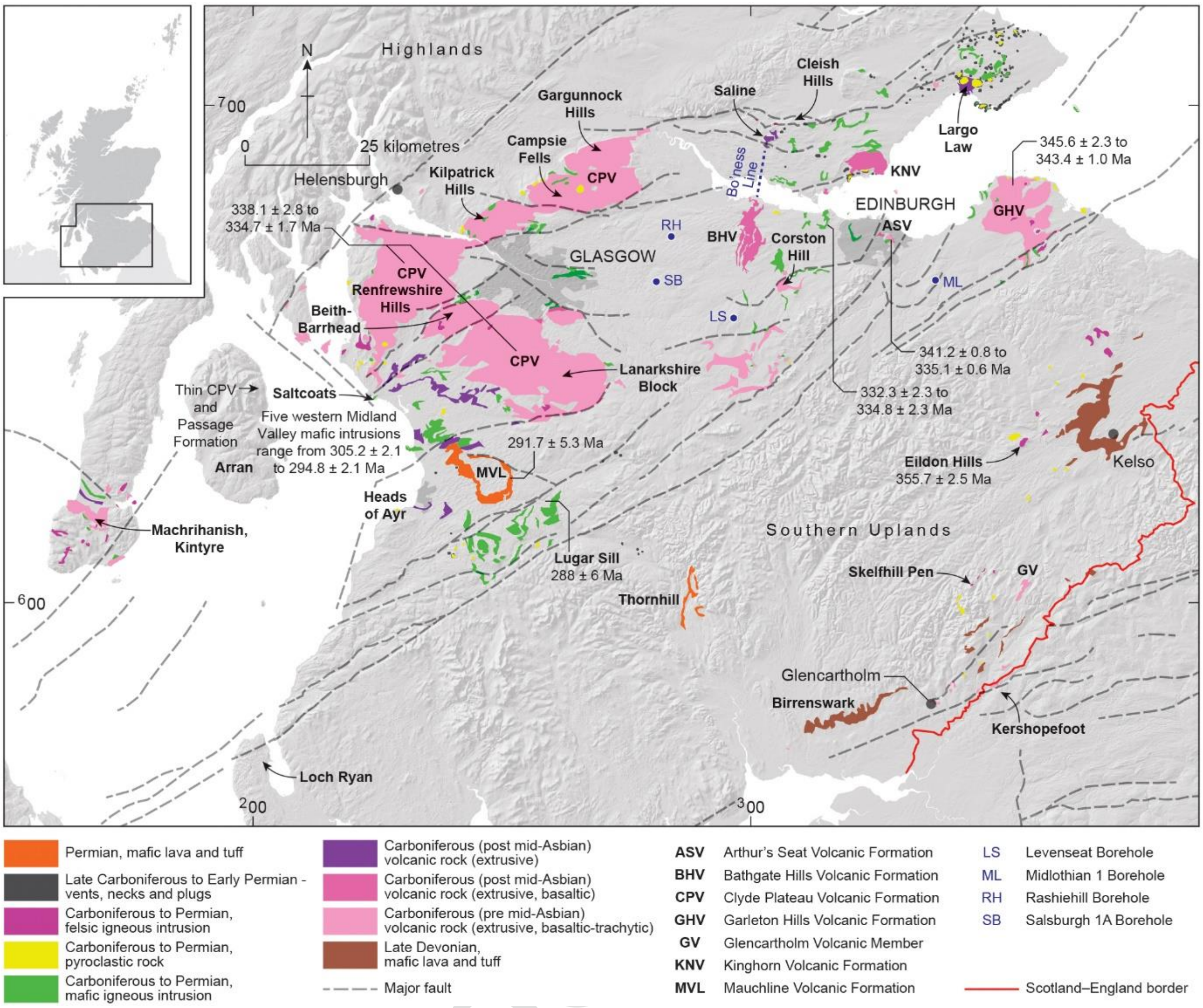

N
Highlands
700
0
25 kilometres
Helensburgh
Gargunnock Hills
Campsie Fells
Kilpatrick Hills
CPV
Saline
Cleish Hills
Largo Law
Bo'ness Line
KNV
345.6 ± 2.3 to 343.4 ± 1.0 Ma
EDINBURGH
GHV
ASV
338.1 ± 2.8 to 334.7 ± 1.7 Ma
RH
BHV
Corston Hill
GLASGOW
SB
ML
LS
CPV
Renfrewshire Hills
Beith-Barrhead
CPV
Lanarkshire Block
341.2 ± 0.8 to 335.1 ± 0.6 Ma
332.3 ± 2.3 to 334.8 ± 2.3 Ma
Thin CPV and Passage Formation
Saltcoats
Five western Midland Valley mafic intrusions range from 305.2 ± 2.1 to 294.8 ± 2.1 Ma
Arran
291.7 ± 5.3 Ma
MVL
Heads of Ayr
Eildon Hills 355.7 ± 2.5 Ma
Kelso
Machrihanish, Kintyre
Southern Uplands
Lugar Sill 288 ± 6 Ma
Skelfhill Pen
GV
600
Thornhill
Glencartholm
Birrenswark
Kershopefoot
Loch Ryan
200
300
Permian, mafic lava and tuff
Late Carboniferous to Early Permian - vents, necks and plugs
Carboniferous to Permian, felsic igneous intrusion
Carboniferous to Permian, pyroclastic rock
Carboniferous to Permian, mafic igneous intrusion
Carboniferous (post mid-Asbian) volcanic rock (extrusive)
Carboniferous (post mid-Asbian) volcanic rock (extrusive, basaltic)
Carboniferous (pre mid-Asbian) volcanic rock (extrusive, basaltic-trachytic)
Late Devonian, mafic lava and tuff
Major fault
ASV Arthur's Seat Volcanic Formation
BHV Bathgate Hills Volcanic Formation
CPV Clyde Plateau Volcanic Formation
GHV Garleton Hills Volcanic Formation
GV Glencartholm Volcanic Member
KNV Kinghorn Volcanic Formation
MVL Mauchline Volcanic Formation
LS Levenseat Borehole
ML Midlothian 1 Borehole
RH Rashiehill Borehole
SB Salsburgh 1A Borehole
Scotland–England border

Fig. 10.16

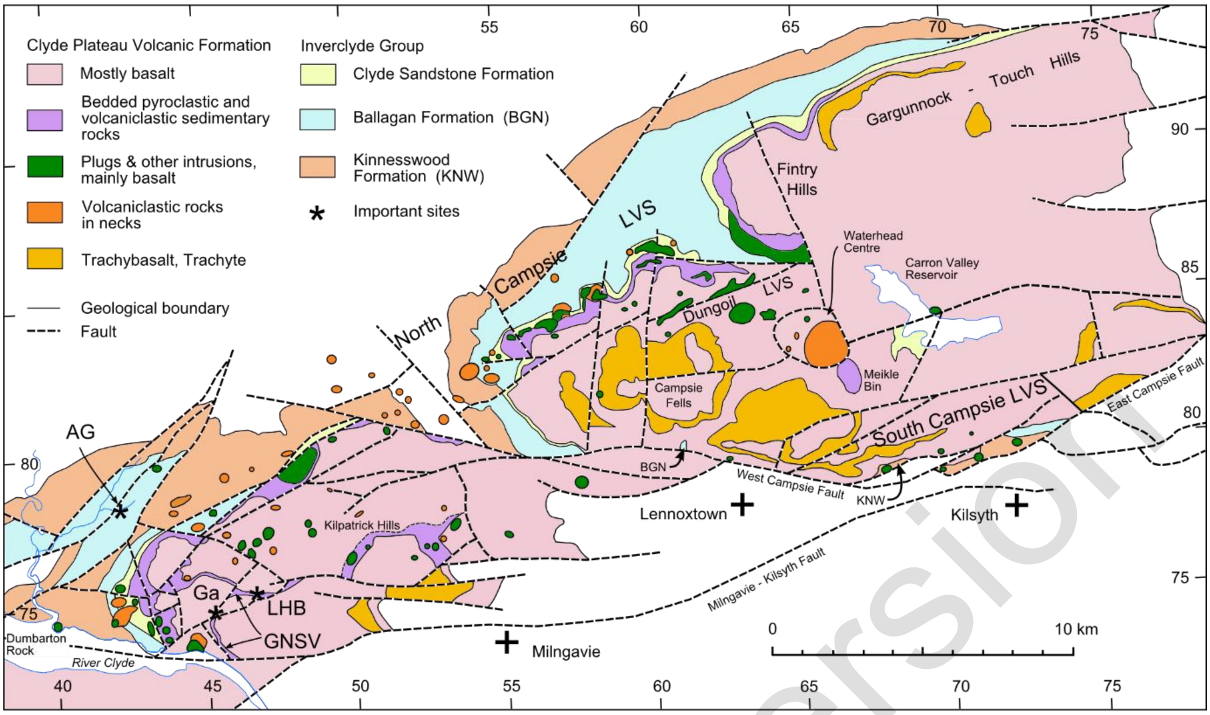


Fig 10.17

Fig 10.18

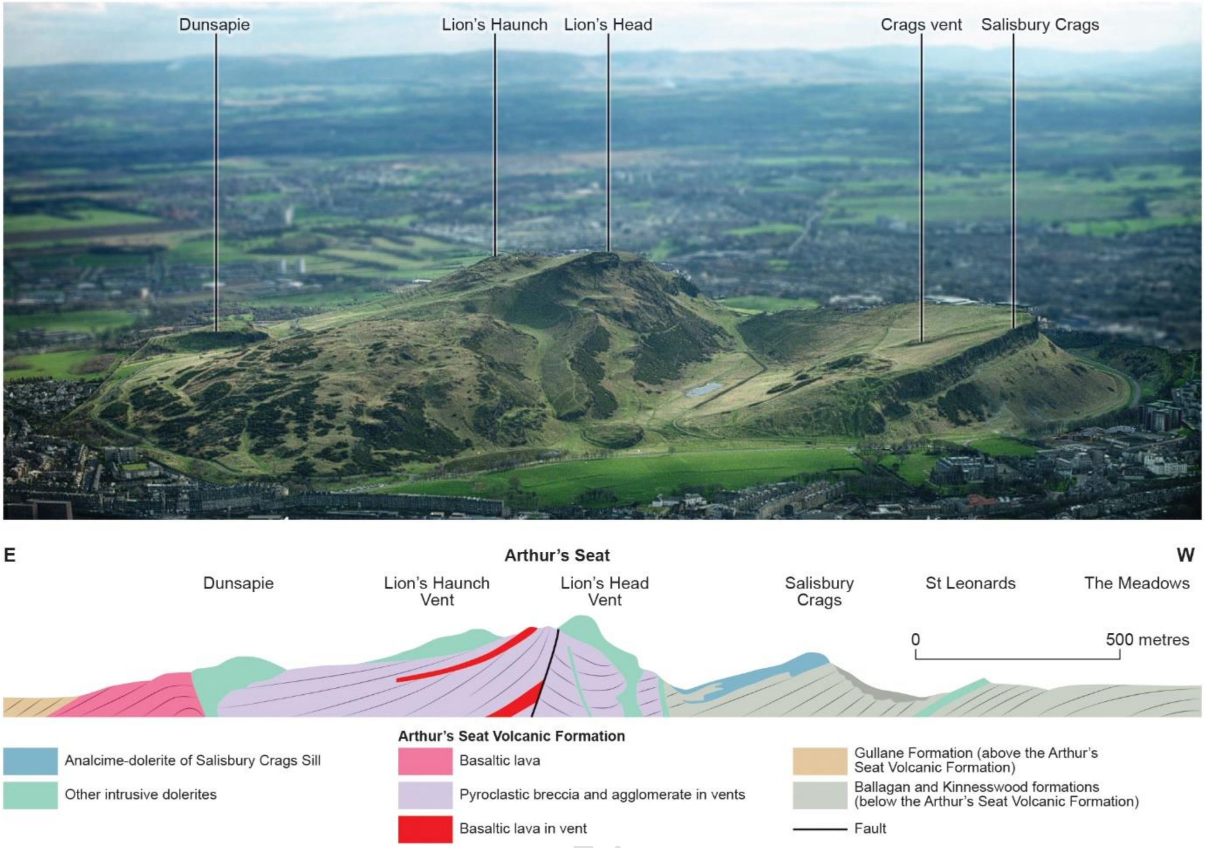

Dunsapie
Lion's Haunch
Lion's Head
Crags vent
Salisbury Crags
E
Arthur's Seat
W
Dunsapie
Lion's Haunch Vent
Lion's Head Vent
Salisbury Crags
St Leonards
The Meadows
0
500 metres
Arthur's Seat Volcanic Formation
Analcime-dolerite of Salisbury Crags Sill
Other intrusive dolerites
Basaltic lava
Pyroclastic breccia and agglomerate in vents
Basaltic lava in vent
Gullane Formation (above the Arthur's Seat Volcanic Formation)
Ballagan and Kinnesswood formations (below the Arthur's Seat Volcanic Formation)
Fault

Fig. 10.19

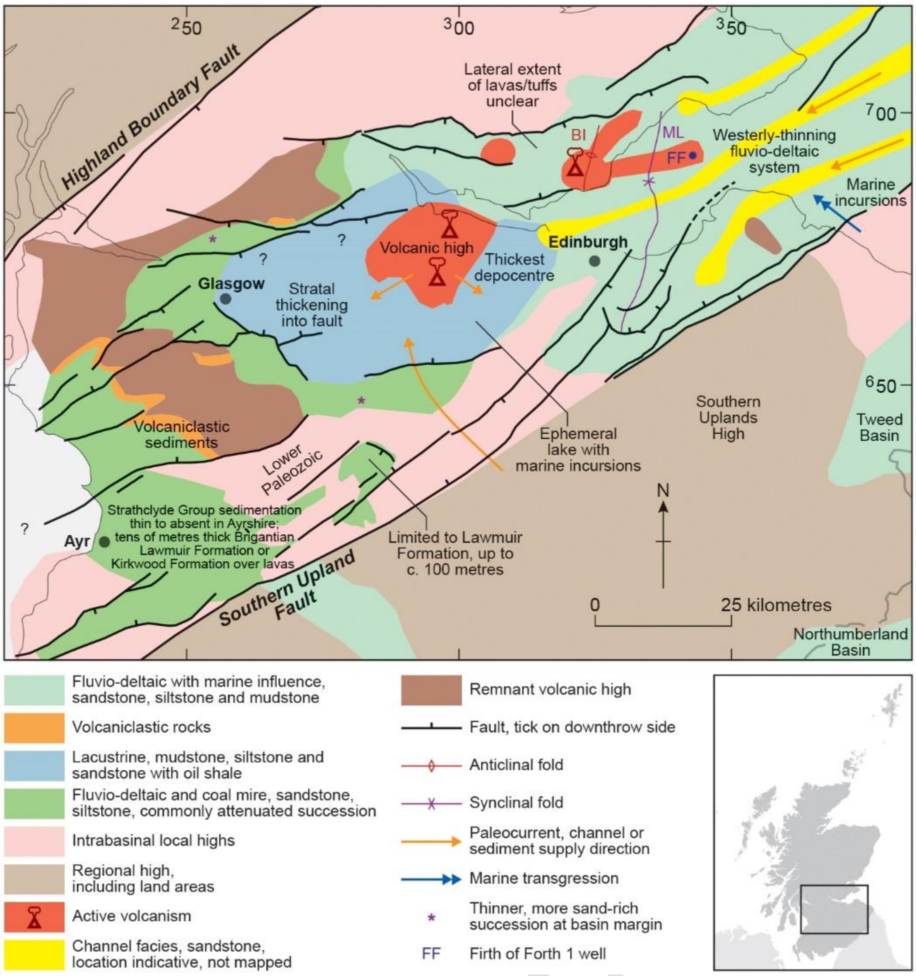

250
300
350
700
650
Highland Boundary Fault
Lateral extent of lavas/tuffs unclear
BI
ML
FF
Westerly-thinning fluvio-deltaic system
Marine incursions
Volcanic high
Edinburgh
Thickest depocentre
Glasgow
Stratal thickening into fault
?
Volcaniclastic sediments
Lower Paleozoic
Ephemeral lake with marine incursions
Southern Uplands High
Tweed Basin
Strathclyde Group sedimentation thin to absent in Ayrshire; tens of metres thick Brigantian Lawmuir Formation or Kirkwood Formation over lavas
Ayr
Limited to Lawmuir Formation, up to c. 100 metres
N
Southern Upland Fault
0
25 kilometres
Northumberland Basin
Fluvio-deltaic with marine influence, sandstone, siltstone and mudstone
Volcaniclastic rocks
Lacustrine, mudstone, siltstone and sandstone with oil shale
Fluvio-deltaic and coal mire, sandstone, siltstone, commonly attenuated succession
Intrabasinal local highs
Regional high, including land areas
Active volcanism
Channel facies, sandstone, location indicative, not mapped
Remnant volcanic high
Fault, tick on downthrow side
Anticlinal fold
Synclinal fold
Paleocurrent, channel or sediment supply direction
Marine transgression
Thinner, more sand-rich succession at basin margin
FF Firth of Forth 1 well

Fig. 10.20

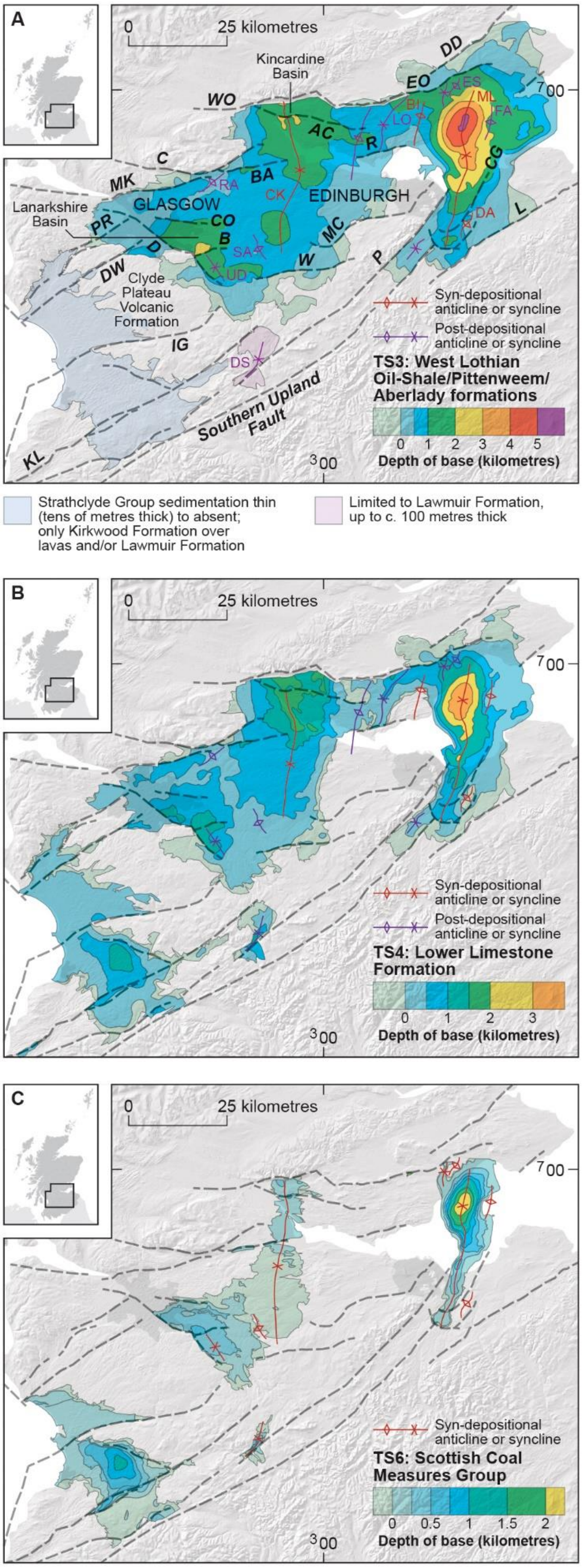

A
0
25 kilometres
Kincardine Basin
DD
EO
WO
ES
ML
FA
BI
LO
AC
R
C
MK
RA
BA
CK
EDINBURGH
CG
GLASGOW
Lanarkshire Basin
PR
CO
B
D
SA
MC
W
P
DA
L
UD
DW
Clyde Plateau Volcanic Formation
IG
DS
Southern Upland Fault
KL
Syn-depositional anticline or syncline
Post-depositional anticline or syncline
TS3: West Lothian Oil-Shale/Pittenweem/ Aberlady formations
0 1 2 3 4 5
Depth of base (kilometres)
Strathclyde Group sedimentation thin (tens of metres thick) to absent; only Kirkwood Formation over lavas and/or Lawmuir Formation
Limited to Lawmuir Formation, up to c. 100 metres thick
B
0
25 kilometres
Syn-depositional anticline or syncline
Post-depositional anticline or syncline
TS4: Lower Limestone Formation
0 1 2 3
Depth of base (kilometres)
C
0
25 kilometres
Syn-depositional anticline or syncline
TS6: Scottish Coal Measures Group
0 0.5 1 1.5 2
Depth of base (kilometres)

Fig. 10.21

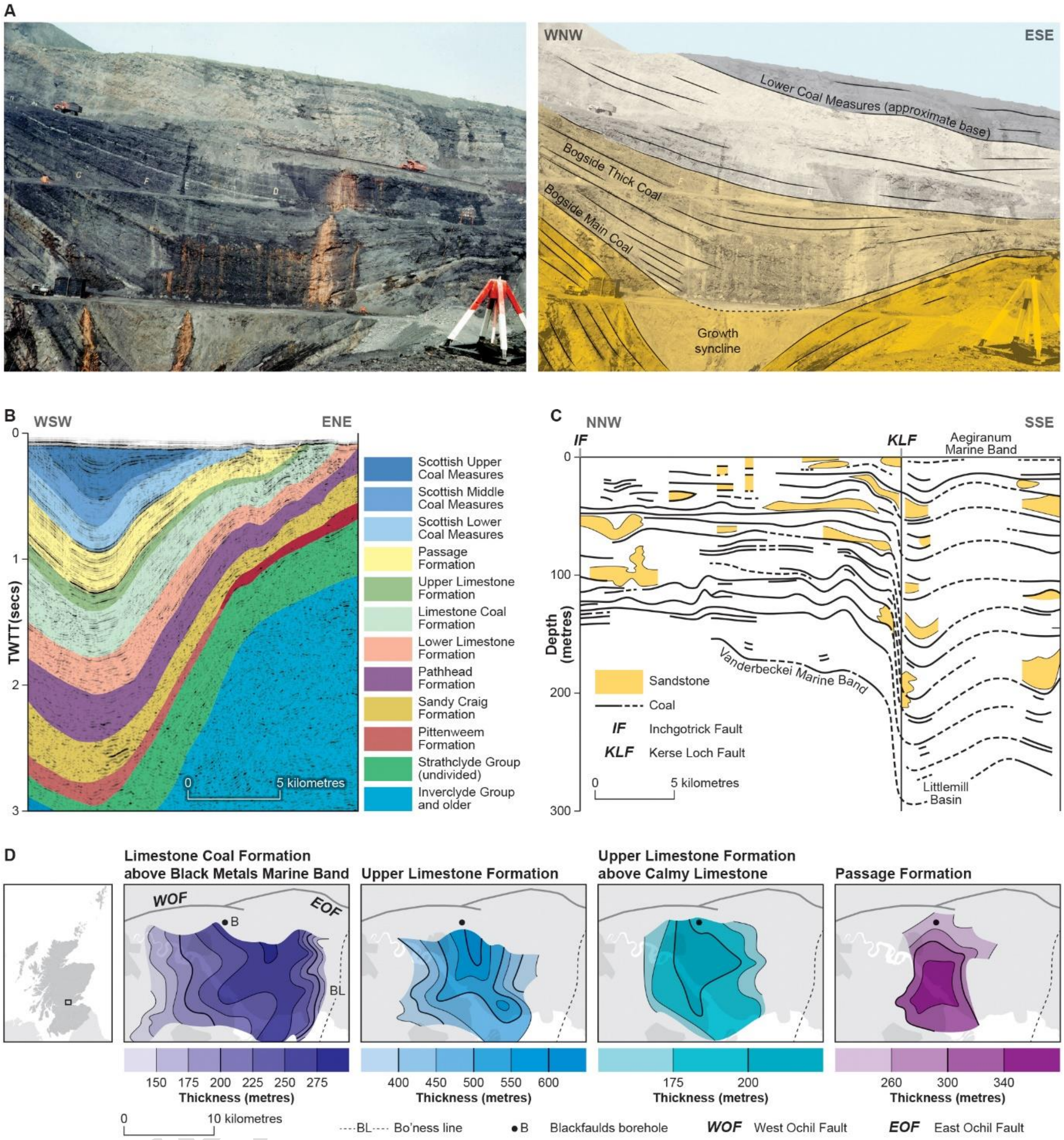
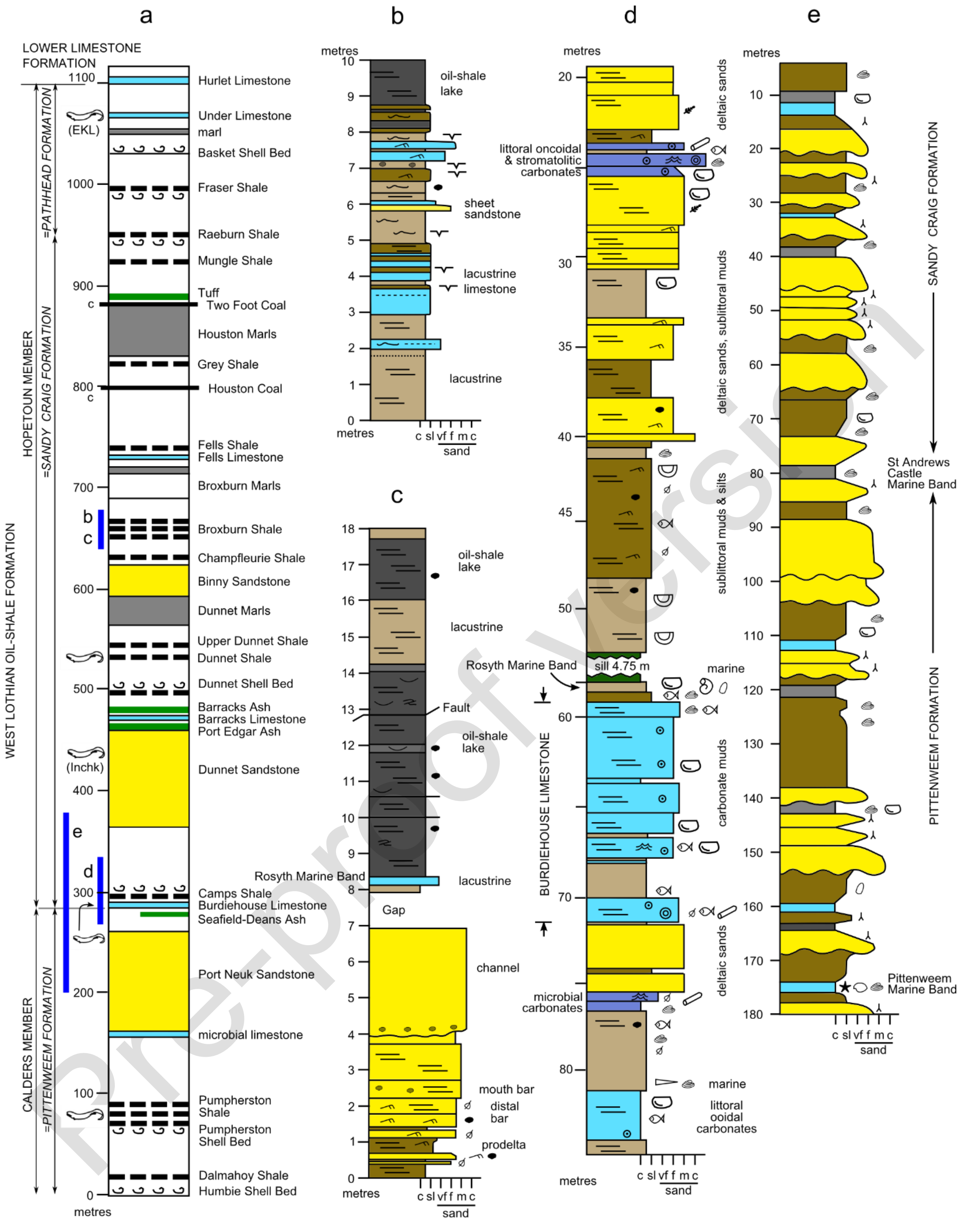

A
WNW
ESE
Lower Coal Measures (approximate base)
Bogside Thick Coal
Bogside Main Coal
Growth syncline
B
WSW
ENE
TWTT(secs)
0
1
2
3
0
5 kilometres
Scottish Upper Coal Measures
Scottish Middle Coal Measures
Scottish Lower Coal Measures
Passage Formation
Upper Limestone Formation
Limestone Coal Formation
Lower Limestone Formation
Pathhead Formation
Sandy Craig Formation
Pittenweem Formation
Strathclyde Group (undivided)
Inverclyde Group and older
C
NNW
SSE
IF
KLF
Aegiranum Marine Band
Depth (metres)
0
100
200
300
Vanderbeckei Marine Band
Sandstone
Coal
IF Inchgotrick Fault
KLF Kerse Loch Fault
0
5 kilometres
Littlemill Basin
D
Limestone Coal Formation above Black Metals Marine Band
Upper Limestone Formation
Upper Limestone Formation above Calmy Limestone
Passage Formation
WOF
EOF
B
BL
150 175 200 225 250 275
Thickness (metres)
400 450 500 550 600
Thickness (metres)
175 200
Thickness (metres)
260 300 340
Thickness (metres)
0
10 kilometres
BL Bo'ness line
B Blackfaulds borehole
WOF West Ochil Fault
EOF East Ochil Fault

Fig. 10.22



a
b
c
d
e
LOWER LIMESTONE FORMATION
Hurlet Limestone
Under Limestone
(EKL)
marl
Basket Shell Bed
Fraser Shale
Raeburn Shale
Mungle Shale
Tuft
Two Foot Coal
Houston Marls
Grey Shale
Houston Coal
Fells Shale
Fells Limestone
Broxburn Marls
Broxburn Shale
Champfleurie Shale
Binny Sandstone
Dunnet Marls
Upper Dunnet Shale
Dunnet Shale
Dunnet Shell Bed
Barracks Ash
Barracks Limestone
Port Edgar Ash
(Inchk)
Dunnet Sandstone
Camps Shale
Burdiehouse Limestone
Seafield-Deans Ash
Port Neuk Sandstone
microbial limestone
Pumpherston Shale
Pumpherston Shell Bed
Dalmahoy Shale
Humbie Shell Bed
metres
=PATHHEAD FORMATION
HOPETOUN MEMBER
=SANDY CRAIG FORMATION
WEST LOTHIAN OIL-SHALE FORMATION
CALDERS MEMBER
=PITTENWEEM FORMATION
oil-shale lake
sheet sandstone
lacustrine limestone
lacustrine
c sl vf f m c
sand
Fault
Rosyth Marine Band
Gap
channel
mouth bar
distal bar
prodelta
littoral oncoidal & stromatolitic carbonates
deltaic sands
deltaic sands, sublittoral muds
sublittoral muds & silts
sill 4.75 m
marine
BURDIEHOUSE LIMESTONE
carbonate muds
microbial carbonates
littoral ooidal carbonates
SANDY CRAIG FORMATION
St Andrews Castle Marine Band
PITTENWEEM FORMATION
Pittenweem Marine Band

Fig. 10.23

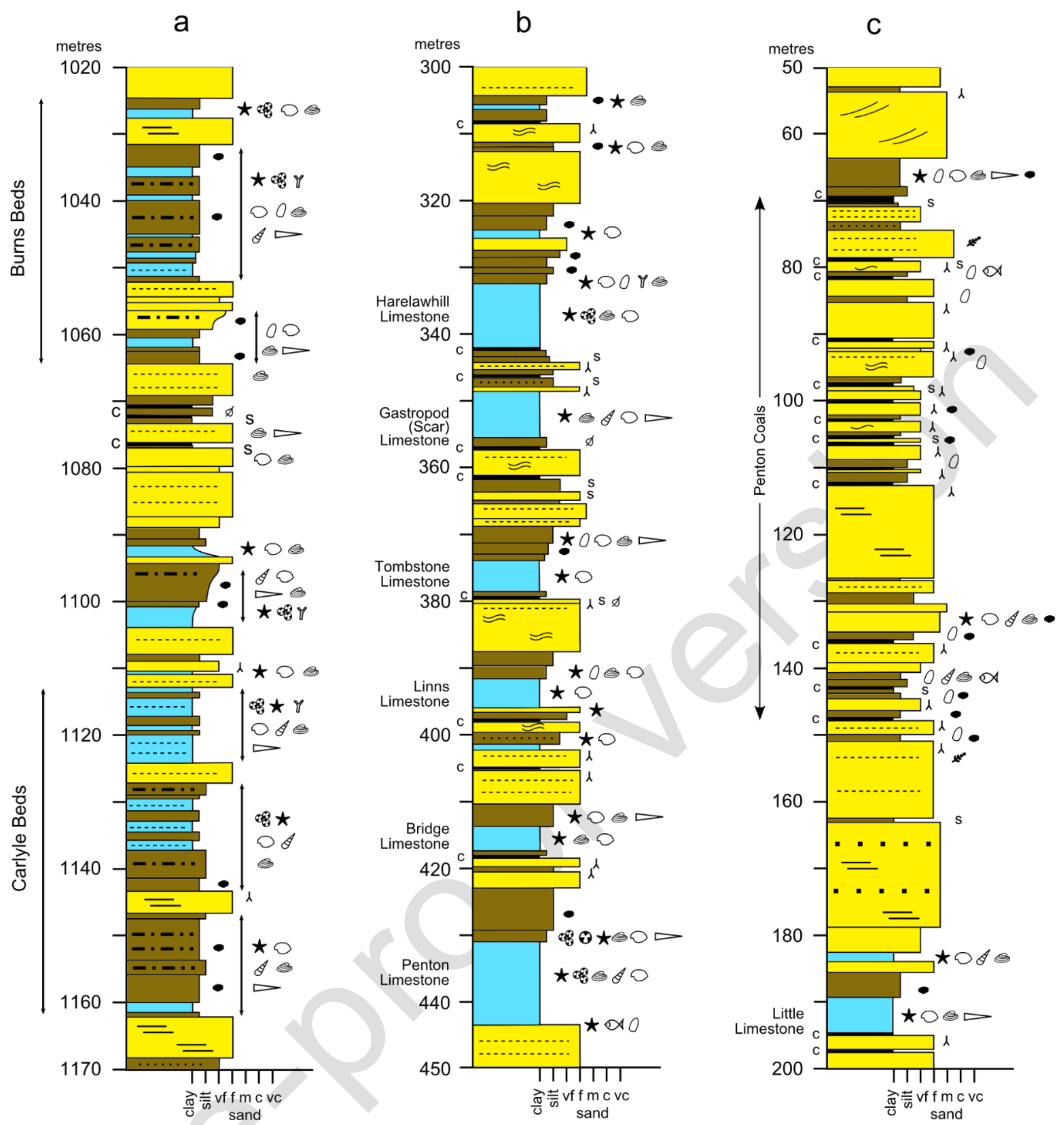

a
b
c
metres
Burns Beds
Carlyle Beds
Harelawhill Limestone
Gastropod (Scar) Limestone
Tombstone Limestone
Linns Limestone
Bridge Limestone
Penton Limestone
Penton Coals
Little Limestone
clay silt vf f m c vc
sand

Fig 10.24

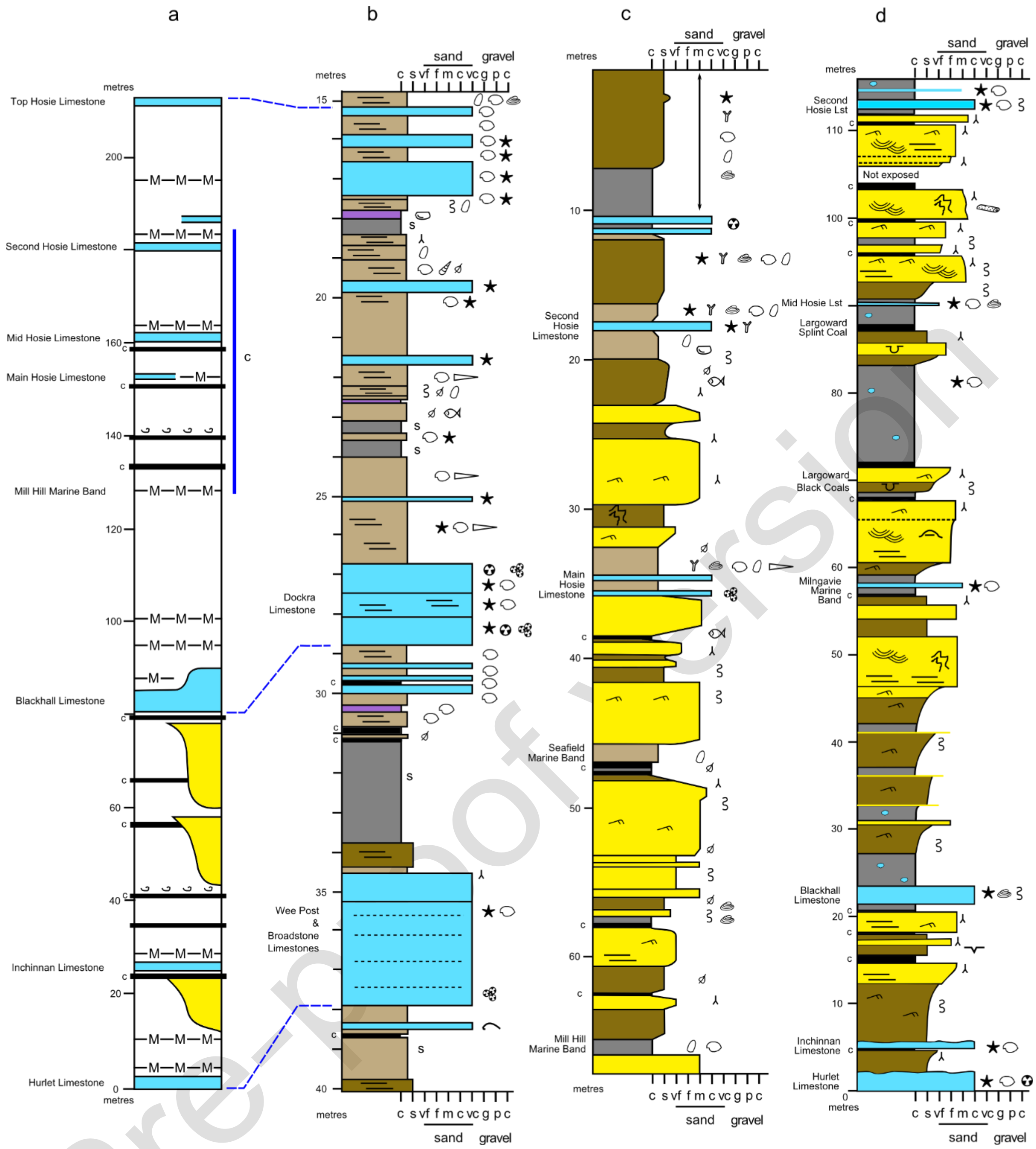

a
b
c
d
metres
Top Hosie Limestone
Second Hosie Limestone
Mid Hosie Limestone
Main Hosie Limestone
Mill Hill Marine Band
Blackhall Limestone
Inchinnan Limestone
Hurlet Limestone
Dockra Limestone
Wee Post & Broadstone Limestones
Second Hosie Limestone
Main Hosie Limestone
Seafield Marine Band
Mill Hill Marine Band
Second Hosie Lst
Not exposed
Mid Hosie Lst
Largoward Splint Coal
Largoward Black Coals
Milngavie Marine Band
Blackhall Limestone
Inchinnan Limestone
Hurlet Limestone
c s vf f m c vc g p c
sand
gravel

Fig. 10.25

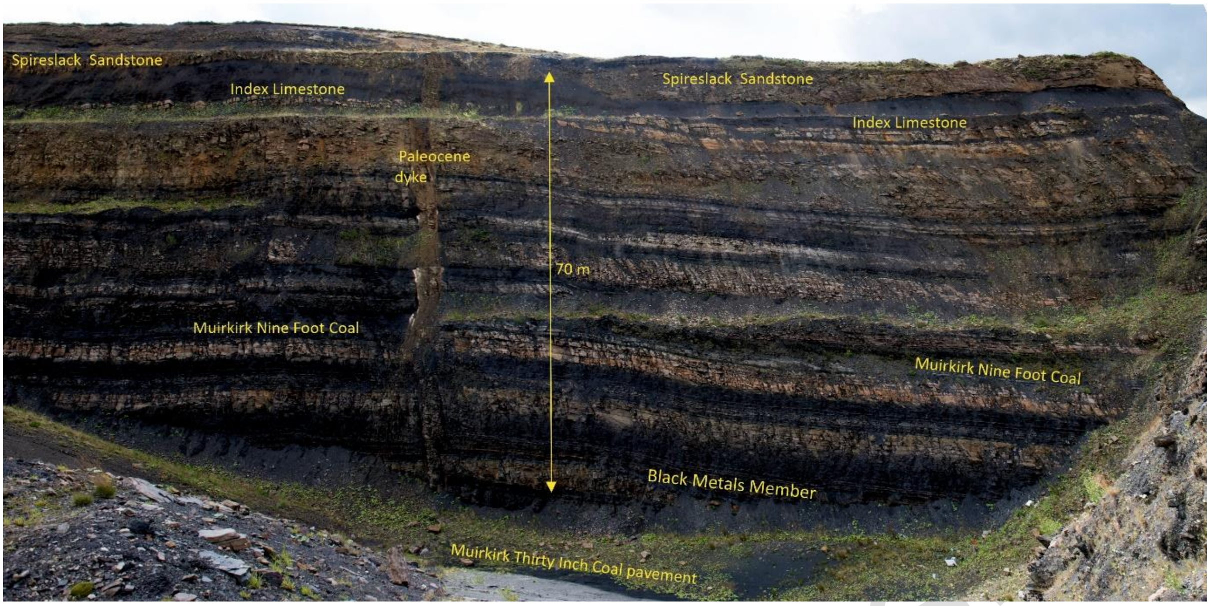
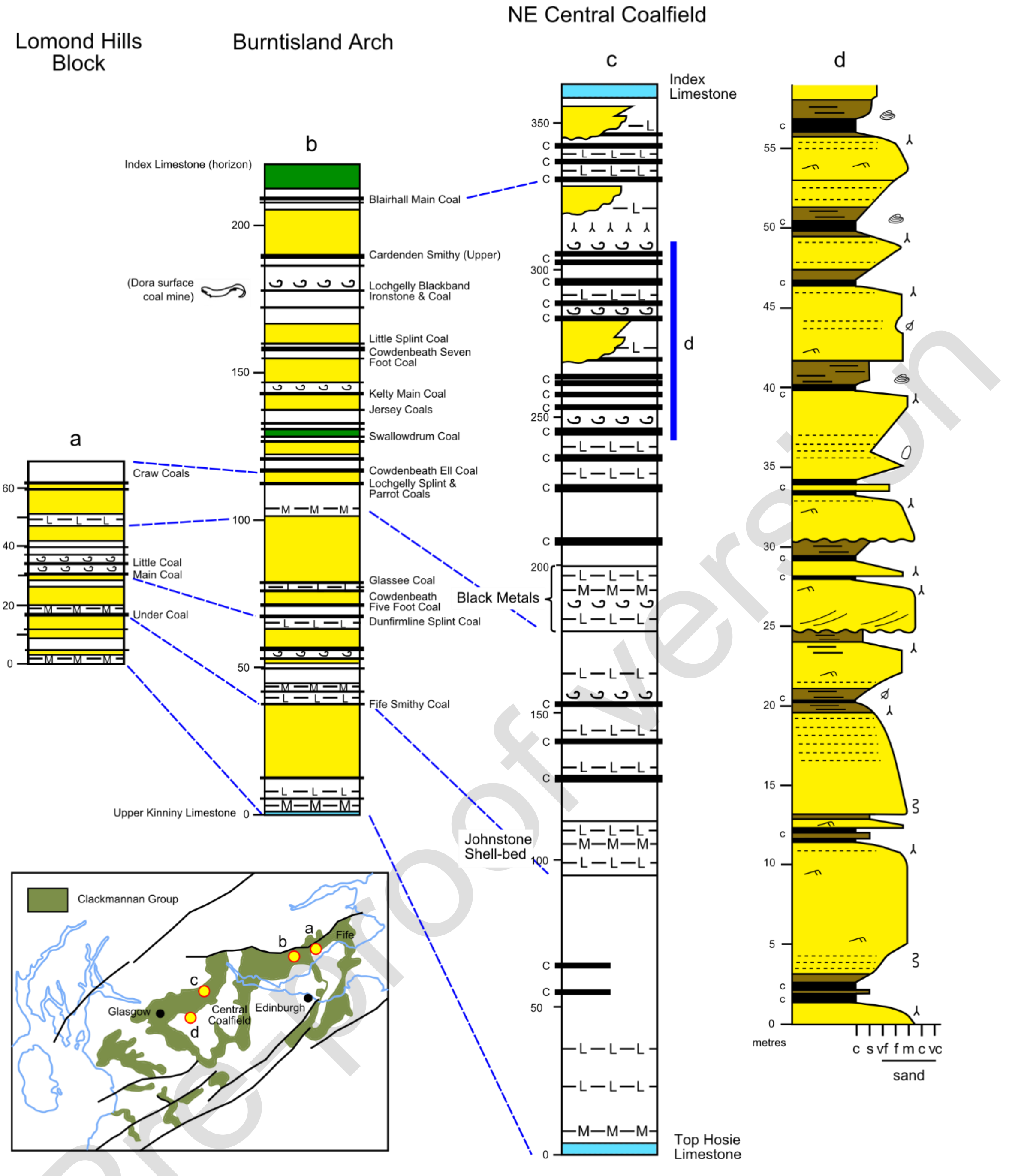

Spireslack Sandstone
Index Limestone
Paleocene dyke
70 m
Spireslack Sandstone
Index Limestone
Muirkirk Nine Foot Coal
Muirkirk Nine Foot Coal
Black Metals Member
Muirkirk Thirty Inch Coal pavement

Fig. 10.26



Lomond Hills Block
Burntisland Arch
NE Central Coalfield
a
b
c
d
Index Limestone (horizon)
Blairhall Main Coal
Cardenden Smithy (Upper)
(Dora surface coal mine)
Lochgelly Blackband Ironstone & Coal
Little Splint Coal
Cowdenbeath Seven Foot Coal
Kelty Main Coal
Jersey Coals
Swallowdrum Coal
Craw Coals
Cowdenbeath Ell Coal
Lochgelly Splint & Parrot Coals
Little Coal
Main Coal
Glassee Coal
Cowdenbeath Five Foot Coal
Dunfirmline Splint Coal
Under Coal
Black Metals
Fife Smithy Coal
Upper Kinniny Limestone
Johnstone Shell-bed
Index Limestone
Top Hosie Limestone
metres
c s vf f m c vc
sand
Clackmannan Group
Fife
Glasgow
Central Coalfield
Edinburgh

Fig. 10.27

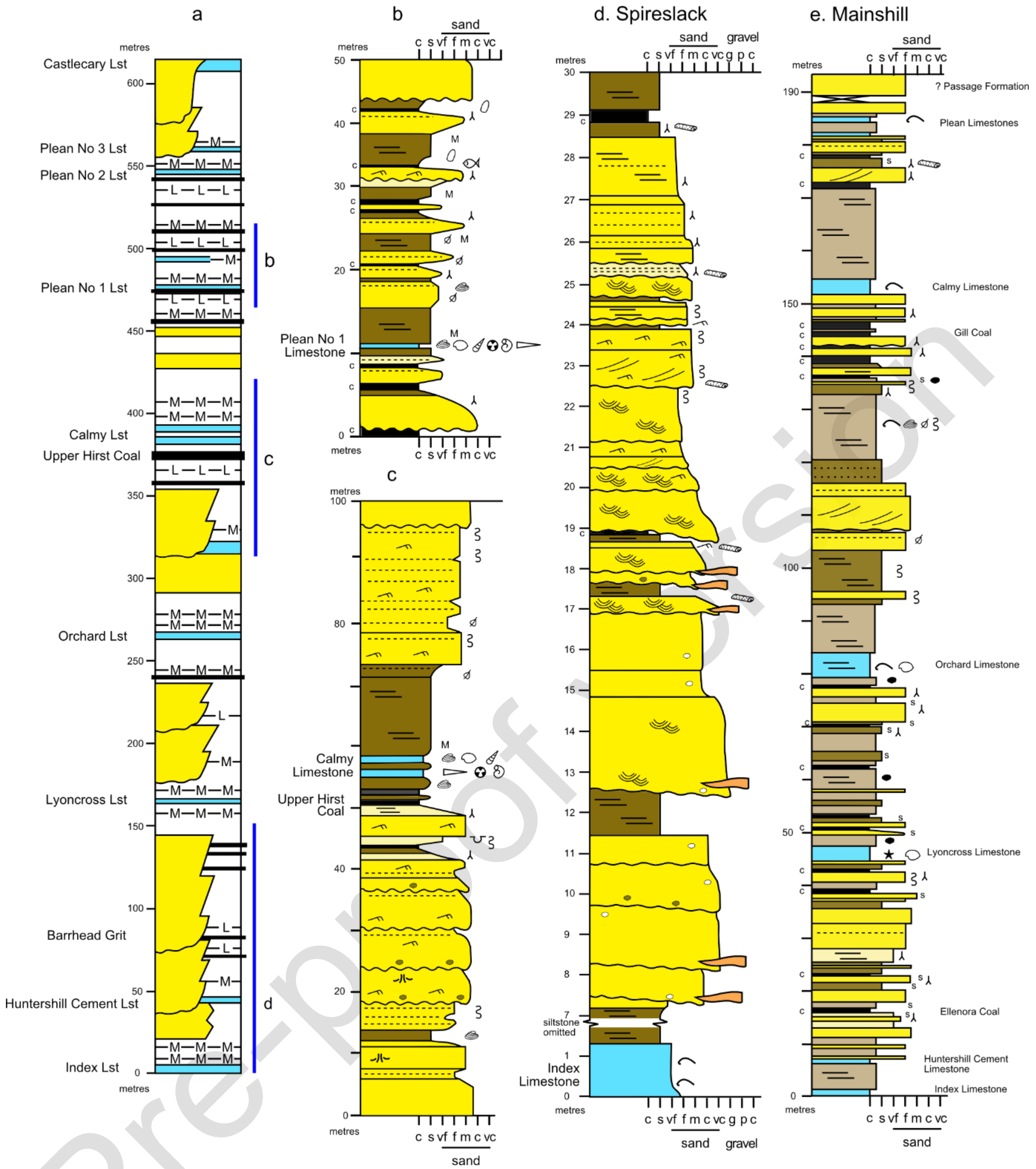

a
b
c
d. Spireslack
e. Mainshill
Castlecary Lst
Plean No 3 Lst
Plean No 2 Lst
Plean No 1 Lst
Calmy Lst
Upper Hirst Coal
Orchard Lst
Lyoncross Lst
Barrhead Grit
Huntershill Cement Lst
Index Lst
metres
Plean No 1 Limestone
Calmy Limestone
Upper Hirst Coal
sand
gravel
c s vf f m c vc g p c
siltstone omitted
Index Limestone
? Passage Formation
Plean Limestones
Calmy Limestone
Gill Coal
Orchard Limestone
Lyoncross Limestone
Ellenora Coal
Huntershill Cement Limestone
Index Limestone

Fig. 10.28

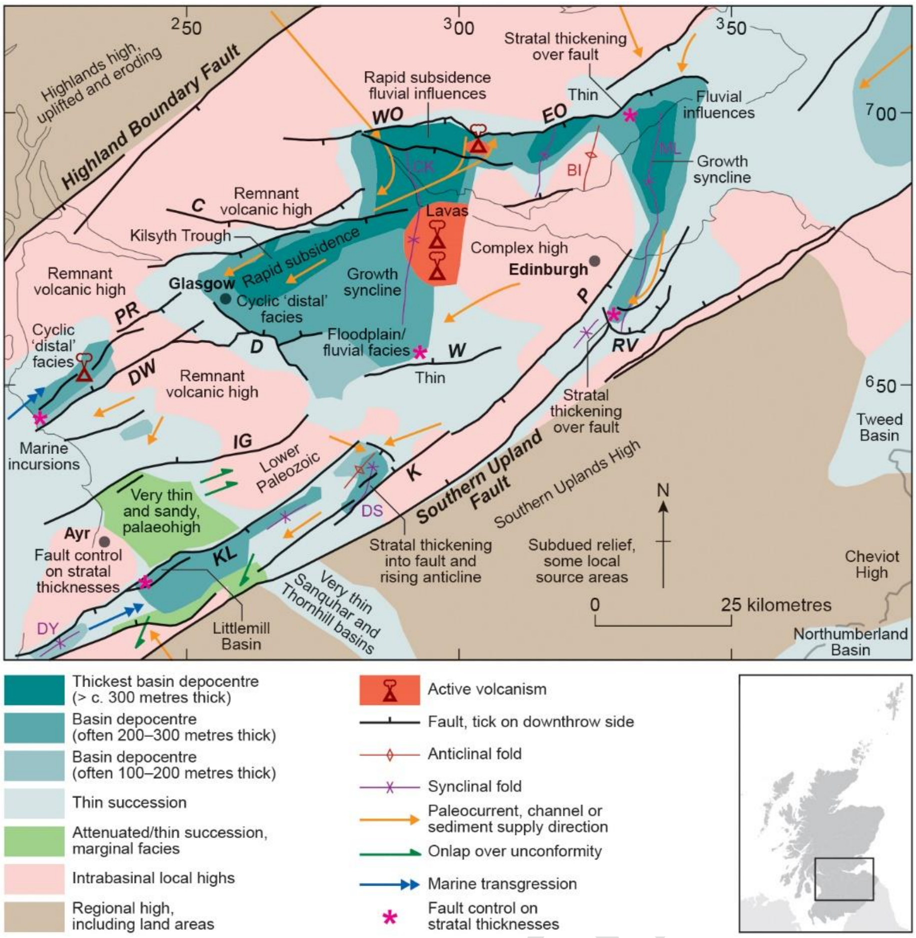


Fig. 10.29

Fig. 10.30

Fig. 10.31

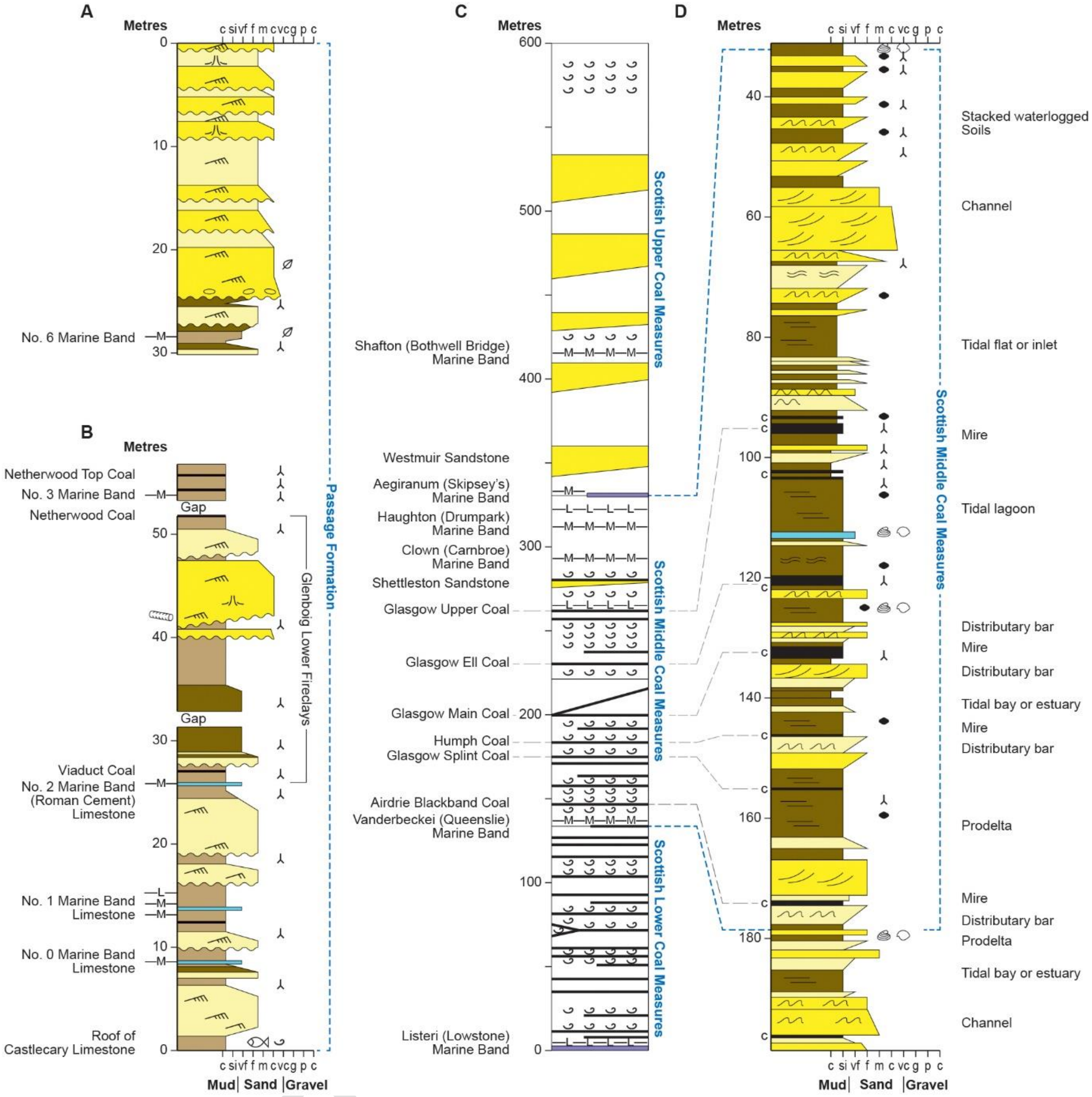

A
Metres
c si vf f m c vc g p c
0
10
20
No. 6 Marine Band
30
B
Metres
Netherwood Top Coal
No. 3 Marine Band
Netherwood Coal
Gap
50
40
Gap
30
Viaduct Coal
No. 2 Marine Band
(Roman Cement)
Limestone
20
No. 1 Marine Band
Limestone
10
No. 0 Marine Band
Limestone
Roof of
Castlecary Limestone
0
Glenboig Lower Fireclays
Passage Formation
Mud
Sand
Gravel
C
Metres
600
500
400
300
200
100
0
Shafton (Bothwell Bridge)
Marine Band
Westmuir Sandstone
Aegiranum (Skipsey's)
Marine Band
Haughton (Drumpark)
Marine Band
Clown (Cambroe)
Marine Band
Shettleston Sandstone
Glasgow Upper Coal
Glasgow Ell Coal
Glasgow Main Coal
Humph Coal
Glasgow Splint Coal
Airdrie Blackband Coal
Vanderbeckei (Queenslie)
Marine Band
Listeri (Lowstone)
Marine Band
Scottish Upper Coal Measures
Scottish Middle Coal Measures
Scottish Lower Coal Measures
D
Metres
40
60
80
100
120
140
160
180
Stacked waterlogged
Soils
Channel
Tidal flat or inlet
Mire
Tidal lagoon
Distributary bar
Mire
Distributary bar
Tidal bay or estuary
Mire
Distributary bar
Prodelta
Mire
Distributary bar
Prodelta
Tidal bay or estuary
Channel
Scottish Middle Coal Measures
Mud
Sand
Gravel

Fig. 10.32

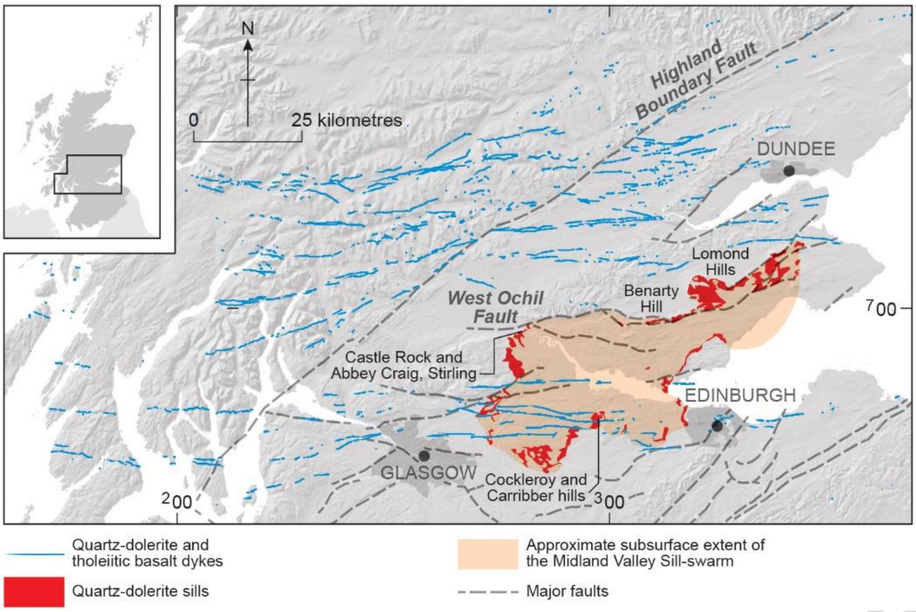


Fig. 10.33

Fig. 10.34

INPUT FOR ALL SAMPLES Decay constant and standard age used for legacy data:				Conversion spreadsheet from Noah McLean at MIT in 2014	
λold	5.543E-10	/yr		(Decay constant from Steiger and Jager, 1977)	Steiger, R.H. & Jäger, E. 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters, 36, 359-362
tstandard, old	98.79	Ma		(GA1550 from Renne et al., 1998)	Renne, P R, Swisher, C C, Deino, A L, Karner, D B, Owens, T L, and DePaolo, D J. 1998. Intercalibration of standards, absolute ages and uncertainties in 40Ar-39Ar dating. Chemical Geology, 145, 117-152
Convert data to this decay constant and standard age:					
λnew	5.5307E-10	± 1.50E-12	/yr, 1σ	(Decay constant from Renne et al 2011 non LSC data)	Response to the comment by W.H. Schwarz et al. On Joint determination of 40K decay constants and 40Ar*/40K for the Fish Canyon sanidine standard, and improved accuracy for 40Ar/39Ar geochronology by P.R. Renne et al. (2010). Geochimica et Cosmochimica Acta, 75, 5097–5100. http://dx.doi.org/
tstandard, new	99.738	± 0.104	Ma, 1σ	(GA1550 from Renne et al, 2011)	

INPUT FOR EACH SAMPLE		OUTPUT		Input for Error Propagation:			Output (all 1σ absolute)			Original publication
	legacy data age:	converted age:		legacy data age	legacy data J		converted age uncertainties:			
Sample Name	$t_{sample, old}$ (Ma)	$t_{sample, new}$ (Ma)	Relative Change	1σ internal	J value	J 1σ unct.	internal	+ standard	+ std + λ	
Monaghan MV69, Garleton Hills	342.05	345.170	0.90%	± 0.64	0.0115930	± 2.319E-05	± 0.65	± 0.73	± 1.19	Monaghan and Pringle (2004)
Monaghan MV18, Garleton Hills	342.43	345.553	0.90%	± 0.53	0.0116200	± 1.627E-05	± 0.53	± 0.63	± 1.13	Monaghan and Pringle (2004)
ASW124, Garleton Hills	336.10	339.170	0.91%	± 1.7	0.0139236	± 6.962E-05	± 1.71	± 1.75	± 1.97	Monaghan and Browne (2010)
ASW412, Arthur's Seat	333.70	336.749	0.91%	± 2.1	0.0139644	± 6.982E-05	± 2.12	± 2.14	± 2.33	Monaghan and Browne (2010)
HS80, Clyde Plateau	329.21	332.221	0.91%	0.7	0.011472	± 2.294E-05	± 0.69	± 0.76	± 1.18	Monaghan and Pringle (2004)
HS78, Clyde Plateau	330.24	333.260	0.91%	0.4	0.011439	± 1.144E-05	± 0.42	± 0.53	± 1.05	Monaghan and Pringle (2004)
HS71, Clyde Plateau	331.83	334.863	0.91%	0.7	0.011627	± 2.325E-05	± 0.68	± 0.76	± 1.18	Monaghan and Pringle (2004)
HS117, Clyde Plateau	332.63	335.670	0.91%	0.8	0.01163	± 2.326E-05	± 0.85	± 0.91	± 1.29	Monaghan and Pringle (2004)
HS116, Clyde Plateau	334.06	337.112	0.91%	1.2	0.011628	± 2.326E-05	± 1.23	± 1.27	± 1.57	Monaghan and Pringle (2004)
HS4, Clyde Plateau	335.04	338.101	0.91%	1.0	0.011614	± 2.323E-05	± 0.98	± 1.04	± 1.38	Monaghan and Pringle (2004)
HS60, Mons Hill (NW Edinburgh)	329.27	332.281	0.91%	± 0.64	0.011555	± 2.311E-05	± 0.65	± 0.72	± 1.16	Monaghan and Pringle (2004)
HS59,Cramond (NW Edinburgh)	331.20	334.228	0.91%	± 0.75	0.011537	± 2.307E-05	± 0.76	± 0.82	± 1.23	Monaghan and Pringle (2004)
HS58, Barnton (NW Edinburgh)	331.80	334.833	0.91%	± 0.64	0.011523	± 2.305E-05	± 0.65	± 0.72	± 1.16	Monaghan and Pringle (2004)
HS28, Carskeoch (West MVS)	259.20	261.605	0.92%	± 0.64	0.011629	± 2.326E-05	± 0.65	± 0.70	± 0.99	Monaghan and Pringle (2004)
HS23, Craigens-Avisyard (West M\	302.40	305.181	0.91%	± 0.58	0.011499	± 2.3E-05	± 0.59	± 0.66	± 1.06	Monaghan and Pringle (2004)
HS145, Cathcart (West MVS)	292.10	294.792	0.91%	± 0.57	0.011603	± 2.321E-05	± 0.57	± 0.64	± 1.03	Monaghan and Pringle (2004)
HS109, Lennoxtown (West MVS)	292.10	294.792	0.91%	± 1.3	0.011612	± 2.322E-05	± 1.31	± 1.34	± 1.56	Monaghan and Pringle (2004)
HS113, Ardrossan (West MVS)	298.30	301.046	0.91%	± 0.64	0.011623	± 2.325E-05	± 0.65	± 0.71	± 1.08	Monaghan and Pringle (2004)
ASW402, Mauchline	289.00	291.665	0.91%	± 2.5	0.0138356	± 6.918E-05	± 2.52	± 2.54	± 2.66	Monaghan and Browne (2010)
ASW421, Beecraigs Qz dolerite dyk	308.00	310.829	0.91%	± 5	0.0135302	± 6.765E-05	± 5.04	± 5.05	± 5.12	Monaghan and Browne (2010)
HS54 Eildon Hills	352.50	355.709	0.90%	± 0.7	0.011568	± 0	± 0.71	± 0.79	± 1.24	Monaghan and Pringle (2004)

Supplementary information table: Recalculated ^{40}Ar-^{39}Ar ages as used in this chapter, using conversion spreadsheet from Noah McLean, MIT supplied in 2014 to recalculate legacy data to the same decay constant and standard age.