The complex tectonic evolution of the Malvern region: crustal accretion followed by multiple extensional and compressional reactivation

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Abstract,
The Malvern Hills include some of the oldest rocks in southern Britain, dated by U-Pb zircon analysis to *c.* 680Ma. They reflect calc-alkaline arc magmatic activity along a margin of the Rodinia palaeocontinent, hints of which are provided by inherited zircon grains as old as 1600Ma. Metamorphic recrystallisation under upper greenschist/amphibolite facies conditions occurred from *c.* 650–600Ma. Subsequently, rifting of the magmatic arc (c.f. the modern western Pacific) at *c.* 565Ma led to the formation of a small oceanic marginal basin, evidenced by basaltic pillow lavas and tuffs of the Warren House Formation, and Kempsey Formation equivalents beneath the Worcester Graben. By early Cambrian time this juvenile crust had stabilised sufficiently for thick quartz arenite-dominated sequences to accumulate, followed by mudstones in mid- to late-Cambrian time. In earliest Ordovician time, subsidence accelerated in a rift basin east of the Malverns, but was terminated by accretion of the Monian Composite Terrane to the Gondwana margin. Rifting led to a microcontinental flake ('East Avalonia') breaking away, eventually to impact with Laurentian terranes on the other margin of the Iapetus Ocean in early Silurian time. Minor inversion of the floor of the Worcester Graben might have occurred during the Acadian (early Devonian) deformation phase, but more significantly, during the Variscan (end Carboniferous) Orogeny, when a 'Rocky Mountain Front'-type uplift was generated opposite a pinch-point within the orogen. Extensional reactivation of the earlier compressional structures in Permian, and particularly, during Triassic time, resulted in the Worcester Graben as we know it today. The structure of the Malvern Hills and the graben is thus the result of a surprisingly long and complex history of crustal accretion, compression and extension.
Keywords: Malvern Hills; Lineament; Worcester Graben; Proto-graben; River Severn Uplift

Introduction
This review considers the geological history of the triangular region labelled 'River Severn Uplift' in Figure 1, separating the Welsh Massif in the west from the Anglo-Brabant Massif (ABM) to the east (Pharaoh 2018). It comprises a fault-bounded wedge of crust, which exhibits a complex history of crustal accretion, followed by multiple extensional and compressional reactivation. Today it corresponds to the Worcester Graben, with the Malvern Hills defining its western margin, but, as will be described, the Permian-Mesozoic graben is superimposed on a much more fundamental structure. This structure likely extends a significant distance farther south beneath the thin-skinned Variscan parautochthonous thrust nappes (Pharaoh 2018). Careful study of clast composition in late Carboniferous sandstones and early Permian breccias in the West Midlands revealed a complex history of fault reversal and reactivation (Wills 1948), and Variscan inversion, long before seismic data were available. In the 1960s, a considerable improvement in palaeogeographical knowledge resulted from coal and hydrocarbon exploration. In the early 1980s, this generated an extensive coverage of 2D seismic reflection data, enabling comprehensive mapping of the Permian and Mesozoic basins of southern Britain (Whittaker *et al.* 1985; Smith *et al.* 2005; Butler 2018).

Crustal structure
The Neoproterozoic basement of southern Britain has been divided into a number of lithotectonic terranes (Pharaoh *et al.* 1987; Pharaoh and Carney 2000). Most of the central part of the ABM is underlain by Ediacaran intermediate and felsic volcaniclastic rocks, comprising the Charnwood Terrane. These crop out in Charnwood Forest, where they are located in a crustal duplex of probable Caledonian age at the north-east margin of the Midlands Microcraton (Fig. 1), and as the Caldecote Volcanic Formation in the Nuneaton area (Carney and Pharaoh 1993; Bridge *et al.* 1998). As described below, the geochemical affinities of basement rocks proved by deep boreholes at Kempsey (in the Worcester Graben), and Withycombe Farm (in Oxfordshire) (Fig. 1) also lie with the Charnian magma type (Pharaoh and Gibbons 1994). From the Malvern Hills westward through the Welsh Borderland, the eastern part of the Welsh Massif is inferred to be underlain by Ediacaran basement of the Wrekin Terrane (Pharaoh and Carney 2000). A suture of late Ediacaran age is inferred to separate the Charnwood and Wrekin terranes along the eastern edge of the Malvern Hills (Pharaoh *et al.* 1987). Reactivation of this Malvern Line or Lineament has controlled extension and inversion along the western edge of the Worcester Graben throughout Palaeozoic and Mesozoic time (Barclay *et al.* 1997). The Neoproterozoic terranes described above were consolidated into the Avalon Composite Terrane (ACT) or Avalon Superterrane (Gibbons 1990; Pharaoh and Carney 2000) shortly before the Precambrian-Cambrian boundary at 541Ma. This probably

took place on the Amazonian margin of Gondwana (Nance and Murphy 1994; Murphy *et al.* 2000; Strachan 2012).

Evidence for the crustal structure of the region is provided by the following geophysical datasets (Figs 2 and 3): 1 Magnetic potential field data; 2 Gravity potential field data; and 3 Seismic reflection data.

Much use has been made of geophysical potential field data (magnetic and gravity potential fields) in the structural interpretation of the concealed basement of southern Britain (e.g. Lee *et al.* 1990, 1991). Magnetic and gravity potential field data acquired by BGS provide a complete regional coverage. The results of interpretation of these data are presented in various BGS memoirs, sub-surface memoirs and geophysical CDs. Two compact magnetic anomalies — 'BMA' (Birmingham Magnetic Anomaly) and 'CEMA' (S Central England Magnetic Anomaly) — have been attributed to the presence of shallow Neoproterozoic (Charnian) metavolcanic rocks (Lee *et al.* 1990; Busby *et al.* 1993). The high magnetic susceptibility of the Charnwood Terrane (and CEMA) suggests that the felsic volcanic and volcaniclastic rocks inferred in the upper crust are replaced by more intermediate, magnetite-rich plutonic magmatic rocks at greater depth. West of the Malvern Line, the Wrekin Terrane is also characterised by strong magnetic anomalies, attributed to Uriconian mafic lavas, and, possibly, to plutonic components akin to the Malvern Complex. The region studied has a relatively muted magnetic signature owing to the presence of a thick sedimentary cover, except where the Malverns Complex is exposed or lies at shallow depth ('MMA', Fig. 2). The gravity anomaly map (Fig. 3) reflects the presence of thick Permian to Mesozoic strata in the Worcester Graben, and in the Wessex-Weald Basin to south of the Variscan Front. On both gravity and magnetic images, the N–S trend of the Malvern Line is clearly visible, extending from the mapped Malverns Complex at crop at least as far south as the Variscan Front. The projection of the line to the north, through the basins of the West Midlands, is less clear, but can be tentatively followed at least as far as the Cheshire Basin, and possibly to the Pendle Lineament.

The Worcester Graben and adjacent concealed Oxfordshire-Berkshire Coalfield areas (Butler 2018) are one of the few parts of the ABM with a good seismic coverage conducted in hydrocarbon exploration. In addition, a small number of seismic reflection profiles gathered by the British Geological Survey provides significant insights to crustal structure in this region (Chadwick 1985; Chadwick and Smith 1988). Figure 4 displays reflection seismic data and their interpretation, forming an E-W transect across the Worcester Graben. Some 2.5–3km of Permian, Triassic and early Jurassic strata fill the graben, the floor of which has a complex subcrop (Fig. 5). Over a large area, Precambrian rocks of the Kempsey Formation are inferred to subcrop (Barclay *et al.* 1997). These are overlain by a Cambrian-Tremadocian sequence, which thickens southward, and by a thin Silurian sequence, including volcanic rocks. Devonian and Carboniferous strata are absent except in the north, in the basins associated with the northern edge of the ABM. In contrast, relatively thick Devonian-Pennsylvanian sequences are found both west of the Malvern Line, in the West Midlands basins; and to the east, in the concealed Oxfordshire-Berkshire Coalfield. The inference is that the Malvern region was strongly inverted after deposition of Pennsylvanian strata, i.e. by the Variscan Orogeny (Chadwick and Smith 1988; Peace and Besly 1997); and that an earlier phase of graben development controlled Cambrian to Tremadocian sedimentation (Smith 1987; Smith and Rushton 1993).

The evidence reviewed here indicates that multiple reactivation of the Malvern crustal suture has occurred, both in extension (late Cambrian-Tremadocian, Triassic) and in compression (?Arenig, ?early Devonian, late Pennsylvanian). It shows that the crust beneath the Malvern Hills and Worcester Graben is significantly weaker than that of the Welsh Massif and the ABM (Pharaoh 2018). Recently, Smit *et al.* (2018) invoked the Malvern Line as the boundary between their western and central crustal domains. They advocate up to 15° of anti-clockwise rotation of the Brabant Massif with respect to the Welsh Massif, along an arc-shaped Malvern Line, to accommodate Mississippian extension in eastern England and the southern North Sea. Published mapping of the Malvern region, and its subsurface continuation to the south, inferred from geophysical and subsurface geological evidence (as reviewed here), indicate that the Malvern Line has a linear N–S trend, which is not arc-shaped or curvilinear, as required by this model (Fig. 6).

Precambrian evolution

The oldest known magmatic rocks in England and Wales are the Stanner-Hanter Complex, a bimodal gabbro-granite suite, crystallised at *c.* 711Ma (Schofield *et al.* 2010). Slightly younger U-Pb ages have been obtained from the Malverns Complex, involved in a transpressional flower structure of Variscan age on the western side of the Worcester Graben (Fig. 1). The strong calc-alkaline signature in mafic and intermediate compositions (Fig. 7) is more reliably confirmed by the Mid-Ocean Ridge Basalt (MORB)-normalised geochemical patterns, which show strong enrichment in large ion lithophile elements (LILE) such as Th and Rb, and by light rare earth elements (LREE) such as Ce, and depletion of high field strength elements (HFSE) such as Nb and Ti (Fig. 8). Granitoid components of the calc-alkaline intrusive complex have been reliably dated to 677±2Ma (Tucker and Pharaoh 1991) using the U-Pb zircon method. A volumetrically smaller component of paragneiss, interpreted as a host to the plutonic rocks, yields zircons with core U-Pb ages as old as 1965±7Ma, with significant concentrations at 1.6 to 1.5Ga, and 1.3 to 1.0Ga (Strachan *et al.* 2007). The complex was subjected to metamorphism at greenschist to amphibolite facies between 670 and 650Ma (Strachan *et al.* 1996). Mesoproterozoic zircon inheritance is present in both Malvern and Stanner-Hanter complexes (Tucker and Pharaoh 1991; Strachan *et al.* 2007; Schofield *et al.* 2010). This is supported by Sm-Nd model ages and favours an origin in the Gondwanan part of Rodinia closest to the Amazon Craton and Mexico (Nance and Murphy 1994; Strachan *et al.* 2007) rather than in the West African Craton, where such rocks are absent. Detrital zircon suites from early Cambrian quartz arenites also support this conclusion (Murphy *et al.* 2004).

Lavas of the Warren House Formation form a small (<1 km^2) outcrop (Fig. 6) on the eastern flank of the Malvern Hills (Penn and French 1971; Thorpe 1974). Altered basalt and basaltic andesite lavas, exhibiting small pillow structures, occur with minor amounts of rhyolitic tuff, the latter yielding concordant U-Pb zircon ages of 566±2Ma (Tucker and Pharaoh 1991). These rocks are at much lower metamorphic grade than the Malverns Complex, with which they were tectnically juxtaposed during Variscan thrusting (Barclay *et al.* 1997). Despite their insignificant outcrop area, the Warren House Formation lavas provide important evidence of a late Proterozoic suture between the Wrekin and Charnwood terranes. Although identical in age to the Uriconian lavas (Tucker and Pharaoh 1991), the geochemical composition of basaltic components differs. The Uriconian basalts have a significant subduction-related component (enrichment of LILE, LREE etc; Fig. 9); the Warren House basalts have a smaller subduction component and are chemically most similar to primitive marginal basin basalts (Thorpe 1972; 1974; Pharaoh *et al.* 1987). The Warren House basalts show comparable depletion in HFSE (such as Nb, Ta, Ti and Y) to Kempsey Formation tuffs proved by the Kempsey Borehole (Fig. 10a, b) in the Worcester Graben (Fig. 1), and to more mafic components of the Charnian suite (Fig. 10c). Thus, rocks of Charnian magmatic affinity (and the Charnwood Terrane) are inferred to underlie the Worcester Graben, and extend to the Malvern Line.

Early Palaeozoic evolution

Brief erosion of the juvenile Neoproterozoic crust preceded a significant marine transgression onto the margin of Gondwana (Brasier and Hewitt 1979), generally presumed to be by the Iapetus Ocean, which began opening in latest Neoproterozoic time, breaking up the supercontinent of Rodinia-Pannotia (Dalziel 1997). That part of the Avalon Composite Terrane (Pharaoh and Carney 2000) comprising the Wrekin and Charnwood terranes (including this region) formed the shallow marine Midland Platform (e.g. Cope *et al.* 1992; Woodcock 2012a). An overstepping cover sequence comprising thin (30–60m) basal shoreface quartz arenitic facies, e.g. the Malvern and Wrekin quartzites, passes up into 200–300m thick nearshore clastics (e.g. the Hollybush Sandstone Formation) (Brasier *et al.* 1978; Woodcock 2012a). This sequence locally contains 'small shelly fossil' horizons comprising hyoliths and primitive molluscs (Brasier 1984) that can be precisely correlated with strata of the upper Terreneuvian Series in the Avalon Peninsula of south-east Newfoundland (Brasier 1992).The same assemblage is found overlying lavas with Charnian magmatic affinity in the Withycombe Farm Borehole in the concealed Oxfordshire-Berkshire Coalfield (Rushton and Molyneux 1990; Pharaoh and Gibbons 1994; Rushton *et al.* 2011) (Fig. 11). The oldest Cambrian (Fortunian) stage is missing, so a time gap of perhaps 15Ma exists from the start of the period at 541Ma. Overlying strata are mid- to late-Cambrian (International epochs 2, 3 and Furongian) mudstones with subordinate sandstones and/or limestones, deposited below wave-base on a gently subsiding shelf. Numerous boreholes drilled for exploration of the concealed Warwickshire Coalfield (Fig. 11), east of the Worcester Graben terminate in Cambrian or earliest Ordovician (Tremadocian) strata (Worssam and Old 1988; Bridge *et al.* 1998). For clarity, not all of the boreholes are labelled in Figure 5, which gives a general impression of their distribution. Most cores are of Furongian age (Rushton *et al.* 2011). The presence of dips up to 60 in many of these boreholes demonstrates that the sequence is strongly folded across a wide area.
Smith and Rushton (1993) recognised that the Worcester Graben, presently filled with Permo-Triassic strata, had an early Palaeozoic antecedent, referred to as the 'Tremadoc Worcester Graben', and here as the 'Worcester Proto-graben'. This major N–S trending structure probably initiated as an 'aulacogen' (Hoffman *et al.* 1974), possibly the 'failed arm' of a continental margin rift prior to opening of the Rheic Ocean. The increasing width of the proto-graben to the south indicates that the margin lay in that direction, reflected in thickening of the Tremadocian strata (to > 2km) at crop in the Tortworth Inlier, and in boreholes (Fig. 5) at Cooles Farm, and at Yarnbury and Shrewton south of the Variscan Front (Smith and Rushton 1993). Subsidence of this N–S trending proto-graben followed reactivation of the Neoproterozoic Malvern Line suture in extension. This anticipated the break-off of a microcontinent from the peri-Gondwana margin, subsequently known as Avalonia. Post-Tremadocian Ordovician strata are not preserved on the platform, so its subsequent subsidence history is not known, unlike the basin (Prigmore *et al.* 1997).

The concensus view is that the faunally-defined Avalonia microcontinent rifted away from Gondwana at high southerly palaeolatitude in late Early Ordovician (Floian) time (Scotese and McKerrow 1991); Prigmore *et al.* 1997; Fortey and Cocks 2003; Cocks and Torsvik 2006; Woodcock 2012b). As it drifted northward, a new (Rheic) ocean basin opened in its wake; and the old (Iapetus) ocean crust was destroyed by subduction zones on both its Laurentian and Avalonian margins. Part of this Iapetus Ocean, referred to as the Tornquist Sea by Cocks and Fortey (1982), lay between Avalonia and Baltica. Faunal contrast with Gondwana only became apparent in

Darriwilian (late Llanvirn) time (Woodcock 2012b). On the Avalonian margin, the earliest subduction magmatism is of late Tremadocian age at Treffgarne and Rhobell in the Welsh Basin (Kokelaar 1986, 1988). Numerous small intrusions belonging to the lamprophyric-microdioritic Midlands Minor Intrusive Suite are encountered in exposed Cambrian-Tremadocian strata (e.g. Malverns, Wrekin, Nuneaton) and numerous boreholes throughout the microcraton (Carney *et al.* 1992; Thorpe *et al.* 1993; Pharaoh *et al.* 1993). They are not observed to intrude Silurian strata, however (Fig. 3 of Wills 1948) (Fig. 3). These geological observations are compatible with the U-Pb baddeleyite age of 442±3Ma (earliest Silurian) for a differentiated sill in the Mancetter area near Nuneaton (Noble *et al.* 1993). Field observations indicate that the minor intrusions were emplaced in a number of co-magmatic pulses (Le Bas 1968; Thorpe *et al.* 1993). In some places, dykes cut the axial planes of chevron folds of bedding in Cambrian-Tremadocian strata. A post-Tremadocian/pre-Silurian age is therefore inferred for this deformation (Carney *et al.* 1992; Bridge *et al.* 1998), for which a Penobscotian cause is therefore conceivable. The mineralogical and geochemical composition of these minor intrusions indicates formation by small degrees of partial melting of lithospheric mantle with subduction enrichment of volatiles, LILE and light REE. A within-plate mantle source also provided a contribution. The Midlands Minor Intrusive Suite and comparable lavas in North Wales have been interpreted to reflect the shutdown of volcanism (and subduction) at the northern edge of Avalonia (Woodcock 2012b).
Subsequently, a Silurian shelf sequence was deposited, generally unconformable upon the Precambrian basement (e.g. in the Heath Farm and Collington boreholes). Upper Cambrian-Tremadocian strata are present in the Fownhope Borehole within the Woolhope Basin (Barron and Molyneux 1992), and in the Usk Borehole (Sovereign plc well completion report) A number of minor basins controlled by syndepositional faults are developed here (Butler *et al.* 1997), perhaps reflecting stronger extension in the region of the microcraton marginal to the developing Welsh Silurian basin, and associated with the volcanism described in the next section.

Silurian strata containing eruptive volcanic units out-crop at Skomer in south-west Wales (mid-Llandovery), at Tortworth in Gloucestershire (upper Llandovery), and in the Mendips at mid-Wenlock) (Van der Kamp 1969; Thorpe *et al.* 1989); lavas of Llandovery age are also encountered in boreholes at Maesteg in south Wales, at Netherton in the Worcester Graben and at Bicester in Oxfordshire (Pharaoh *et al.* 1991). The lavas form a reflective marker horizon on reflection seismic lines and can be mapped between the borehole provings. All of the volcanic centres are located within *c.* 50km of the Variscan Front, anticipating the subsequent development of the Variscides (Turner 1935; Pharaoh *et al.* 1991, 1993; Fortey *et al.* 1996). In addition, thin ash (bentonite) horizons are more widely distributed both spatially and temporally (Fortey *et al.* 1996), but may not necessarily have been derived from the same volcanic centres (Woodcock 2012c). The chemical composition of the lavas varies from basalt through basaltic-andesite to minor amounts of rhyolite, with both within-plate and subduction magmatic signatures (Thorpe *et al.* 1989; Pharaoh *et al.* 1991). Distinct peralkaline and ocean island basalt series are recognised at Skomer (Thorpe *et al.* 1989), whereas the Mendip and Tortworth occurrences have calc-alkaline affinities (Van der Kamp 1969). This could reflect development of an extensional rift zone on the northern margin of the Rheic Ocean, with a lithosphere previously contaminated by Avalonian or Iapetan subduction (Pharaoh *et al.* 1991); by subduction of the Rheic Ocean northward under the Avalonia plate, following a polarity switch (Fortey *et al.* 1996; Woodcock 2012c); or, given the variety of magmatic series, by a post-subduction sequence recording slab break-off. The third hypothesis presently looks the most reasonable, given that the faunal evidence appears to favour opening of the Rheic Ocean from Floian time onwards (and perhaps earlier) (Scotese and McKerrow 1991; Fortey and Cocks 2003) some 30Ma to 40Ma earlier than the Skomer volcanism. As noted above, in Brabant, magmatism continuing until 433Ma (early Silurian time) might also be associated with a polarity switch to northward subduction of the Rheic Ocean (Linnemann *et al.* 2012).

Closure of the Rheic Ocean basin, with impingement of the Armorican or Iberian microcontinents upon Avalonia, was invoked by Soper *et al.* (1987) as the cause of the late Caledonian Acadian Orogeny. The Mid-Devonian Acadian Phase is contemporaneous with the Ligerian or 'Eo-Variscan' Phase recognised throughout the Variscides (Ziegler 1990; Matte 2001). High-pressure metamorphism of this age is identified in numerous Variscan Massifs — for example in north-west Iberia, in southern Armorica and in Bohemia (Lardeaux *et al.* 2014) — and reflects collision and obduction of continental terranes in an early ('Eo-Variscan') phase of the Variscan Orogeny. It seems likely that Avalonia was involved in these collisions, albeit peripherally. However, as Woodcock *et al.* (2007) have pointed out, much of the critical evidence for orogeny at this time (e.g. compressional deformation and subduction magmatism) is absent in Cornubia (Devon and Cornwall), the intervening region where it should be present. To resolve these difficulties, Woodcock *et al.* (2007) and Woodcock (2012d) envisaged displacement of the arc/forearc system on the northern Rheic margin by *c.* 400km of dextral shear along a putative Bristol Channel-Bray Fault Zone, the presence of which had already been advocated by Holder and Leveridge (1986). The hypothesis proposes that the crust of what is now Cornubia originated in what is now the western side of the Paris Basin, and was translated to its present position in post-Acadian or early Variscan time, possibly during the late Carboniferous (Woodcock 2012d). Further discussion of this interesting topic is outside the scope of this review.

Late Palaeozoic evolution

By early Devonian time, the accretionary collage of the Caledonide Orogen had been welded into a mountain belt, part of the supercontinent known as 'Laurussia', or the 'Old Red Continent' (Ziegler 1990). Orogen-wide sinistral transtension is most obviously expressed in major fault zones such as the Great Glen and Highland Boundary fault systems, and associated with voluminous granite magmatism (Dewey and Strachan 2003; Soper and Woodcock 2003). Early Devonian strata are absent in the floor of the Worcester Graben. They were probably deposited here, but eroded following severe Variscan inversion along the axis of the Tremadocian proto-graben, for considerable thicknesses (up to 2,500m) of such strata are preserved in South Wales and along the Welsh Borders to west of the Malvern Line, and in an E-W orientated synclinal basin underlying the Thames Valley, extending from Gloucestershire to east Kent (Mortimer and Chaloner 1972; Ellison *et al.* 2004). The proto-graben received the attenuated late Palaeozoic sequence typical of a location within the ABM: a thin onlapping sequence of upper Devonian strata; Mississippian strata usually absent; and onlapping late Pennsylvanian strata of the Upper Pennine Coal Measure and Warwickshire groups (Foster *et al.* 1979). The proto-graben possibly escaped inversion in the Acadian phase, but during late Carboniferous (?Stephanian time), it was inverted as a positive flower structure/horst (Chadwick and Smith 1988), with thrusting westwards at the Malvern Line and eastwards into the Oxford Basin (Peace and Besly 1997). Neoproterozoic volcaniclastic rocks were unroofed at Kempsey in the northern, most squeezed, part of the proto-graben.

By early Carboniferous time, a regime of N–S extension had become established, possibly resulting from back-arc extension in the hinterland of volcanic arcs established on the southern margin of Laurussia (Leeder 1982; Franke *et al.* 2017). Three major pulses of rapid extension and subsidence have been observed in the Mississippian strata of the Carboniferous Limestone Supergroup deposited across a wide, equatorial platform in northern Wales and northern England (Gawthorpe *et al.* 1989; Fraser *et al.* 1990). On the margins of the ABM, major discontinuities such as angular unconformities, palaeosols and karstified surfaces testify to uplift and emergence (Walkden and Davies 1983; Bridges and Chapman 1988; Ambrose and Carney 1997). It is likely that any Mississippian strata deposited in the region would have been thin, marginal sequences, eroded during early phases of Variscan uplift.

In late Pennsylvanian time, intra-plate stress from the developing Variscan Orogen of central Europe began to impact on the British area. Flexural subsidence on a lithospheric scale resulted in downwarping of the crust and development of a foreland basin along the southern margin of the ABM (Besly and Kelling 1988), initially reflected in minor sequence discordances. These processes resulted in the accumulation of thick late Westphalian to earliest Stephanian 'Barren' and 'Pennant' Coal Measures in Kent, across Oxfordshire–Berkshire (Foster *et al.* 1979) and in South Wales (*see* Fig. 11). The crust of the British area responded to N–S Variscan shortening in a strongly heterogeneous fashion (Corfield *et al.* 1996), typically by compressional reactivation of the original extensional faults. In the wider orogenic context, in central Europe, the narrow Rhenohercynian Basin was closed and inverted (Franke *et al.* 2017), producing thin-skinned nappes containing Devono-Carboniferous strata underlying the Weald and Wessex basins in southern England (Butler 2018). Orthogonal closure and crustal shortening of the Rhenohercynian Basin brought the North Armorican promontory of the Variscan internide zone and intervening accreted crust of the Saxothuringian Zone beneath the English Channel into closer juxtaposition with the ABM.

The crust underlying the Permo-Mesozoic Worcester Graben (representing the inverted stump of the Worcester Proto-graben) resembles a wedge driven into the Variscan foreland, separating the Welsh Massif in the west from the ABM (Fig. 11). The schematic cross-section in Figure 12 shows strong uplift between the Malvern Line in the west ('Malvern Axis thrusts') and the Alcester Thrust in the east (Chadwick and Smith 1988; Barclay *et al.* 1997). There are close analogues to these uplifted wedges in 'mountain front uplift' structures such as the Wind River Uplift, east of the Rocky Mountains, as recognised by Smith (1987) and by Peace and Besly (1997). Evidence for this 'Malvernian' phase of uplift was, however, identified much earlier from studies of outcrop in the Malvern and Abberley Hills (e.g. Groom 1902) and in the clast content of late Carboniferous and early Permian formations in the Midlands coalfields (Trueman 1946, 1947; Wills 1948). To better reflect its mountain-front origin, the term 'River Severn Uplift' (e.g. *see* Fig. 10) was introduced by Pharaoh (2018) for this structure, previously referred to as the Worcester High by Smith (1987). In Figure 13, the River Severn Uplift is located opposite a 'pinch-point' in the Variscides, adjacent to the Archaean crust of the North Armorican promontory. It appears that the strong crust of this Archaean nucleus was perfectly positioned as an indenter to focus orogenic stress and exploit the mechanical weakness of the Malvern Line. Strong inversion occurred on both flanks of the structure, apparently directed westward on the Malvern Line (Chadwick 1985), and eastward in a fold-thrust belt on the edge of the concealed Oxfordshire-Berkshire Coalfield (Chadwick and Smith 1988; Peace and Besly 1997; Barclay *et al.* 1997). The 'apparent' translations identified on W–E oriented 2D seismic sections cannot of course constrain the magnitude of any component of strike-slip on the same structures, which, given the N–S Variscan compression, could have been significant. Reverse movement also occurred on other reactivated structures farther north in the foreland (e.g. *see* Corfield *et*

al. 1996). Close to the Malvern region, these included the Warton Fault bounding the Nuneaton early Palaeozoic inlier, and the Thringstone Fault bounding the south-west edge of the Charnwood Forest block.
Uplift along the N–S trending axis of the proto-graben resulted in removal of perhaps 3km of early Palaeozoic strata, together with any Devonian and Mississippian strata, and erosion down to the Precambrian level, as proved in the Kempsey Borehole. The effect of the uplift is reflected clearly in the subcrop patterns of the Somerset and Bristol Coalfield to the west of the Malvern Line, and of the concealed Oxfordshire-Berkshire Coalfield, east of the Inkberrow-Haselor Hill-Lickey End fault system (*see* Fig. 11).

A further complication is the possible reorientation of the orogenic stress field to E-W compression, in Stephanian to early Permian time, reflecting collision in the Uralide Orogen (Ziegler 1990; Pharaoh *et al.* 2018). Late Variscan reorientation of the stress field was invoked by French geologists (Gélard *et al.* 1986; Blès *et al.* 1989), and subsequently supported by Ziegler (1990), to explain the apparent structural complexity of internal Variscide massifs. Although the hypothesis has fallen out of favour in France (e.g. Faure 1995), it was adopted by Pharaoh *et al.* (2018) to explain the geometry of N–S trending fold structures of latest Pennsylvanian–early Permian age in the East Irish Sea, Midland Valley and Forth Approaches of Scotland, and elsewhere. Any E-W compressive intraplate stress superimposed on the River Severn Uplift would have further facilitated its uplift and erosion, as described in the next paragraph.

The Clent Breccia of earliest Permian age (*c.* 298Ma) has a highly variable clast composition, and records the rapid erosion of the River Severn Uplift down to its Precambrian core within perhaps 10Ma. The possibility of previous uplift and erosion during Penobscotian (early Ordovician) and Acadian (early Devonian) orogenic phases cannot be entirely excluded. A major stratigraphic hiatus of *c.* 20Ma is associated with the Saalian and Altmark unconformities recognised in central Europe (Ziegler 1990; Gast *et al.* 2010). In late Permian time (*c.* 260Ma), the Worcester Graben began to subside between the ABM and the Welsh Massif, preserving up to 1.5km of the late Permian aeolian Bridgnorth Sandstone.

Mesozoic–Cenozoic evolution

In early Triassic time (Scythian, *c.* 246Ma), Britain was almost completely occupied by the deserts in which the 'New Red Sandstones' were deposited (Warrington and Ivimey-Cook 1992). Dominantly fluviatile sandstones of the Sherwood Sandstone Group were deposited in a vast braided river system extending from Northern Armorica via a fairway through south and central England to marine basins in the southern North Sea and Irish Sea (Whittaker 1985; Smith 1985; Newall 2017). This fairway was tectonically controlled by, and entrained within, the rapidly subsiding Worcester Graben. The main syndepositional graben-bounding faults — the East Malvern Fault in the west (Chadwick 1985) and the Inkberrow-Haselor Hill-Lickey End Fault System in the east (Chadwick and Evans 2005) (Fig. 12) — developed as extensional shortcuts in the hangingwall of the Variscan compressional faults at the margins of the River Severn Uplift, described above. Up to 2.5km of Sherwood Sandstone Group strata, and the overlying Mercia Mudstone Group, accumulated in the Worcester Graben, which, along with deep graben in the southern North Sea, Cheshire Basin, Eastern Irish Sea and North Channel, formed part of the Permo-Triassic Central European Basin System (Scheck-Wenderoth *et al.* 2008). The latter is a N–S trending rift system reflecting W–E extension, which initiated the break-up of the Pangaea Supercontinent. Latest Triassic strata (Rhaetian, *c.* 207Ma) represent a marine incursion penetrating into the graben.

In Jurassic time, extension reoriented to a N–S direction, associated with the rotation of Iberia and the opening of the Bay of Biscay (Chadwick *et al.* 1989), so that the favourably orientated, E-W striking Variscan compressional structures south of the Variscan Front in southern Britain were reactivated in extension. Despite this, subsidence in the Worcester Graben continued, Jurassic strata thinning eastwards onto the London-Brabant Platform (Whittaker 1985).Cretaceous and Cenozoic strata are absent from the Worcester Graben, so the contemporary history can only be surmised indirectly from surrounding regions. It is likely that rising sea level in mid- to late-Cretaceous time coupled with regional thermal subsidence enabled the Upper Greensand and Chalk groups to blanket the ABM, including the Worcester Graben, leaving the Welsh Massif as the nearest landmass (Hancock and Rawson 1992); however, these strata were entirely removed following Alpine uplift in Cenozoic time. The Welsh Massif, decoupled from the ABM by the Malvern Line-Worcester Graben, suffered intermittent uplift and erosion of its Mesozoic and Cenozoic cover, probably as a result of thermally induced uplift associated with plume magmatism (Brodie and White 1994) and opening of the North Atlantic during early Cenozoic time.

Conclusions

The long and complex tectonic history of accretion and reactivation of the crust in the Malvern-Worcester Graben region can be summarised as follows:

- early calc-alkaline arc magmatism (680–660Ma) at the Amazonian margin of Rodinia
- almandine-amphibolite and greenschist metamorphism/ductile deformation (650–610Ma)

• uplift of the meta-igneous Malverns Complex (*c.* 600 Ma)
• arc-marginal basin formation (566–560Ma)
• 'Avalon Orogeny', terrane amalgamation and suturing (*c.* 545Ma)
• development of Worcester 'Proto-graben' near the Gondwana margin (Cambrian-early Tremadoc)
• Penobscotian Phase (early Ordovician) — ?inversion of proto-graben
• Avalonia's drift from Gondwana (post-Arenig)/subduction of Iapetus-Tornquist ocean (Ordovician)/subduction shutdown (Ashgill)
• gently subsiding shale-carbonate platform with local small extensional basins (Silurian)
• tholeiitic and calc-alkaline volcanism (early to mid-Silurian) — ?subduction and closure of the Rheic Ocean
• Acadian Phase (early Devonian) — ?further inversion of proto-graben
• extensional reactivation of basement structures in surrounding regions (Carboniferous) — Malverns and Worcester Basin part of the Wales-Anglo-Brabant Massif
• Variscan Orogeny (late Westphalian-Stephanian) — positive inversion and creation of the 'River Severn Uplift' as a 'mountain front uplift
• Uralian Orogeny (Stephanian–early Permian) — intra-plate stress from Uralian Orogen enhances uplift
• extensional reactivation and formation of Worcester Graben (Permo-Triassic, Jurassic and ?Cretaceous)
• ?Alpine inversion, uplift and erosion (Cenozoic)

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Figure 5 is based on maps of the Acadian Unconformity developed by Nigel Smith throughout his career at the British Geological Survey. Reviews by Bill Barclay and David Schofield are gratefully acknowledged. This paper is published with the approval of the Executive Director, British Geological Survey.

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Captions

Figure 1 Tectonic boundaries of Neoproterozoic crust within the Avalon and Monian composite terranes of central Britain north of the Variscan Front (after Pharaoh and Carney 2000; Pharaoh 2018). Terranes are indicated by different colours; seismic transect X-X1 is depicted in Fig. 4.

Faults and lineaments: AL=Askrigg Line, BAF=Bala Fault, BEF=Bryneglwys Fault, CHT=Carmel Head Thrust, CPFS=Causey Pike Fault System, CSF=Church Stretton Fault Zone, DL=Dent Line, D-SHL=Dowsing-South Hewett Lineament, EGL=Eakring-Glinton Lineament, EVF=Enville Fault, FHFZ=Vale of Pickering-Flamborough Head Fault Zone, LE-HH-IFS=Lickey End-Haselor Hill-Inkberrow Fault System, IS=Iapetus Suture Zone, ISLS=Irish Sea Lineament (South), LEF=Lask Edge Fault, LLF=Lowther Lodge Fault, LSZ=Lŷn Shear Zone, MCEM?=Conjectured Microcraton Eastern Margin, MCFZ=Morley-Campsall Fault Zone, MCWM=Microcraton NW Margin, MDFB=Môn-Deemster Fold-Thrust Belt, ML=Malvern Line, MSFS=Menai Strait Fault System, PA=Pennine Axis, PL=Pendle Lineament, PLL=Pontesford-Linley Fault, RFB=Ribblesdale Foldbelt N margin, RRF=Red Rock Fault, SBL=Southern Borrowdale Lineament, SCF=South Craven Fault, ST=Skiddaw Thrust, TF=Thringstone Fault, UF=Unnamed Fault, VF=Variscan Front, WF=Wem Fault, WBFS=Welsh Borderland Fault

System, WFZ=Wicklow Fault Zone.
Solid red ornament—Precambrian outcrop: CF=Charnwood Forest, MH=Malvern Hills, N=Nuneaton.
Dots—boreholes proving Precambrian: BaH=Bardon Hill, BrT=Bryn Teg, Col=Collington 1, Edg=Edgmond 1, Fow=Fownhope 1, Gli=Glinton 1, HeF=Heath Farm 1, Kem=Kempsey 1, MoQ=Morley Quarry, Ort=Orton, OxH=Oxendon Hall, StB=Stretton Baskerville, WiF=Withycombe Farm, Wrb=Wrekin Buildings (Telford 2).

Figure 2 Magnetic potential field: anomaly colour scales range from positive (red) to negative (blue).
Magnetic anomalies described in the text: BMA=Birmingham Magnetic Anomaly, DSIMA=Derby-St Ives Magnetic Anomaly, FINMA=Furness-Ingleton-Norfolk Magnetic Anomaly (after Wills 1978; Pharaoh *et al.* 1993), CEMA=South Central England Magnetic Anomaly (after Lee *et al.* 1990; Busby *et al.* 1993), CCMA=Central Channel Magnetic anomalies, HMA=Harlech Magnetic Anomaly, MMA=Malvern Magnetic Anomaly, WBMA=Welsh Borderland Magnetic Anomaly. (For key to major faults and lineaments see Fig. 1.)

Figure 3 Gravity potential fields, Bouguer anomaly onshore combined with free air anomaly offshore: anomaly colour scales range from positive (red) to negative (blue); magnetic anomalies depicted in Fig. 2 included for reference. (For key to major faults and lineaments see Fig. 1.)

Figure 4 W–E seismic transect across the Worcester Basin and its margins (reproduced from Barclay *et al.* 1997). Location shown on Fig. 1. Based on seismic reflection data acquired by BGS (Chadwick 1985; Chadwick and Smith 1988; Chadwick and Evans 2005).

Figure 5 Cambrian-Tremadocian outcrop and borehole provings in southern Britain (base map for UK from unpublished mapping of the Acadian Unconformity by Nigel Smith). For key to major faults and lineaments see Fig. 1.
Outcrop (solid ornament) borehole provings:
Early–Middle Cambrian (black): Fob=Fobbing, SaF=Sapcote Freeholt (Elmesthorpe), Fow=Fownhope 1; Kin=Kineton, Me3=Merevale No. 3, MoF=Moor Farm, Rot=Rotherwood, Tic=Ticknall (Calke Abbey), WiF=Withycombe Farm.
Possible Cambrian provings: Bay=Bardney 1, GH2=Ellington, Fos=Foston 1, GaH=Galley Hill, Gro=Grove 3, Hus=Hunstanton 1, Gh10=Huntingdon 10, GH5=Huntingdon 5, Lex=Lexham 1, Noc=Nocton 1, Sib=Sibsey 1, SCr=South Creake 1, Spa=Spalding 1, Stx=Stixwould 1, Wel=Welton 1, Wes=Wessenden 1, Wig=Wiggenhall 1, Wis=Wisbech 1, Cof=Cooles Farm 1 (Minety).
Tremadocian provings (red): Baf=Barford, CaW=Calvert (West), Cof=Cooles Farm 1 (Minety), CrH=Crown Hills (Evington), Dad=Dadlington, EWh=East Worldham 1, Fow=Fownhope 1, GaF=Gables Farm, HoB=Hollies Barn, LFE=Leicester Forest East, LiL=Lillingstone Lovell, Me2=Merevale No. 2, Mer=Meriden, Shw=Shrewton, Tat=Tattenhoe, Tri=Tring (Superior), Tw4=Twyford 4, Wec=Westcott No. 1, Wyb=Wyboston, Yar=Yarnbury.

Figure 6 Simplified geological map of the Malvern Hills (after Lambert and Holland 1971; Barclay *et al.* 1997; Barclay and Pharaoh 2000).

Figure 7 AFM diagram for samples of the Malvern Complex: boundary between tholeiitic (T) and calc-alkaline (C-A) fields (after Irvine and Barager 1971; reproduced from Barclay *et al.* (1997).

Figure 8 Geochemical patterns for components of the Malvern Complex, with MORB-normalised values (after Pearce 1982; reproduced from Barclay *et al.* 1997): a=Cumulate ultramafic and mafic amphibolites, b=Non-cumulate mafic amphibolites, c=Amphibolites of dioritic and tonalitic composition, d=Metagranitic rocks .

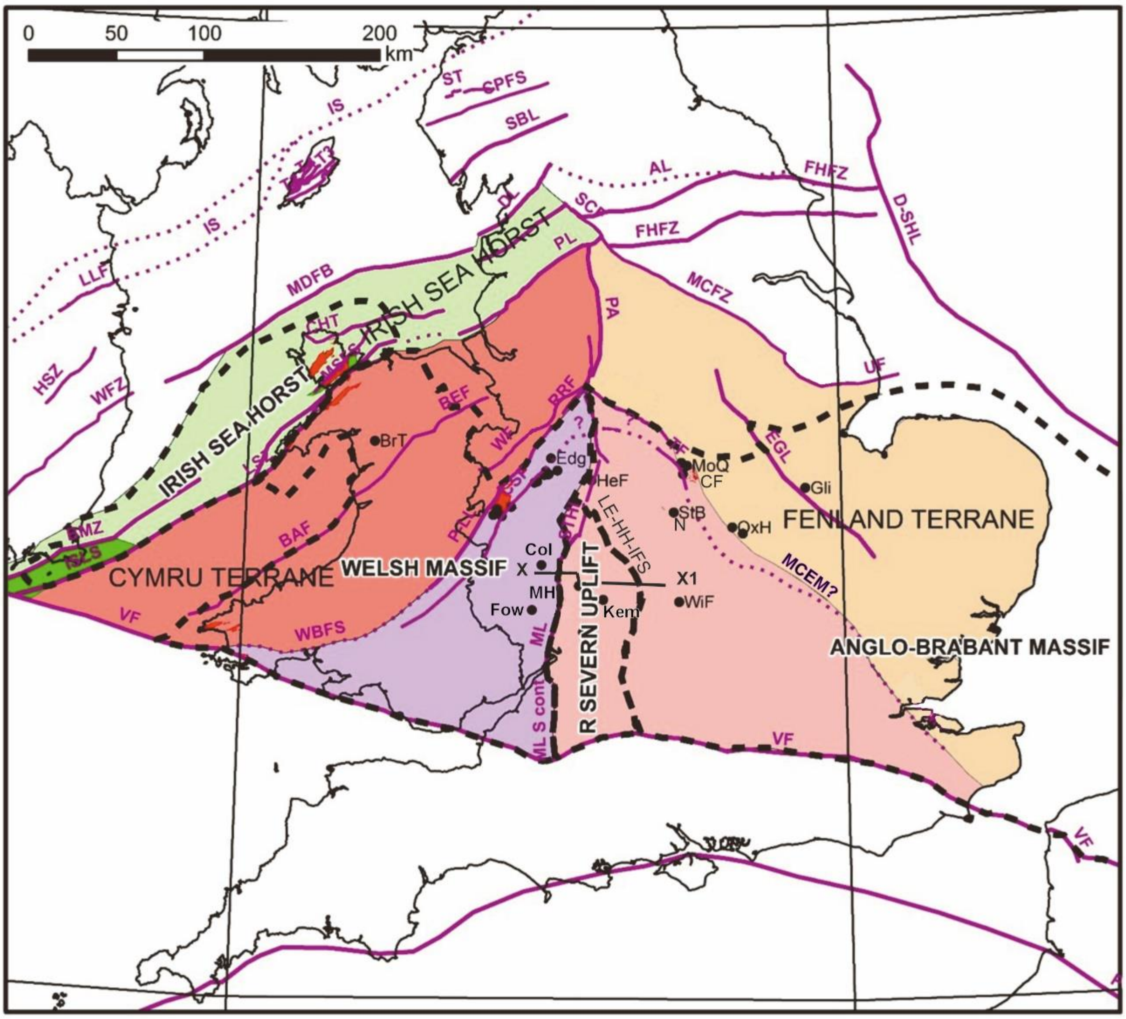
Figure 9 Geochemical patterns for late Neoproterozoic metavolcanics suites, with MORB-normalised values after (Pearce 1982; reproduced from Barclay *et al.* 1997): a=Uriconian volcanic group lavas, b=Warren House Formation lavas, solid symbol=mafic compositions, open symbol=felsic compositions.

Figure 10 Geochemical patterns for components of the Kempsey Formation and microdioritic Charnwood magma types, with MORB-normalised values (after Pearce 1982; reproduced from Barclay *et al.* 1997): a=Clasts of intermediate tuff from core samples of the Kempsey Formation, b=Tuffaceous matrix to clasts and lithic sandstones from core samples of the Kempsey Formation, c=Diorites from the Charnwood area, representative of the Charnian magma type (after Pharaoh *et al.* 1987).

Figure 11 Variscan inversion structures surrounding the ABM (exposed geology after BGS 1:625000 digital mapping; concealed basins after BGS 1999 and Pharaoh *et al.* 2011; Variscan structures after BGS 1996). (For key to major faults and lineaments see Fig. 1.): UORS=Upper Old Red Sandstone (Upper Devonian), CL Sgp=Carboniferous Limestone Supergroup (Visean-Tournaisian), MG Gp=Millstone Grit Group (Namurian), L PCM Gp=Lower Pennine Coal Measures Group (Westphalian A), U PCM Gp=Upper Pennine Coal Measures Group (Westphalian B/C), W Gp=Warwickshire Group (Westphalian C/D); concealed Carboniferous basins (shades of blue): B&SC=Bristol and Somerset Coalfield, KC=Kent Coalfield, OBC=concealed Oxfordshire-Berkshire Coalfield, WC=Warwickshire Coalfield, SWC=S Wales Coalfield.

Figure 12 Restored schematic cross-section (cf. Fig. 4), to illustrate the structural evolution of the region: a=Late Carboniferous times, before Variscan movements; b=Variscan compression leads to crustal shortening and apparent reverse faulting (‘positive inversion’) along the Malvern Axis and thrust, and development of a mountain-front uplift; c=end-Carboniferous to early Permian times-regional uplift and erosion enhanced by Uralian intra-plate stress; d=Permo-Triassic tension leads to extensional reactivation of Variscan fractures, with subsidence (‘negative inversion’) controlled by major basin-margin normal faults. Note that this simplified model does not incorporate the evidence for late Cambrian-Tremadocian subsidence (the Worcester Proto-graben or ‘aulacogen’) or possible earlier phases of inversion, during the Penobscotian (early Ordovician) and Acadian (early Devonian) orogenic phases (reproduced from Barclay *et al.* 1997).

Figure 13 Variscan orogenic terranes of western Europe. Note the juxtaposition of the River Seven Uplift (RSU) to a pinch-point in the Rhenohercynian Terrane resulting from indentation by the Archaean Icartian Domain embedded within the Cadomian North Brittany Terrane (after Pharaoh *et al.* 2017).



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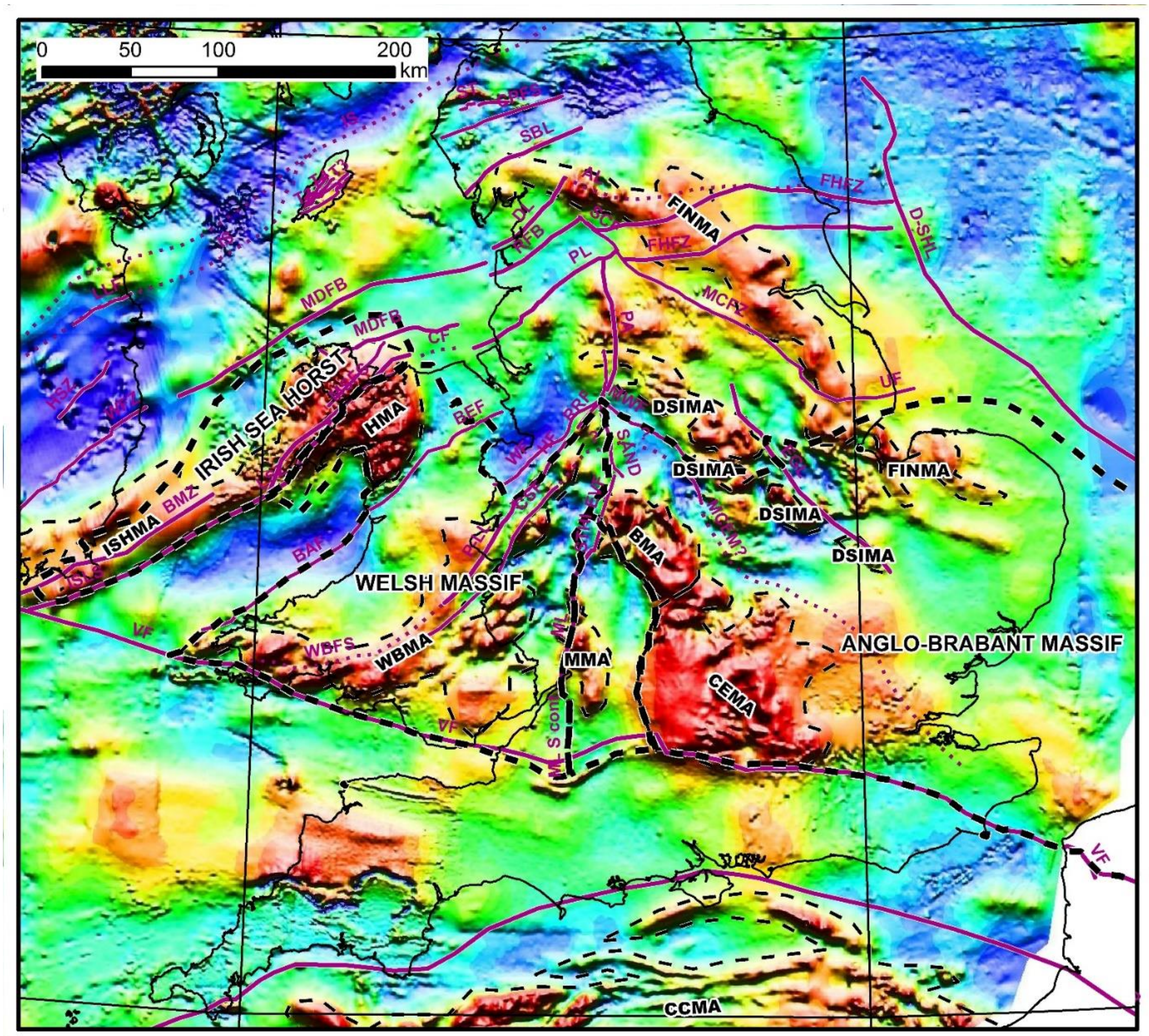

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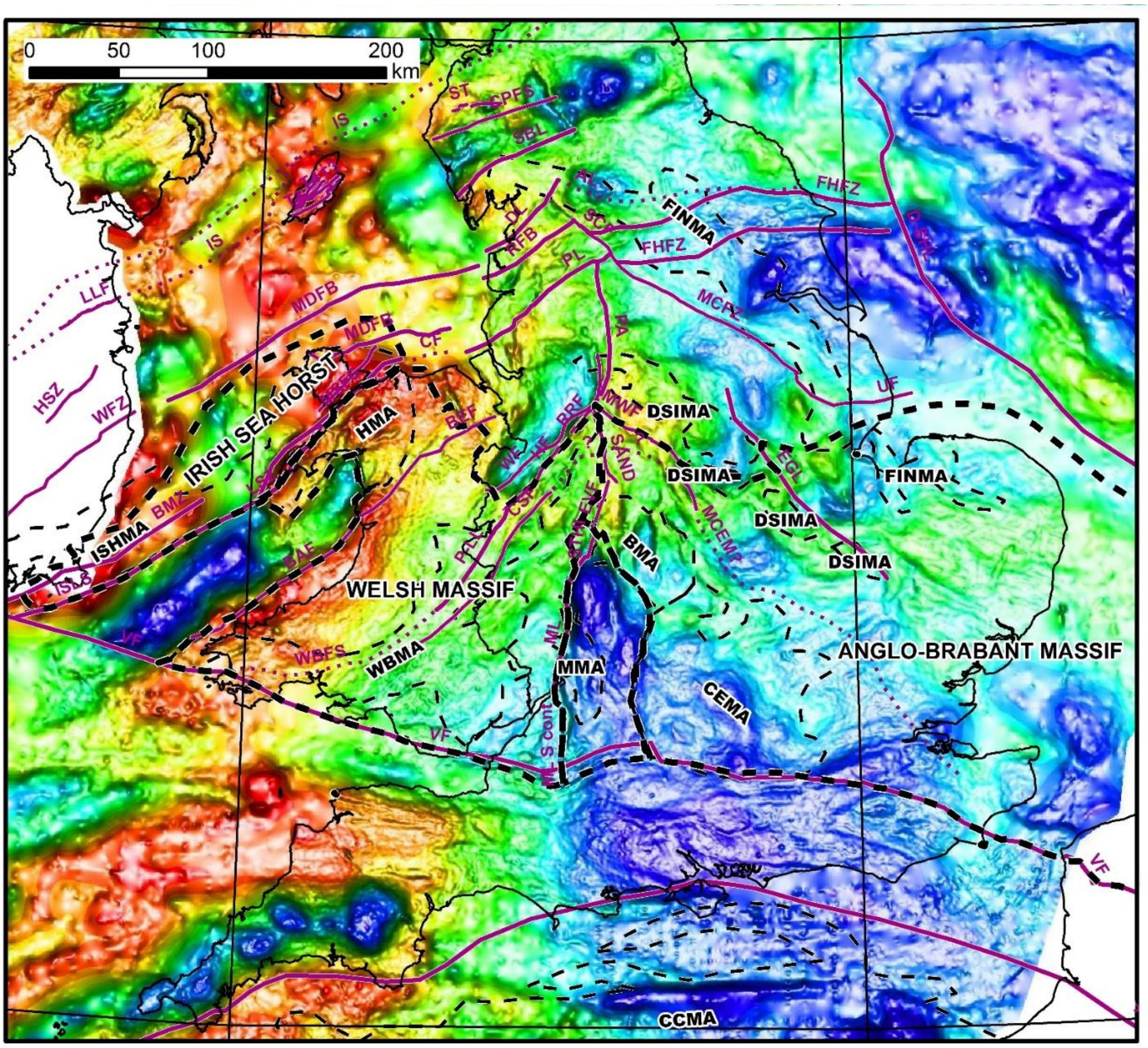

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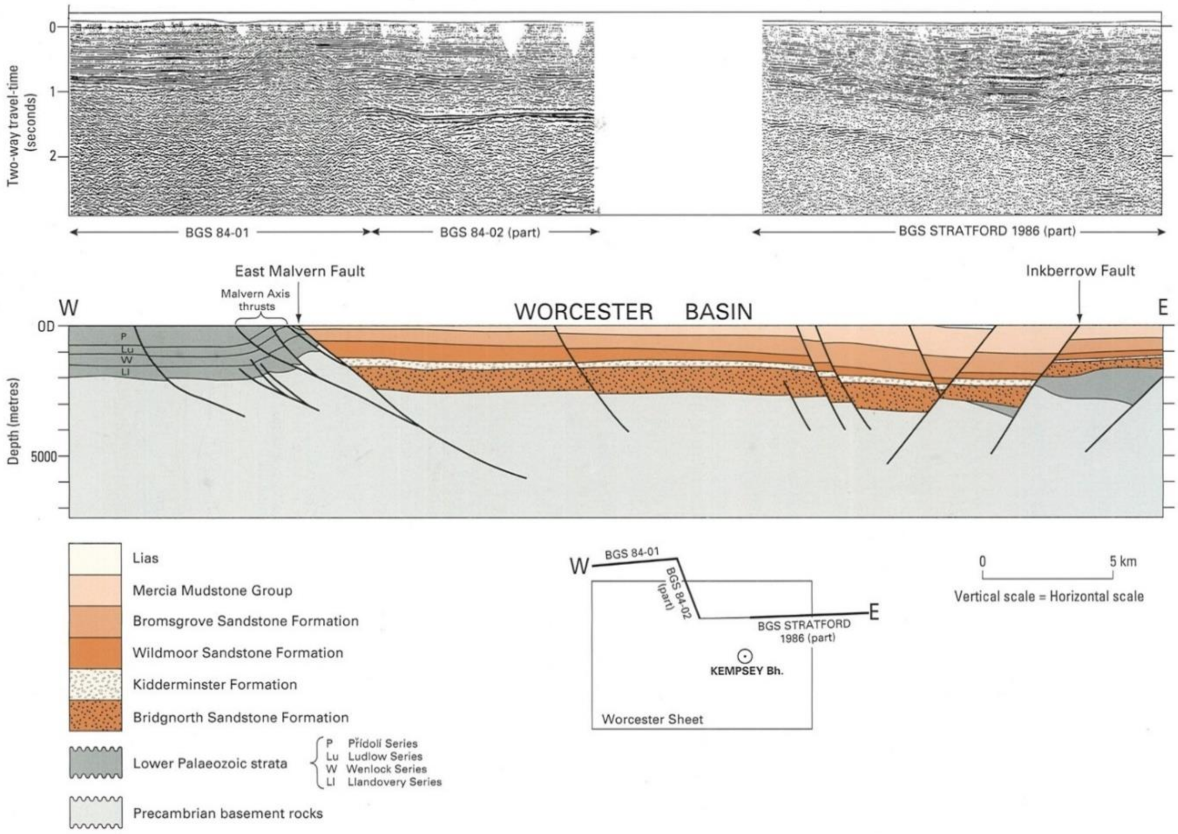

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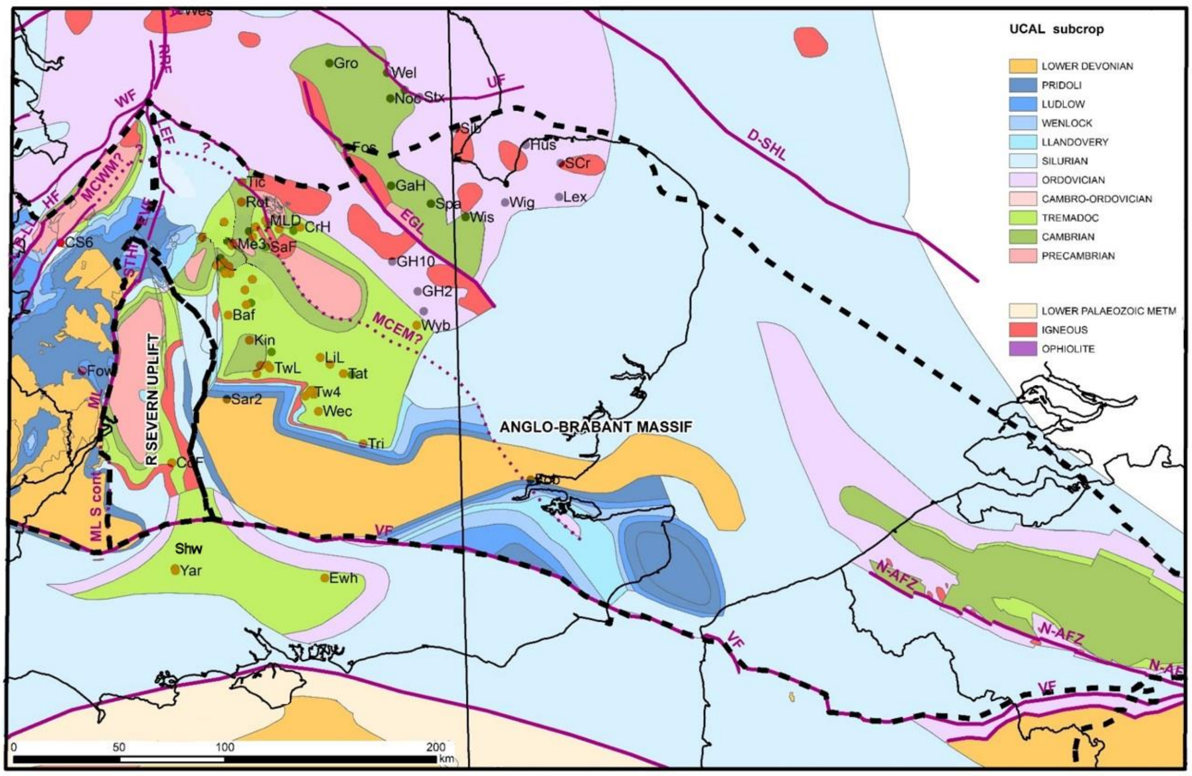

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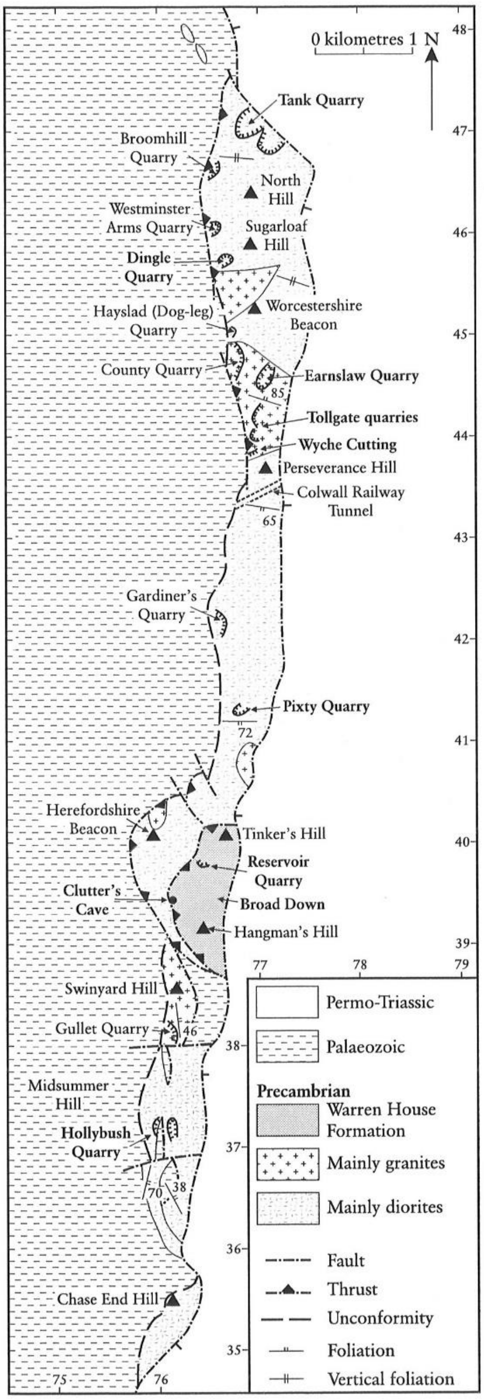

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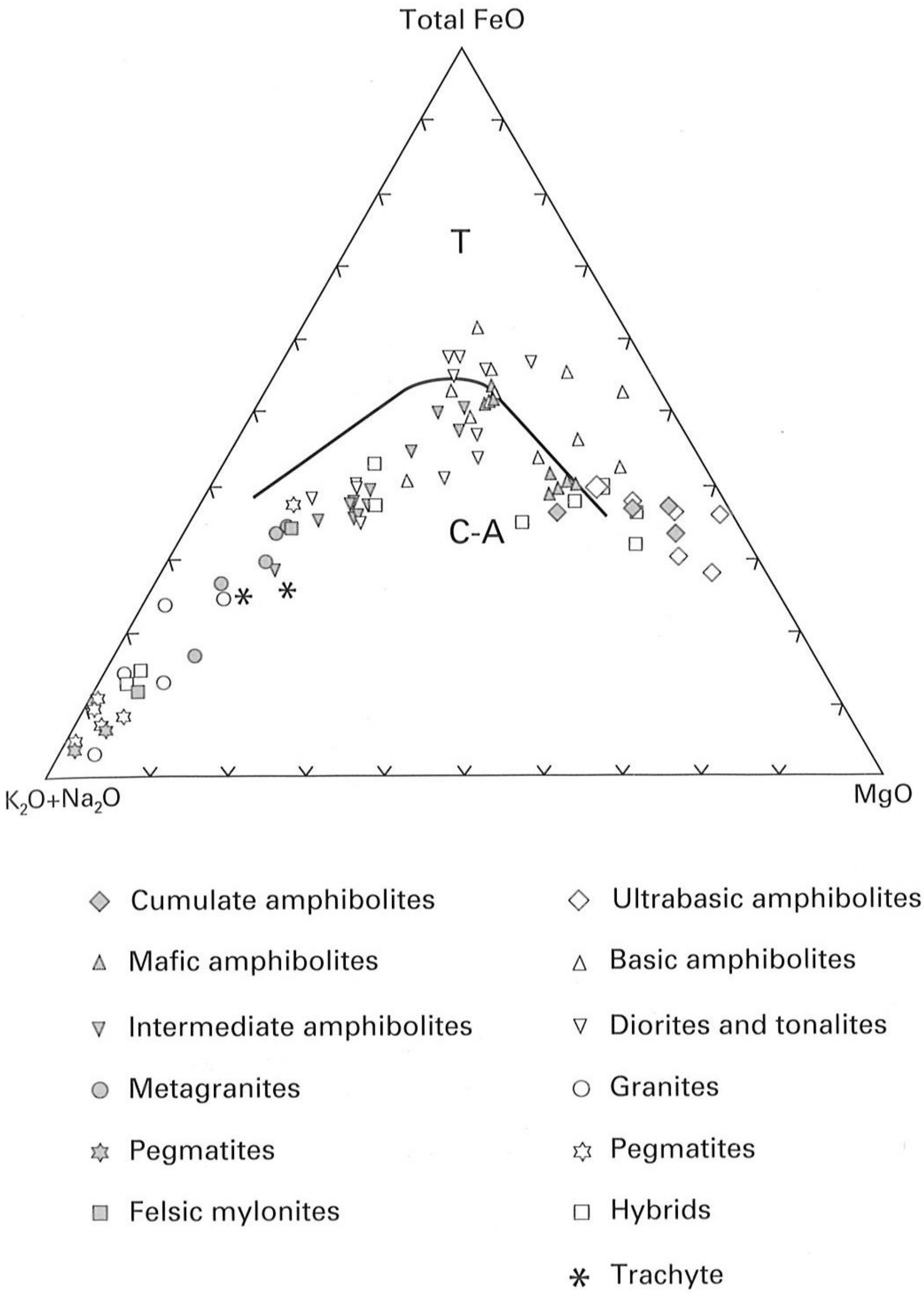

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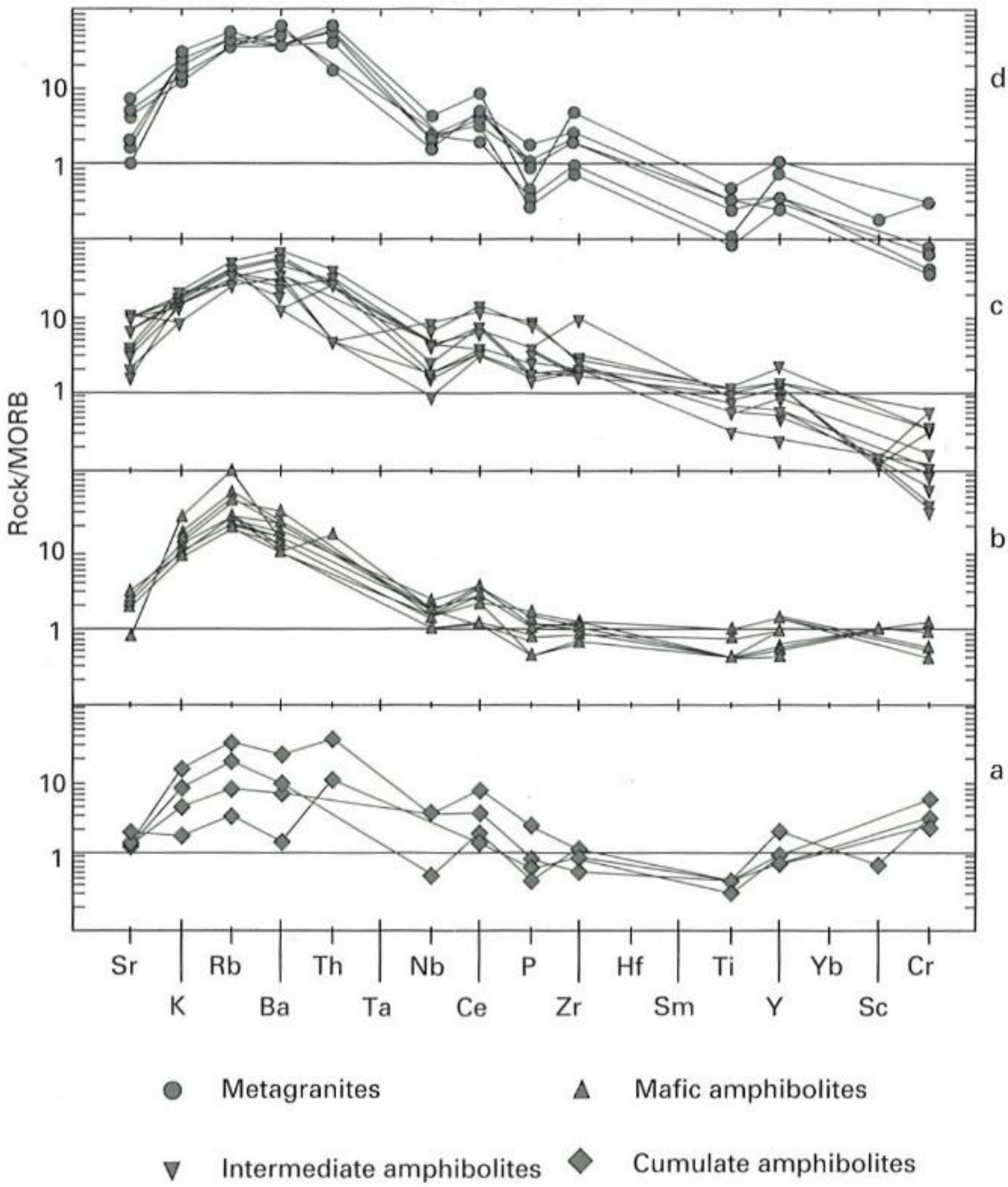

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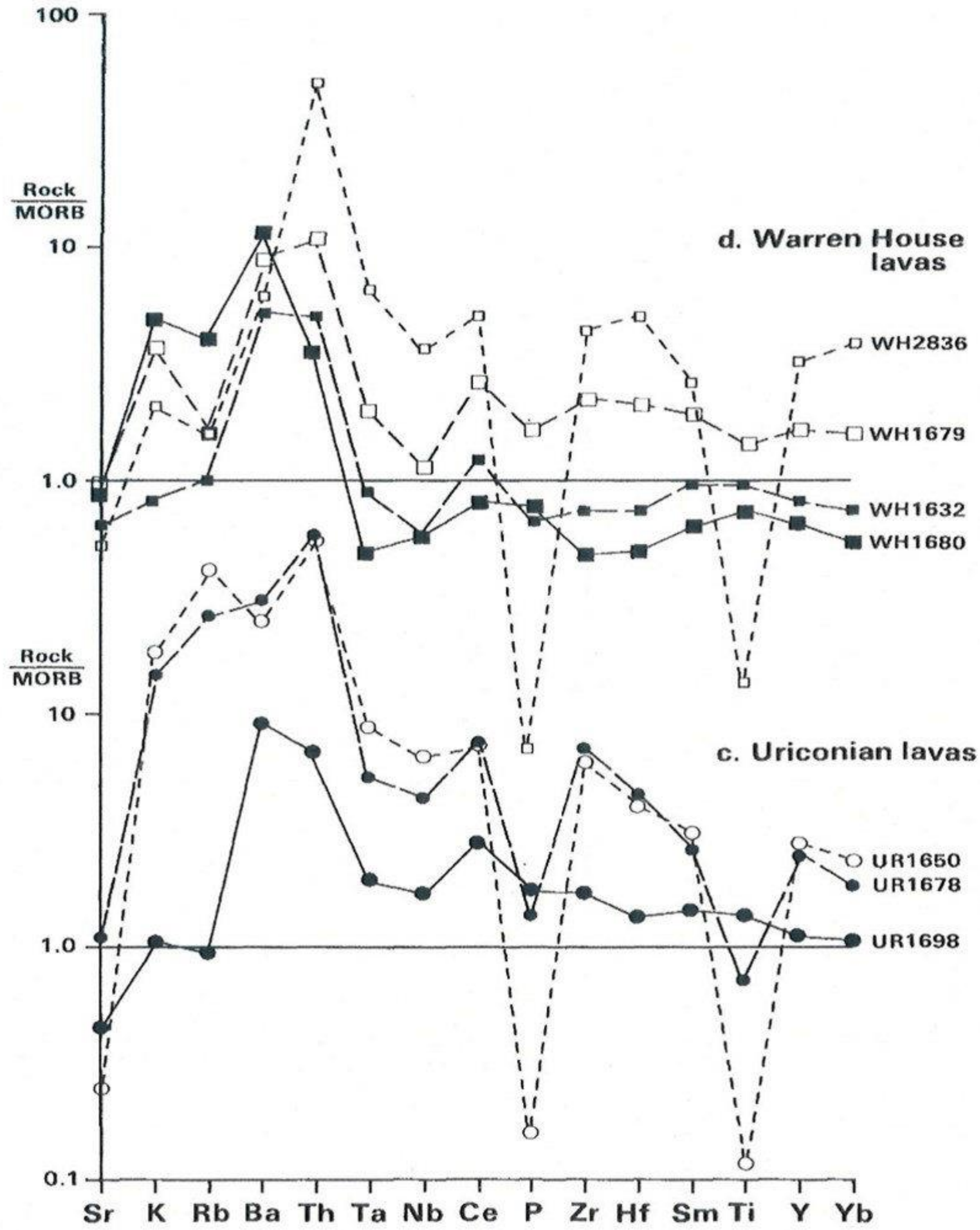

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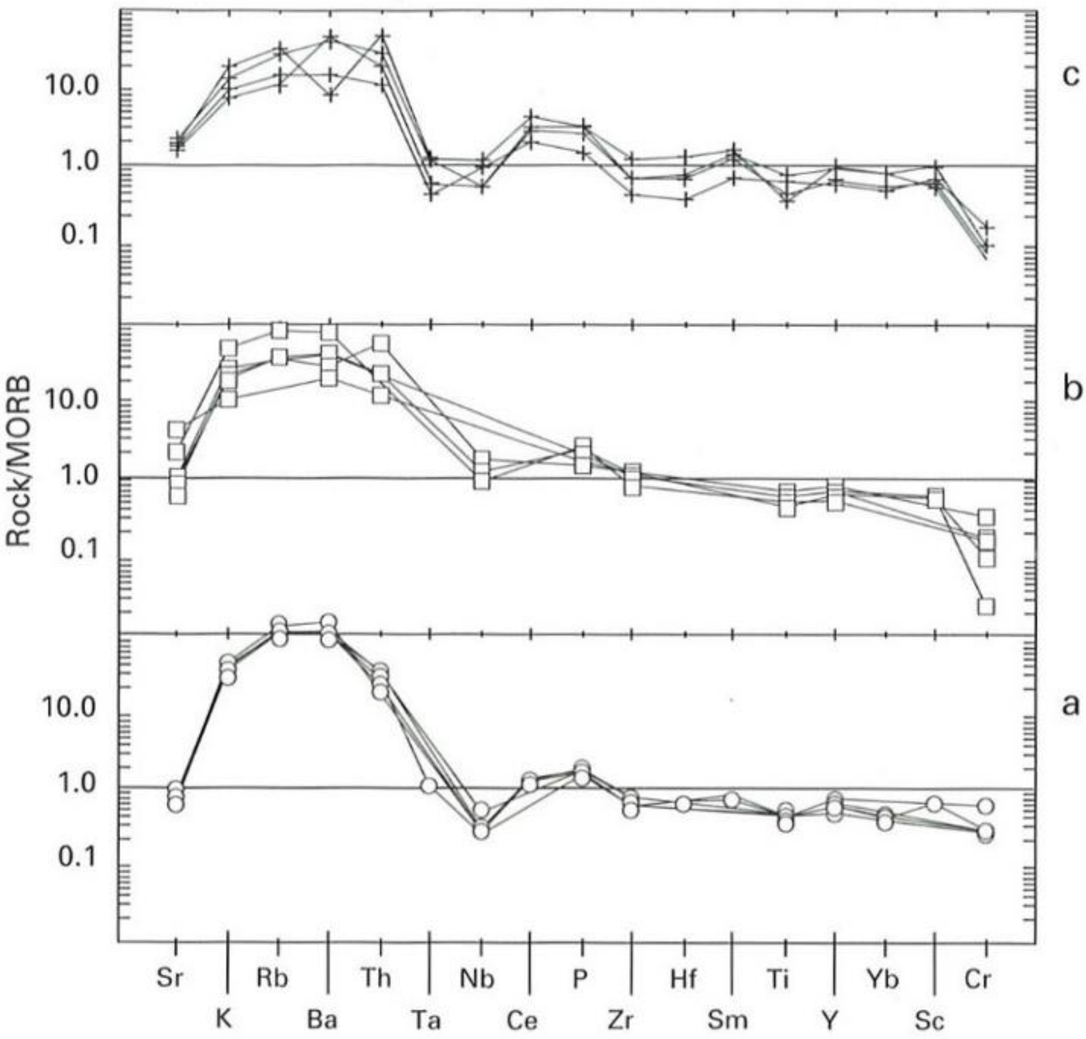

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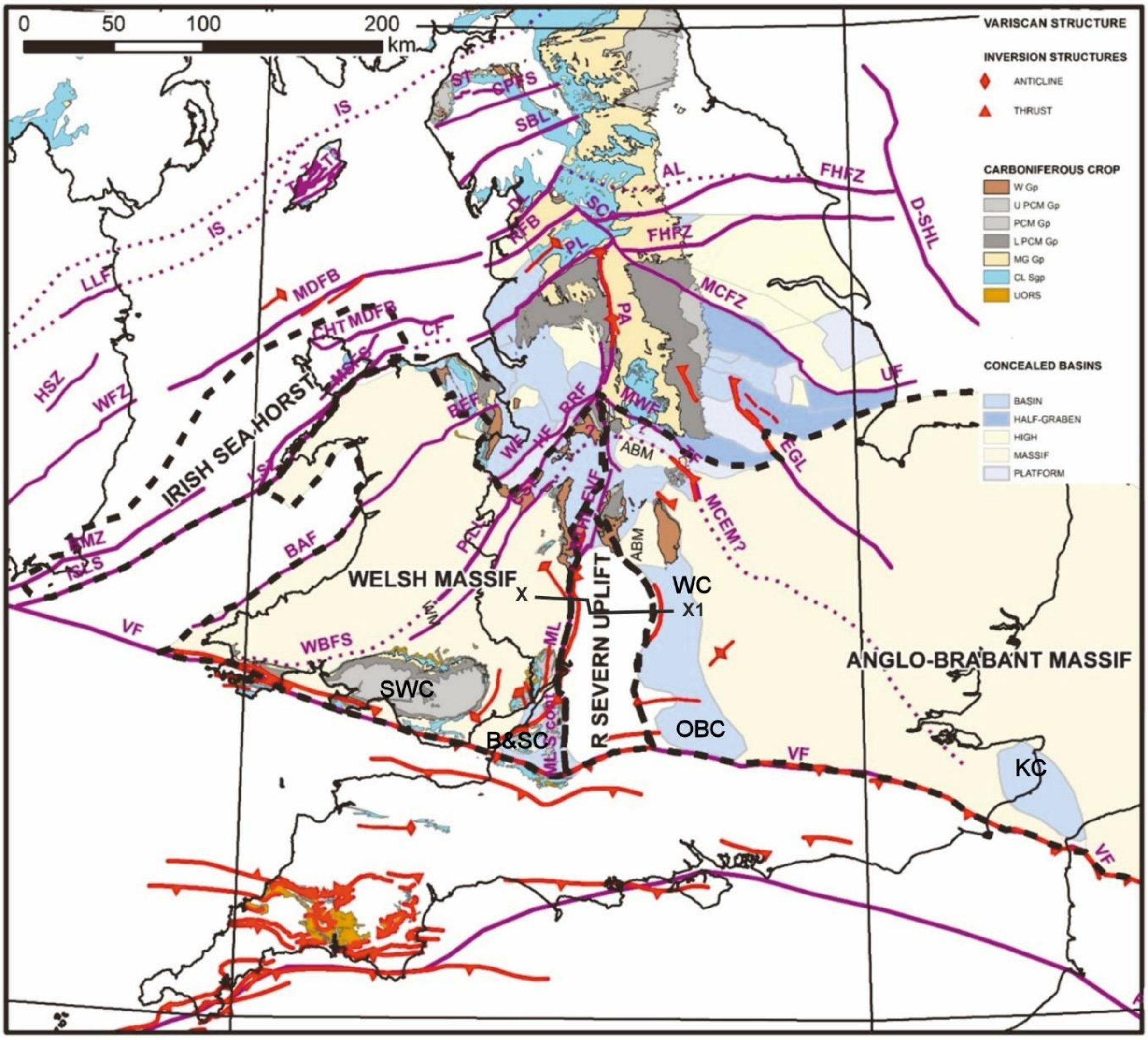

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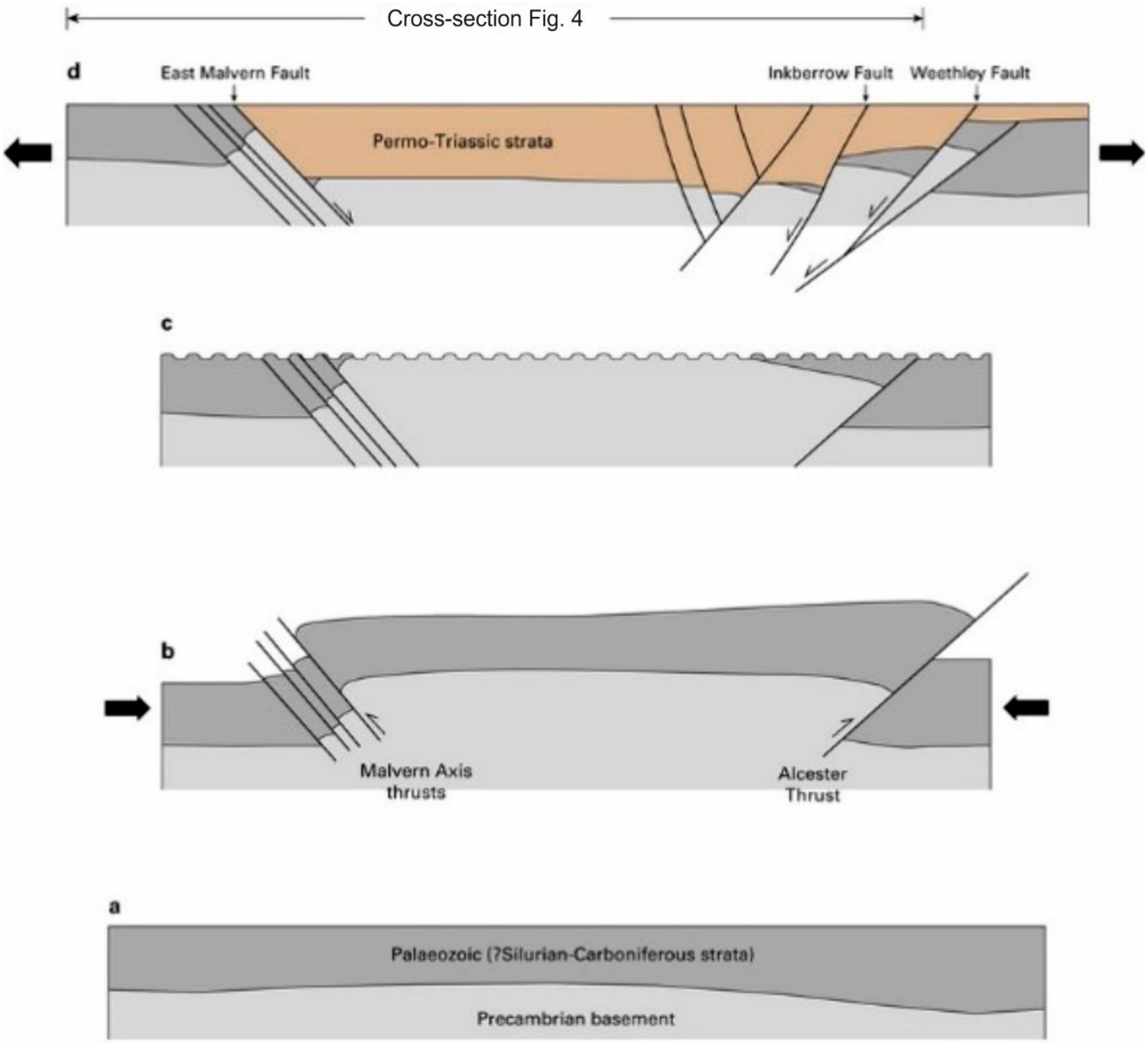

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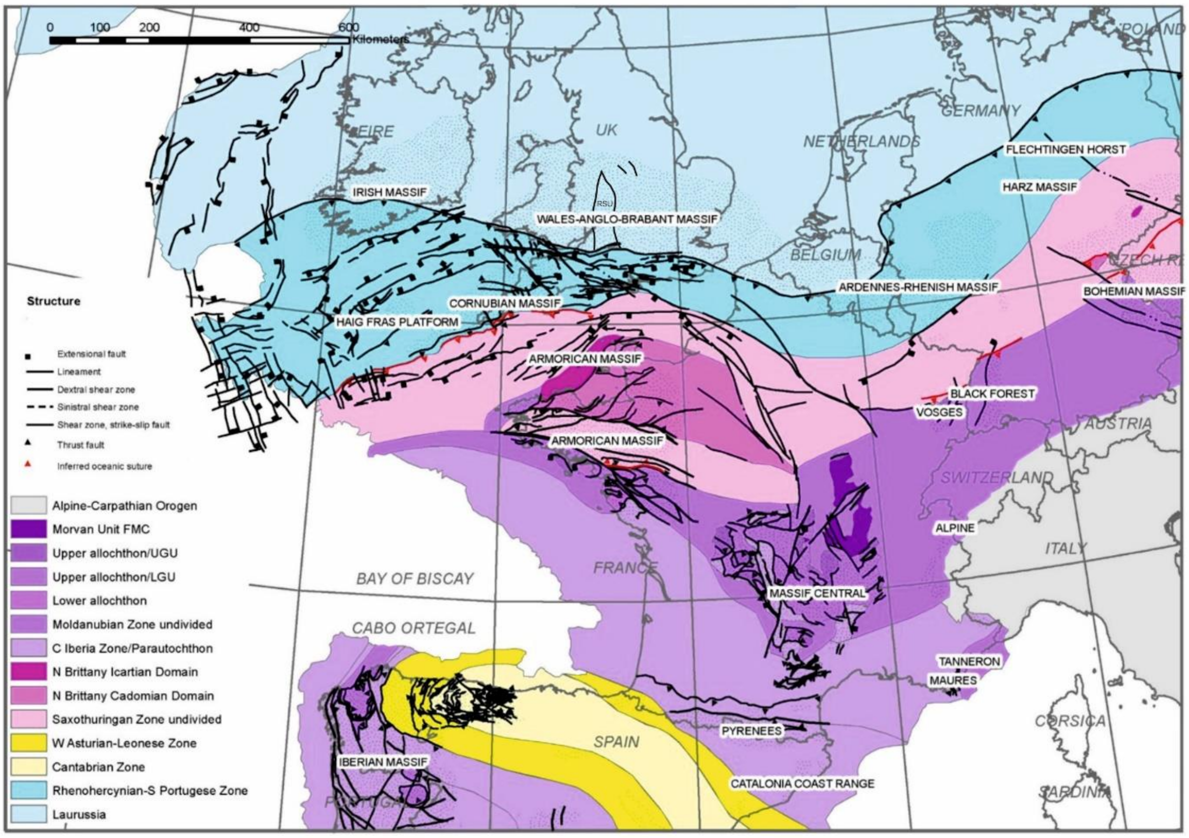

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