

Seismostratigraphic analysis of Paleozoic sequences of the Midlands Microcraton

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Abstract: A regional review of publicly available seismic reflection lines and wells enables the identification across the Midlands Microcraton (MMC) of four Paleozoic seismostratigraphic megasequences, bounded by the Shelveian, Acadian, Symon and Variscan unconformities. The southern boundary of the MMC is drawn at a line of major change in pre-Permian subcrop, and most of central southern England is considered underlain by Paleozoic rocks of MMC character. The Lower Silurian Shelveian Unconformity cuts down through Ordovician and Cambrian rocks to the Precambrian and largely defines the distribution of these rocks in the region. However, more than 2500 m of Tremadoc shales are preserved SW of Swindon. Above the Shelveian, a characteristic shallow-marine Silurian is overlain by up to 3000 m of Old Red Sandstone facies, preserved in a north-south-orientated syncline. The Acadian Unconformity cuts down through folded Lower Paleozoic rocks, with the Frasnian transgression overlying Precambrian in places. Little Carboniferous was deposited across the MMC until uppermost Westphalian–Stephanian Warwickshire Group sandstones and coals were laid down across the erosion surface of the Symon Unconformity. The northern boundary of thin-skinned Variscan thrusting can be interpreted on seismic data but appears to have had little effect on the regional pre-Permian subcrop.

This paper presents the results of a regional review of the area of the Midlands Microcraton (MMC) using the digital, post-stack seismic lines, and well and borehole formation tops and times (Fig. 1), freely available to academic users through the UK Onshore Geophysical Library (UKOGL), together with lithological descriptions from released wells. This area has been of little interest for oil and gas exploration over the past 25 years, and the details of the Paleozoic rocks are not widely known. Few seismic lines have been recorded over the eastern and westernmost parts of the MMC, and lines recorded over the rest of the area vary greatly in vintage and quality. However, many of the lines in the central area show remarkably good detail of both Lower and Upper Paleozoic sequences and tectonic events. Interpretation has enabled the identification of four major unconformities, which define the distribution of Paleozoic rocks beneath the Permian and Triassic cover across the MMC. It has also enabled the recognition of a series of ‘packages’ of seismic character that can be used to identify the four seismostratigraphic megasequences separated by these unconformities. It is hoped that the information presented here will stimulate interest in the area and lead to more detailed studies for both commercial and academic purposes.

Definition of the Midlands Microcraton

The Midlands Microcraton (MMC) (Pharaoh *et al.* 1987) is a wedge-shaped area, the NE and NW margins of which were defined as bounding an area comparatively undisturbed by Caledonide folds, the Midlands Massif, by Turner (1949). It was relatively unaffected by major crustal deformation from at least Llandovery times until the present day, although it was not entirely stable. It is bounded to the NW by the Pontesford Lineament (Woodcock 1984), a series of faults that form part of the boundary of the Lower Paleozoic Welsh Basin, and to the NE by a series of faults that form the boundary to the Anglo-Brabant Acadian deformation zone (Smith *et al.* 2005). The plate movements that defined these boundaries are described in detail in Smith *et al.* (2005) and will not be addressed here. The boundaries to the NE and NW are postulated to have been accentuated by the northwards movement of the MMC at the time of the Acadian deformation, creating thrusting and sinistral strike-slip along the NW boundary, with thrusting and dextral strike-slip along the NE boundary (Soper *et al.* 1987). The southern boundary of the MMC has previously been taken at the inferred northern margin of Variscan foreland deformation, referred to as the ‘Variscan Front’ and here located after Chadwick *et al.* (1989).

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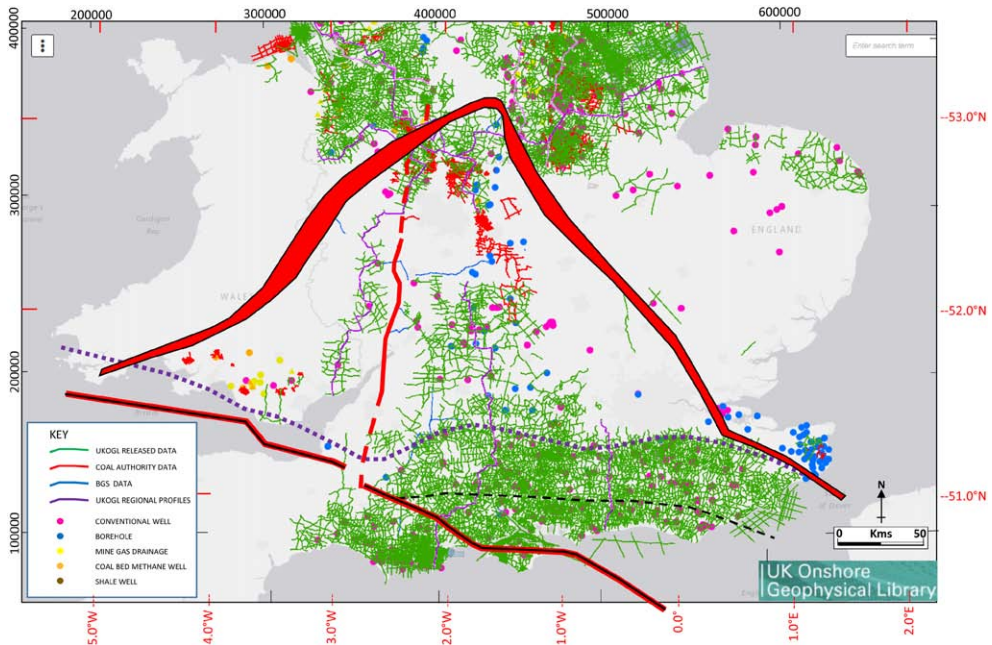


Fig. 1. Database of seismic lines and basic well information freely available through UKOGL (www.ukogl.org.uk) and used in this study. Structural elements are labelled in Figure 2.

Although the line of the Variscan Front (Fig. 2) does coincide with the northern margins of the Mesozoic Pewsey and Weald basins, thin-skinned thrusting occurs well north of this line. However, the interpreted subcrop maps indicate no significant change in the Paleozoic sequences over most of central southern England from those of the MMC further north. There are two alternative lines along which to take the southern boundary of the MMC: the first is the line south of which the Old Red Sandstone facies seen in core and cuttings samples from released wells appears to be more indurated and is possibly equivalent to the Devonian sandstones of north Devon; and the second is the better-defined northern boundary of the subcrop of highly deformed Devonian and Carboniferous shales identified by well and borehole information beneath the Permo-Trias. In Dorset, this boundary also marks the northern extent of the thick Permian Aylesbeare Mudstone sequence (Butler 1998). This second alternative is taken as the boundary of the Variscide Rhenohercynian Terrane and the southern margin of the MMC.

Seismic megasequences in the Paleozoic of the MMC

Figure 3 illustrates the four megasequences here recognized in the Paleozoic of the MMC. These have

been simplified because they are primarily based on the recognition of ‘packages’ of seismic events, rather than detailed stratigraphy. Nevertheless, the bases of the packages bear some resemblance to the ‘carpets’ identified under the MMC by Wills (1978). In general, the underlying Precambrian includes few events that can be followed on the seismic, although traces of major faults and indications of strong dips can be seen. A marked, angular unconformity between the Cambrian and Precambrian is seen at outcrop in Shropshire (Greig *et al.* 1968) and can sometimes be identified on seismic line data in parts of the Welsh Borderlands (Fig. 4). However, it cannot be mapped over any significant area.

The Cambrian sequence is poorly represented in outcrop across the MMC but appears to consist of a series of sandstones and shales, probably age-equivalent to the sequence seen in outcrop at Comley (Smith *et al.* 2005), forming stacked, relatively high-amplitude events, and its appearance is quite characteristic. However, the upper part of the Cambrian, equivalent to the White Leaved Oak Shale of Merioneth age in the Malvern area, is indistinguishable from the Tremadoc, and these shales together form a very characteristic opaque seismic character (combined as ‘Tremadoc’ on the interpreted seismic lines). Smith & Rushton (1993) interpreted the thick Tremadoc seen on isolated seismic lines in the Worcester Graben area as the remnants

PALAEZOIC OF THE MIDLANDS MICROCRATON

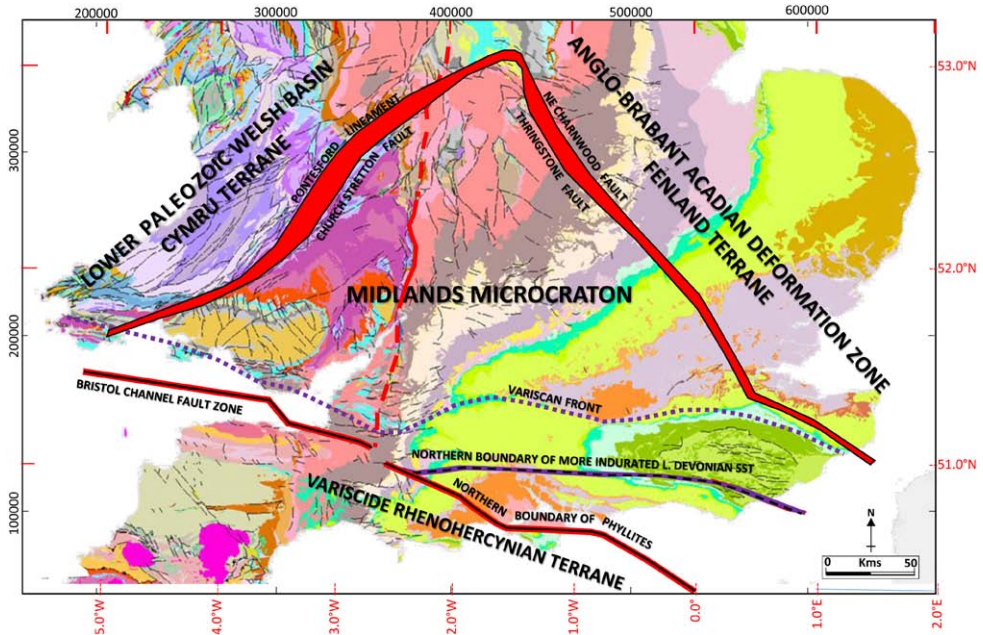


Fig. 2. The Midlands Microcraton: terrane boundaries, adapted from Pharaoh *et al.* (1987), and possible southern limits. The base map was taken from the published 1:625 000 geological map with the permission of the British Geological Survey.

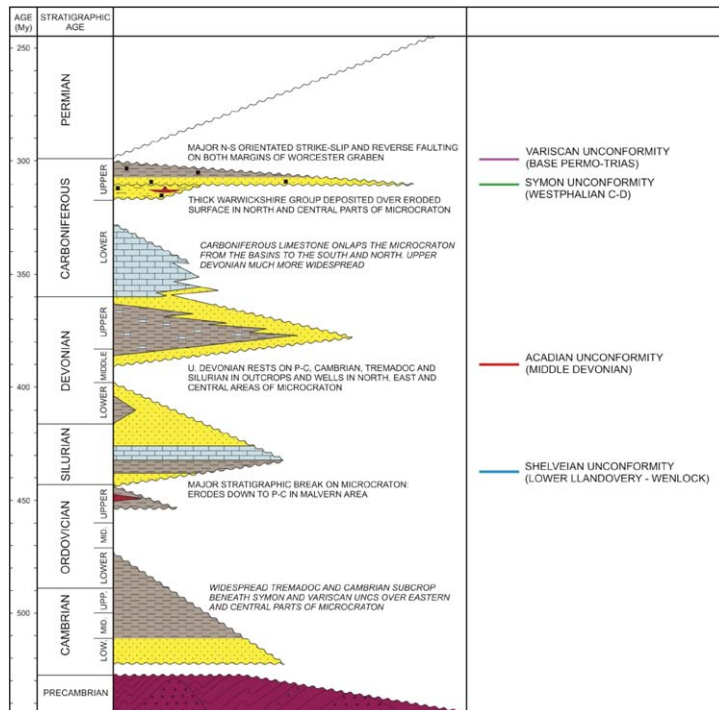


Fig. 3. Paleozoic stratigraphy of the MMC, showing the ages of the four megasequences and the unconformities that separate them.

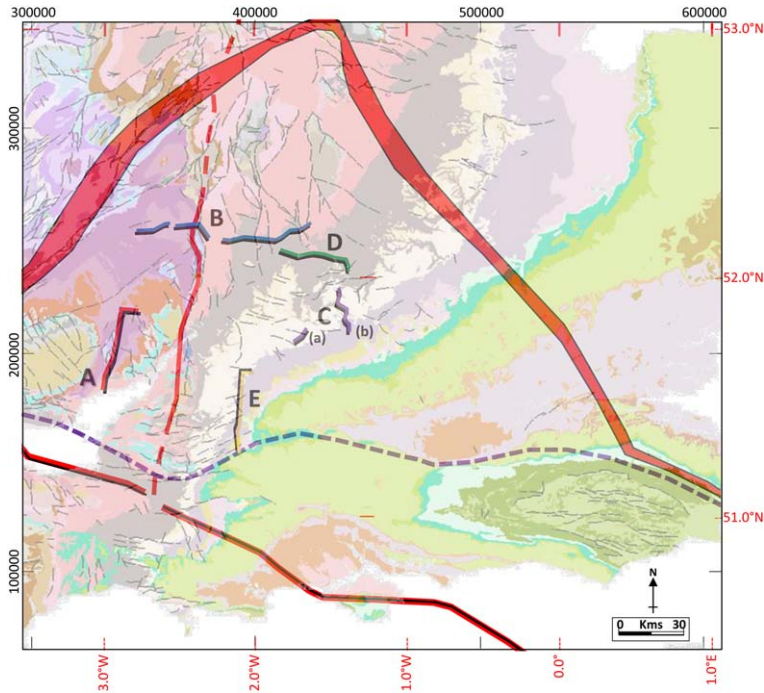


Fig. 4. The location of seismic lines used to illustrate this paper. The base map was taken from the published 1:625 000 geological map with the permission of the British Geological Survey.

of deposition in a series of extensional graben. The current study suggests it is more likely that a relatively uniform, passive margin sequence of Tremadoc was deposited over most of the central part of the MMC but was uplifted and eroded by the Selveian Unconformity. It is interesting to note that well-preserved Tremadocian acritarchs were identified at two levels within Emsian-age Lower Old Red Sandstone of the Apley Barn borehole (Richardson & Rasul 1979). Further erosion took place at the Acadian and Variscan unconformities to give rise to the currently preserved thicknesses. Above the eroded Ordovician and older rocks, the banded amplitudes created by the limestones, shales and volcanics of the Llandovery–Ludlow sequence form a recognizable package below the seismically opaque Old Red Sandstone of Pridolf–Early Devonian age. The contrast between the Cambrian, Tremadoc and Silurian seismic character was used by Smith *et al.* (2005, fig. 8) as a guide to interpret the BGS Duffield seismic line, in the northern apex of the MMC. The Upper Devonian rocks have a similar seismic character to the Lower Devonian and the two can rarely be differentiated away from well control, while the Lower Carboniferous limestones can be recognized where they subcrop the Triassic in the southern part of the MMC by characteristic remnant

topographical highs, often underlain by small thrusts. Over most of the north central part of the MMC, the youngest pre-Permian package is formed by the Warwickshire Group, which has a very characteristic series of high-amplitude events at its base.

The Selveian Unconformity

The unconformity seen near the base of the Llandovery in the Welsh Borderlands appears to have had a major impact across the MMC. This unconformity was named Selveian by Toghil (1992), who mapped the Selve Inlier in Shropshire. Review of seismic and borehole data, combined with previous work by Smith (1987) and Smith *et al.* (2005), indicate that the Selveian Unconformity removes the upper and middle parts of the Ordovician over most of the MMC, leaving just the Tremadoc, and cuts down to the Precambrian in parts of the NW region of the MMC. However, the Caradoc seems to be present beneath it in parts of Shropshire and, possibly, Herefordshire (Fig. 5), and Arenig rocks were recorded in well Strat A-1 on the northern margin of the Weald Basin. The age of the outcropping rocks above the unconformity ranges from Early Llandovery (Rhuddanian) in Gwent and Herefordshire to

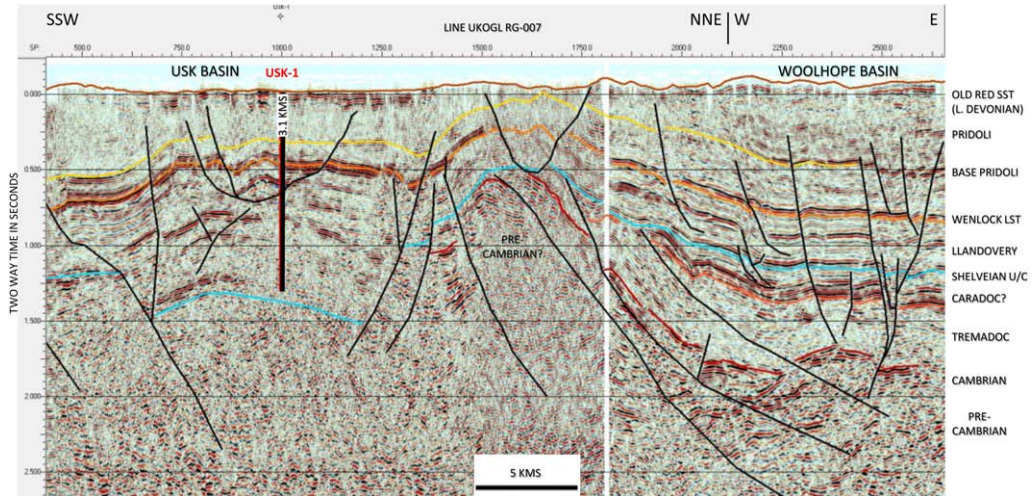


Fig. 5. Seismic Line A, through the southern Welsh Borderlands, showing the anomalous Usk Basin and tight folding below the Selveian Unconformity.

Wenlock in parts of Shropshire (Greig *et al.* 1968). The Llandovery–Ludlow rocks form a characteristic banded package on seismic lines, which enables them to be mapped across the MMC, possibly as far as the Weald Basin, despite a general lack of well control. Woodcock & Pharaoh (1993) compared the facies of the limited penetrations of Silurian rocks in East Anglia with those of the Welsh Basin and concluded that they were very similar: two primarily deep-water, shale-dominated sequences separated by the thin shelf sequence postulated to have been deposited over the MMC. However, there is little information available from wells to determine the lithologies of this shelf sequence or the exact age of the subsurface rocks overlying the Selveian Unconformity, which probably range in age from latest Ordovician to Wenlock.

There is widespread evidence of folding and minor thrusting beneath the Selveian Unconformity (Fig. 5), although the opaque nature of the Tremadoc makes it difficult to see evidence of deformation within it. However, well evidence indicates the presence of very variable dips and reverse faulting within this sequence. Figure 5 is part of regional profile UKOGL RG-007 (available from the UKOGL website: www.ukogl.org.uk) through an area studied in detail by Butler *et al.* (1997). Part of the line was interpreted by Barclay & Smith (2002), who postulated the presence of Caradoc above the Tremadoc in the northern part of Figure 5. Unfortunately, the next well control is Fownhope-1, 17 km to the NNE, which is on the other side of the Woolhope Fault, a thrust with a strike-slip component, and it is difficult to correlate the horizons across it. The line demonstrates tight folding and thrusting below

what is interpreted to be the Selveian Unconformity in a WSW–ENE-orientated, unnamed high that separates the Usk Basin from the Woolhope Basin. Well Usk-1 is anomalous, because it penetrated a very thick sequence of clastics of Llandovery age and was still within rocks dated as Rhuddanian at total depth. The Usk Basin appears to have formed as an extensional graben that filled with the products of erosion around its northern and eastern margins, and was apparently no longer active by the end of the Llandovery. Seismic lines to the west of Usk-1 indicate the presence of a thick wedge of seismically opaque sediments that pinch out before reaching the well. These may be shales forming an extension of the Welsh Basin sequence that opens up off the margin of the MMC to the NW (Woodcock *et al.* 1996; Butler *et al.* 1997), although the Usk Basin still lies 50 km or more from the Pontesford Lineament.

In the area to the west and north of the Malvern Hills, the Selveian Unconformity appears to cut down to the Precambrian, as it does on the SE side of the Church Stretton Fault (Greig *et al.* 1968) and in the Telford area (Smith *et al.* 2005). Figure 6 presents a compiled seismic cross-section from west to east across the Malvern Line. The interpretation indicates that the Precambrian basement encountered below the Variscan Unconformity in Kempsey-1 (Whittaker 1980a), which lies some 3.5 km south of the compiled line in the gap between BGS84-02 and BGS86-03, is part of a major Selveian high that extended over a large area of Herefordshire and Worcestershire. The Silurian sequences above the unconformity show no sign of thinning towards the Malvern Line (Fig. 7). It is postulated that the occurrence of Precambrian subcrop beneath the

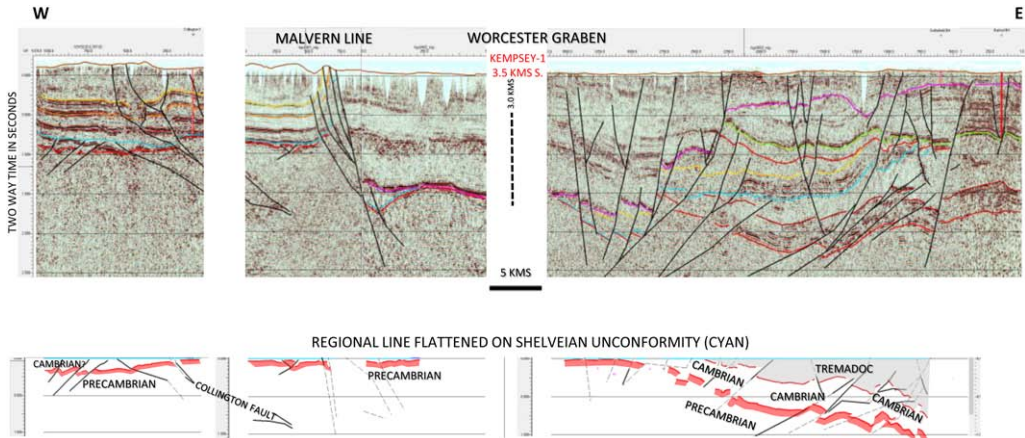


Fig. 6. Seismic Line B: regional compilation from north Herefordshire across the Malvern Line to Stratford-on-Avon, together with events flattened on Selveian Unconformity to demonstrate the interpreted regional Selveian high. Lines BGS84 -01, BGS84-02 and BGS86-03 were reprocessed by UKOGL in 2012 and used with the permission of the British Geological Survey. ©NERC 2012.

Permian in the centre of the Worcester Graben is the result of erosion of this extensive high zone by unconformities at Selveian, Acadian and two Variscan episodes, rather than a simple Variscan uplift and later inversion of what is now the Permian Basin by Variscan thrusts reaching the pre-Permian surface at the Malverns in the west and the zone of the Inkberrow Fault in the east, as proposed by Chadwick (1993) and Peace & Besly (1997). This is in agreement with Smith (1987), who inferred a Precambrian

subcrop beneath the Devonian in the Worcester Graben area. The steep nature of the faulting on the Malvern Line suggests strike-slip-induced reversed faulting, although there is clear deep-seated evidence of thrusting on the Collington Fault, which may be of Acadian age but unfortunately reaches the surface (Brandon 1989) in an area where there is no outcrop younger than Early Devonian.

The eastern half of Seismic Line B (Fig. 8) demonstrates the increased preservation of Tremadoc and

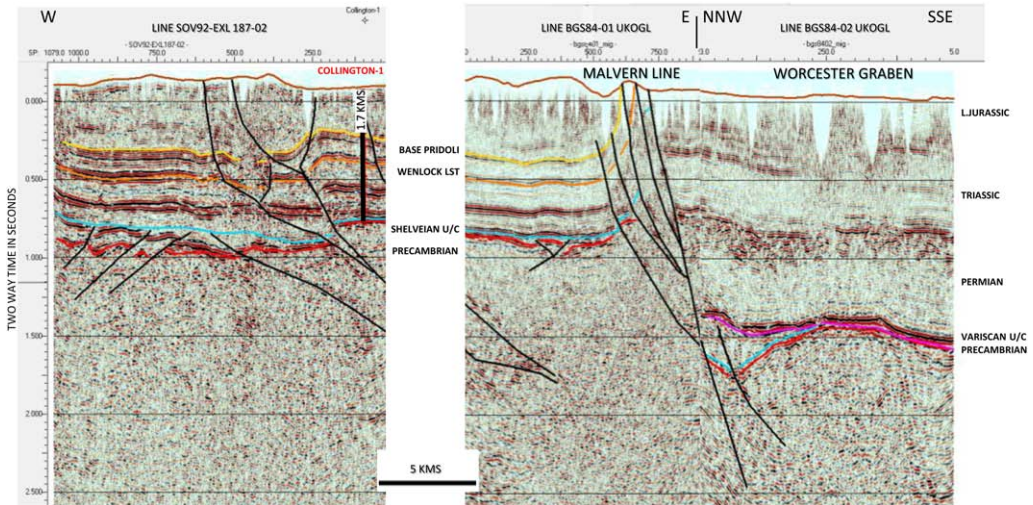


Fig. 7. Western half of Seismic Line B, showing detail of the Collington Fault and the Malvern Line. Lines BGS84-01 and BGS84-02 were reprocessed by UKOGL in 2012 and used with the permission of the British Geological Survey. ©NERC 2012.

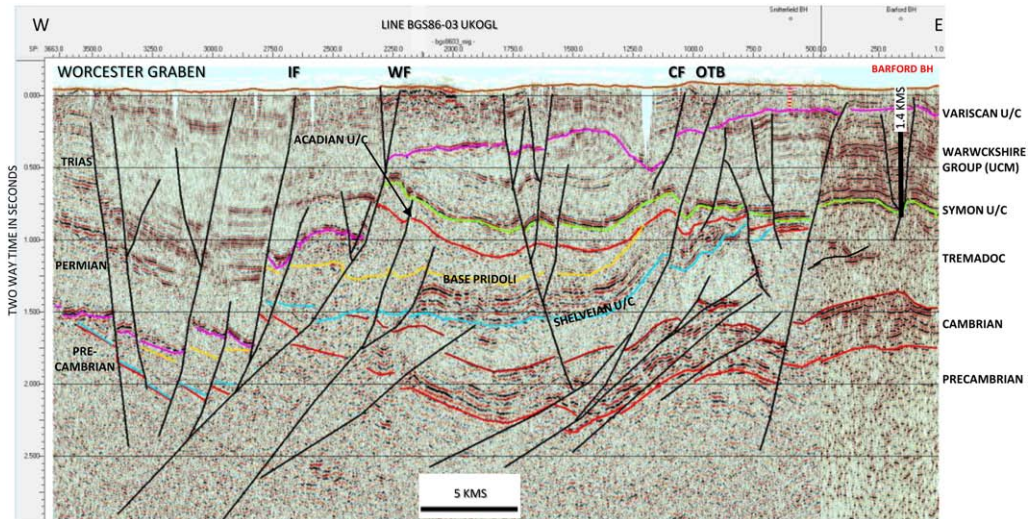


Fig. 8. Eastern half of Seismic Line B, showing the Shelveian, Acadian, Symon and Variscan unconformities. The line was reprocessed by UKOGL in 2012 and used with the permission of the British Geological Survey. ©NERC 2012. IF, Inkberrow Fault; WF, Weethley Fault; CF, Clopton Fault; OTB, Oxfordshire Thrust Belt.

Cambrian rocks towards the east, and also shows the characteristic seismic response of the events at these levels (cf. the northern part of Fig. 5). The Cambrian events appear to show tight folding and reverse faulting similar to that seen in Figure 5, on the other side of the Malvern Line, and there is some evidence of similar deformation within the Tremadoc in the eastern part of the line. This predates the Shelveian Unconformity and presumably took place during the Late Ordovician.

The concealed Llandovery–Lower Devonian megasequence

As noted earlier, the Silurian beds seen to the west of the Malverns on Figures 6 and 7 show no evidence of thinning towards the present-day Worcester Graben, and it seems reasonable to suppose that they continued across to link up with the thinner sequence of the same age interpreted in Figure 8. It is also likely that rocks of Přídolí and Early Devonian age were deposited across this area. On the eastern side of the Worcester Graben, it is postulated that the Shelveian erosion becomes less extreme away from the centre of the graben, and that progressively younger rocks are preserved beneath a thin Llandovery, Wenlock and Ludlow sequence, defined by characteristic banded amplitudes on the seismic data.

To the east of the Worcester Graben, beneath the Oxfordshire Coalfield, lies a syncline in which is preserved a thick sequence of Lower Devonian and

Přídolí Old Red Sandstone (ORS) facies. Figure 9 shows the approximate outline of the thick ORS, although the western boundary is difficult to interpret because it is caught up in the tight folding and faulting associated with Variscan movements along the eastern margin of the present-day Worcester Graben. Although the ORS has a generally opaque seismic character, with few continuous seismic markers, there is little evidence from Figure 10 and other lines in the area that it thins towards its truncated margin below the Acadian Unconformity. There are few thick penetrations of this sequence in the region, and the two wells with velocity surveys available, Faringdon-1 and the Steeple Aston BH (Poole 1977), indicate interval velocities of approximately 3900 m s^{-1} for their short penetrations of both Upper and Lower Devonian. This is slower than the 4343 m s^{-1} interval velocity for the 695 m thickness of the ORS in Usk-1 and may indicate less burial. In estimating the maximum thickness beneath the Oxfordshire Basin, an interval velocity of 3900 m s^{-1} has been used, which equates to around 3000 m of ORS.

The Acadian Unconformity

There is good evidence from wells across the eastern and central parts of the MMC that the Acadian Unconformity cuts down deeply into the Lower Paleozoic rocks. The Frasnian marine transgression and Famennian regression can be recognized in wells and outcrop from Brightling-1 to Willesden-1, across to Steeple

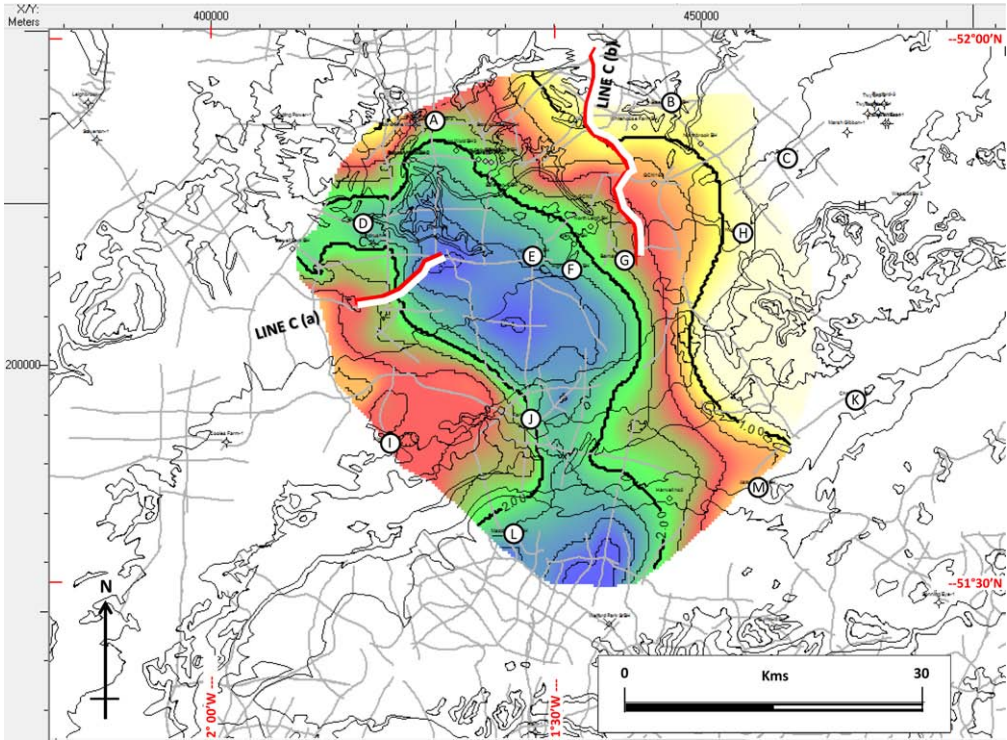


Fig. 9. Form-line time-structure map on the Shelveian Unconformity, indicating the shape of the overlying thick Lower Devonian-Přídolí ORS basin (C.I. 250 ms). Key wells are indicated by the following letters: A, Ash Farm-1; B, Steeple Aston BH; C, Bicester-1; D, Sherbourne-1; E, Apley Barn-1; F, High Cogges BH; G, Barnard Gate BH; H, Noke Hill G-1; I, Highworth-1; J, Faringdon-1; K, Chalgrove BH; L, Maddle Farm BH; M, Aston Tirrold BH. Grey lines show seismic coverage.

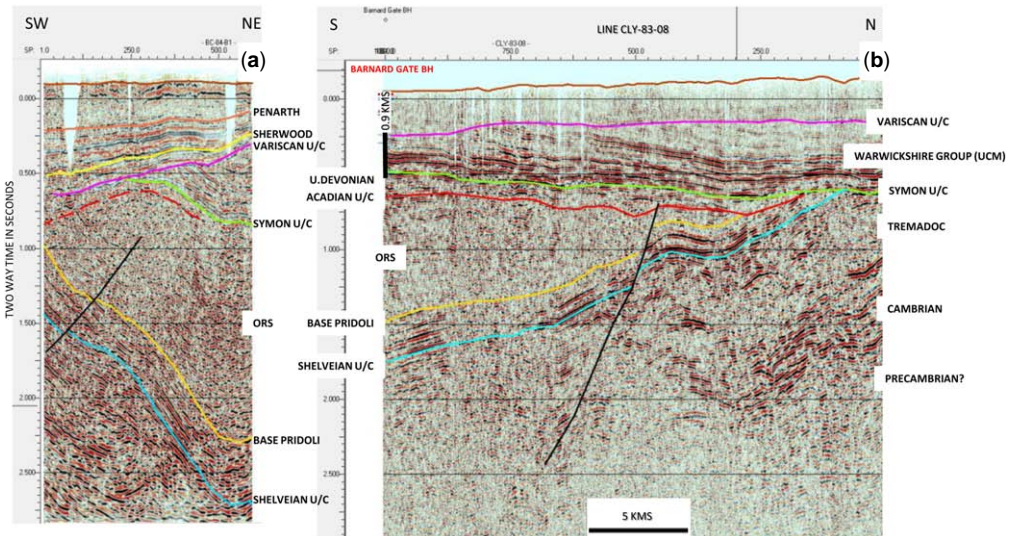


Fig. 10. Seismic Line C: (a) & (b) illustrating the thick ORS preserved in a syncline beneath the Oxfordshire Coal Basin. The truncation beneath the Acadian Unconformity can be seen in (b), where the presence of Upper Devonian is tied to the Barnard Gate BH, but is more speculative in (a).

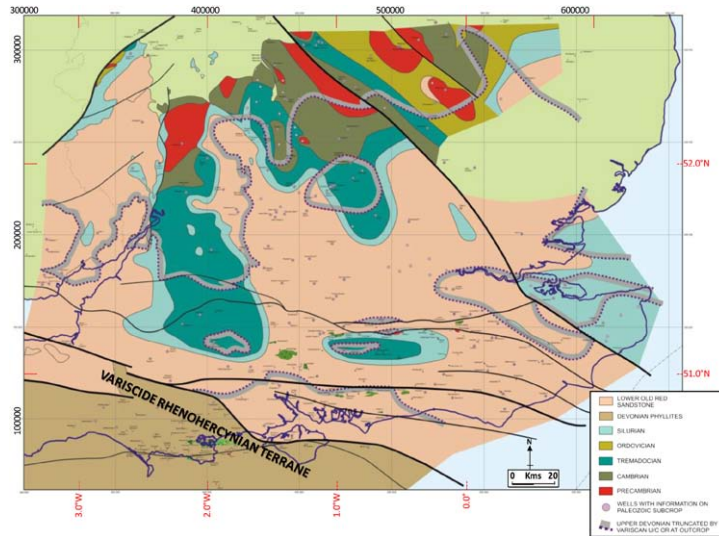


Fig. 11. Map showing the interpreted subcrop to the Acadian Unconformity, based on well, seismic and outcrop information and relying heavily on previous work by Smith (1987), Smith *et al.* (2005) and Pharaoh *et al.* (2011) for the NE part.

Aston BH and over the Malvern Line as far as Powys (Wills 1952; Butler 1981). Similarly, the late Famennian transgression and transition to the Carboniferous Lower Limestone Shale can be seen in wells and outcrop from SE England to South Wales. However, this unconformity is not often resolved on seismic data. Interpretation of the position of the Acadian Unconformity in Figure 8 is based on evidence of truncation on this and other seismic lines to the south (Fig. 10b), combined with nearby well evidence. The Acadian Unconformity is interpreted to truncate the Lower Devonian and Přídolí ORS facies, with its characteristic opaque seismic character, and to cut down as far as the Tremadoc in Figure 8.

It is difficult to determine when the Silurian–Upper Devonian beds were removed from the floor of the present-day Worcester Graben. Work by Barclay *et al.* (2013) has demonstrated that the Halesowen Beds (Warwickshire Group) unconformably overlie both the Precambrian and the Přídolí in trenches excavated across the Malvern Line fault complex close to line BGS84-01, which would place the uplift and erosion on this margin of the Worcester Graben no later than the Symon Unconformity. Outcrop control in the Tortworth Inlier (Cave *et al.* 1977) and eastern Mendips (Green *et al.* 1965), although the mapped unconformity here may be a thrust boundary (Hancock 1982), indicates that the Acadian cuts down to Wenlock or Llandovery to the south of the Malverns, and outcrops and boreholes west of Nuneaton indicate that the Acadian cuts down to the Tremadoc and Cambrian to the NE

of the Malverns. Interpretation of seismic data in the Devizes area of Wiltshire suggests that the Acadian Unconformity eroded down to the Tremadoc south of the Worcester Graben. On balance, it seems likely that much of the Silurian and Lower Devonian sequence was removed from the Worcester Graben area during Acadian uplift. The map of interpreted Acadian subcrop (Fig. 11) has borrowed heavily from the previous work of Pharaoh *et al.* (1991, 2011), Smith (1987) and Smith *et al.* (2005) for the northern and eastern parts of the MMC, and is subject to the limitations of sparse borehole data points over much of the area. An attempt has been made to define the present-day limits of the Acadian Unconformity (it is present on the dotted side of the grey shaded line in Fig. 11), beyond which the Upper Devonian has been removed by a combination of the Symon and Variscan unconformities, and the map is even more speculative.

The Symon Unconformity

The Symon Unconformity, at the base of the Warwickshire Group (UCM), is very clearly seen in Figures 8 and 10. There is considerable angular truncation at this unconformity on seismic lines across the area but, where the Acadian Unconformity can be seen, it appears that much of the erosion may have taken place at this older level. Figure 10b demonstrates this on one of the few seismic lines that shows both unconformities.

The Warwickshire Group

The sequence making up the Oxfordshire Coalfield has been described in detail by Dunham & Poole (1974). The beds are age-equivalent to the Halesowen, Keele and Enville groups of the Warwickshire and South Staffordshire Coalfields, the Coal Measures of the Forest of Dean, and the upper part of the Coal Measures of the Kent Coalfield; the uppermost parts being of Stephanian age (Waters *et al.* 2011). Across the MMC, they overlie a surface already greatly eroded by the Acadian Unconformity but also overstep the Lower Coal Measures and the feather edge of the Carboniferous Limestone in the Reading Coal Basin. The preserved area of the Warwickshire Group subcrop beneath the Variscan Unconformity has been mapped from boreholes by Dunham & Poole (1974) and Foster *et al.* (1989), but examination of seismic data indicates that it once covered a much larger area and, although there appears to be regional thinning towards the NE (Poole 1977) (Fig. 10b) there is little evidence of a depositional margin to the north or east. Away from the complexities of the Oxfordshire Thrust Zone, the Warwickshire Group shows regional tilting prior to Variscan erosion. Olivine-bearing basalts and dolerite, with dolerite sills, have been described from the Lower and Middle Coal Measures of the Reading Coal Basin (Foster *et al.* 1989) but there is seismic evidence of an apparent igneous intrusion uplifting and breaking through the Warwickshire Group on the NE margin of the Oxfordshire Coalfield at about National Grid Reference [45200 24600]. This shows as a pronounced negative on both the published reduced-to-pole magnetic field -2 and 10 km continuation residual maps (Busby *et al.* 2006) but does not appear to have any significant effect on the residual gravity maps. It is truncated by the Variscan Unconformity, which is here overlain by Triassic Sherwood Sandstone.

Late Variscan tectonics and the Variscan Unconformity

The Oxfordshire Thrust Belt (OTB) was named by Peace & Besly (1997) to encompass the intense late Variscan deformation seen in parts of the eastern boundary of the Worcester Graben. These authors had access to good-quality seismic lines acquired by Clyde Petroleum in the 1980s over the area between Stow-on-the-Wold and just north of Chipping Camden, where the late Variscan faulting and folding is most intense. Further seismic data now available demonstrate that the intense structuration dies out very rapidly south of this area (see line RG-004 in Butler & Jamieson 2013), although Peace & Besly (1997) demonstrated reverse faulting

in the Upton borehole, some 12 km south of Stow-on-the-Wold. Comparison between Figures 8 and 11, which are about 10 km apart at the OTB location, shows that it also dies out northwards. It is possible that this intense deformation zone is bounded by strike-slip faults: a lineation orientated NE–SW was identified from gravity information in the BGS Worcester Sheet Memoir (Barclay *et al.* 1997) and may define the northern boundary of this zone, although the actual track of this lineation intersects Figure 8 at about the location of the Inkberrow Fault and no seismic data are available for some 50 km to the north. Barclay *et al.* (1997) noted that the projection of this lineation coincides with the southern limit of exposed Malvern Complex rocks, although it appears to have little effect on the Permian–Triassic strata. It also has the same orientation as the Severn Estuary Fault Zone of Wilson *et al.* (1988). Note the differences in data quality and consequent interpretation of line BGS86-03 (Fig. 8) between the reprocessed version published here and the original version published by Chadwick & Smith (1988). Note also that the Clopton Fault now appears to sole out into the Warwickshire Group.

Figure 12 demonstrates the nature of the tight folding and thrusting seen in the Oxfordshire Thrust Zone and also the reversal of the overall sense of fault movement caused by extension at the beginning of Permian times to create the Worcester Graben. Figure 13 shows a reconstruction of the horizons interpreted in Figure 8, by flattening on the Variscan Unconformity, demonstrating the persistent nature of the Precambrian cored high beneath the Worcester Graben. Although the central part of the Worcester Graben includes a thick Permian section, in its southern extension and on the margins of the basin the Variscan Unconformity is overlain by Triassic Sherwood Sandstone or Mercia Mudstone. Erosion of these areas continued for some considerable time and was presumably responsible for recycling the Warwickshire Group sediments into the Permian and lower Triassic sequence.

The Gloucestershire and Wiltshire Tremadoc Basin, and the Variscan Front

South of the Permian depocentre of the Worcester Graben, there is a large area in which rocks of Tremadoc seismic character subcrop beneath the base Permian–Triassic. The main age control for this part of the MMC was provided by the drilling of Cooles Farm-1 in 1976. This well penetrated a 2281 m-thick section of Tremadoc and Upper Cambrian White Leaved Oak shales below the Triassic Bunter Pebble Beds, before reaching a total depth of 3513 m in what was assumed to be Hollybush Sandstone (Shell 1976). Smith (1993) published an interpretation of

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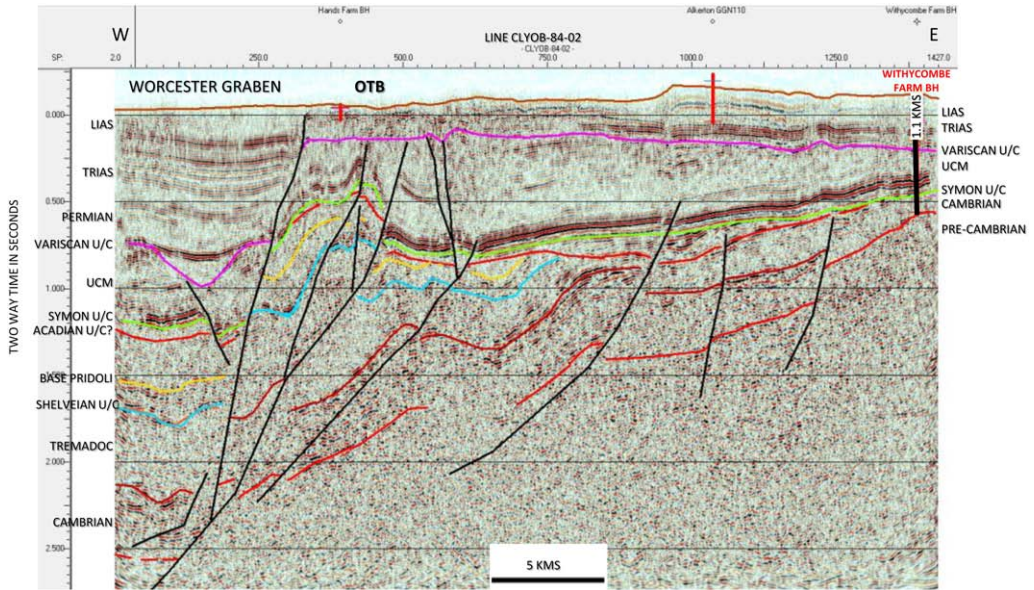


Fig. 12. Line D through the zone of Variscan deformation along the eastern side of the Worcester Graben. Note that the main Variscan deformation post-dates the deposition of the Warwickshire Group (UCM).

seismic line CLY-83-10, running eastwards from Cooles farm-1 to Faringdon-1. Line E (Fig. 14) runs through Cooles Farm-1 and then turns south along IGS79-01, reprocessed by UKOGL, to Devizes-1, which lies close to the line of the Variscan Front, and encountered the transition from post-Acadian Upper Devonian sandstones and shales to basal Carboniferous Limestone. The northern part of the line shows the top Hollybush Sand ('Cambrian') reflector and the package beneath it to be affected by the tight folding and thrusting characteristic of the Cambrian elsewhere in the MMC. The opaque nature of the

Tremadoc rarely allows recognition of deformation on the seismic data, although well data provide evidence of this. A reverse fault was interpreted in Cooles Farm-1 by Shell (1976, based on the dip-meter) and is shown in Figure 14. The beds above it dip at between 8° and 23° to the SE, those below dip at between 13° and 24° to the SW, although the lower part of the Tremadoc and the Upper Cambrian change back to variable dips to the south and SE. Dips within the 1251 m-thick Tremadoc section of Shrewton-1, south of Devizes, range from 20° to 43° to the SW, although dips of 35°–50° to the

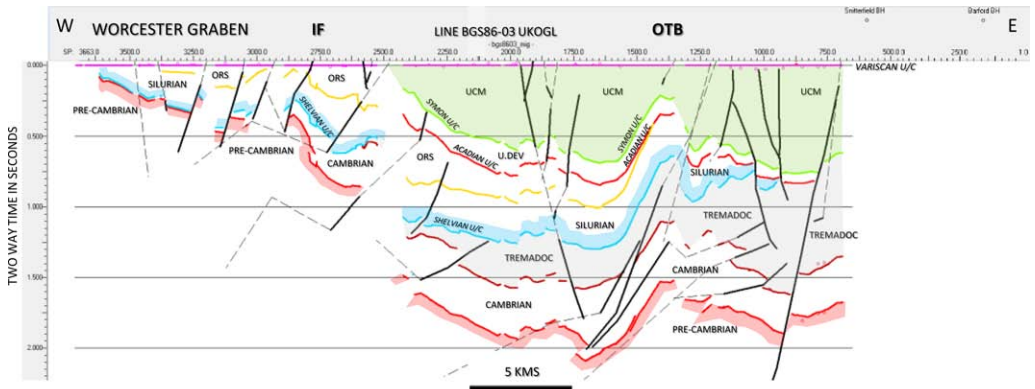


Fig. 13. Interpretation of the eastern half of Line B, flattened on the Variscan Unconformity. No attempt has been made to redraft the fault planes. The TWT scale is in seconds.

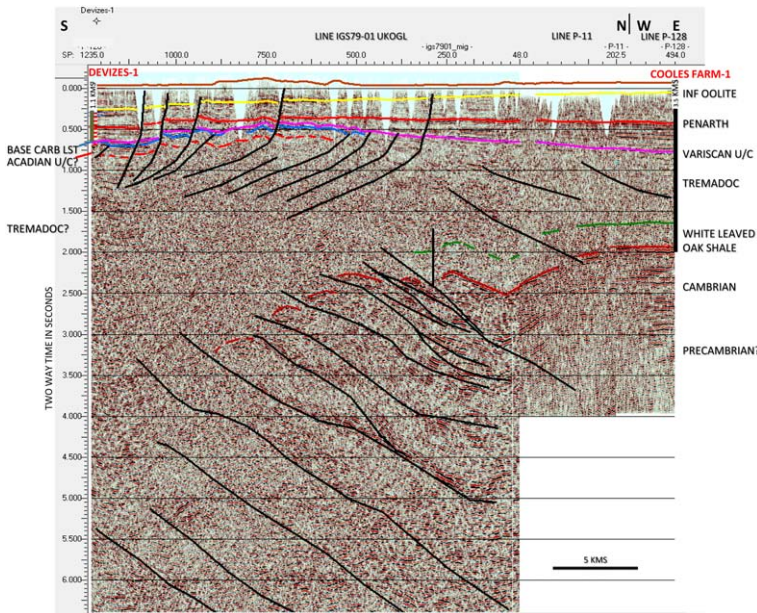


Fig. 14. Line E: a composite line linking Devizes-1 to Cooles Farm-1, providing ties to the Tremadoc and Cambrian in the north, and the Lower Carboniferous and Upper Devonian in the south. Line IGS79-01 was reprocessed by UKOGL in 2012 and is included by permission of the British Geological Survey. ©NERC 2012.

NNW were recorded from the uppermost 40 m of the Tremadoc section penetrated by the well, which did not reach the bottom of this stage (Whittaker 1980b).

Figure 14 (Line E) seems to show a change in structural style from a thick package of Cambrian and Ordovician (and probably Precambrian) in the north, with reverse faulting generally southerly directed (although there is no good quality east–west data available to indicate the true direction) to thin-skinned thrust faulting directed to the north. The southern portion of the line appears to show several palaeotopographical highs at the base Triassic (Variscan) Unconformity, similar to those seen on seismic data south of the Mendip Hills where Variscan thrusts affect the Carboniferous Limestone (e.g. see Holloway 1982). The northern limit of these base Triassic perturbations occurs at about CDP 300 on line IGS79-01 and this is probably the local limit of Variscan deformation, although it is well to the north of the generally accepted Variscan Front (Fig. 2). Although Devizes-1 encountered the basal Carboniferous and Upper Devonian, evidence from seismic data linking Devizes-1 to Shrewton-1 suggests that the Tremadoc is not far below the Upper Devonian at this location due to Acadian erosion. The Tremadoc and Cambrian sequences are affected by a series of broad folds in this area but line IGS79-01 probably runs sub-parallel to the

fold axes. Although the deep data quality worsens on the southern end of the line, it is still possible to map events suggestive of the Cambrian at around 3–4 s two-way time (TWT). These suggest that thicker Tremadoc is preserved beneath a combination of the Acadian and Variscan unconformities to the south. Immediately to the west of the northern end of line IGS79-01 (Fig. 14), the Cambrian package at the base of the Tremadoc can be seen on several east–west lines to change rapidly from almost horizontal to steeply dipping, the fold limb rising westwards with a strike of about N10°E up to about 12 km west of line IGS79-01, when data quality becomes too poor. However, Cave *et al.* (1977) estimated the minimum thickness for the entire Tremadoc in the Tortworth Inlier, some 25 km west of the northern end of IGS79-01, to be 2286 m, without seeing either the top or base of the sequence, which might suggest the structure becomes synclinal again beyond the limit of the seismic data. The rocks in this inlier of poorly exposed outcrops show some tight folding and slickensides, with dips in various directions measured at between 4° and 70° to vertical, suggesting that measured thicknesses may be exaggerated by structural complications (Cave *et al.* 1977). The overall impression of the Cambrian and Tremadoc seismic package in this area of NW Wiltshire and SE Gloucestershire is that it has been compressed

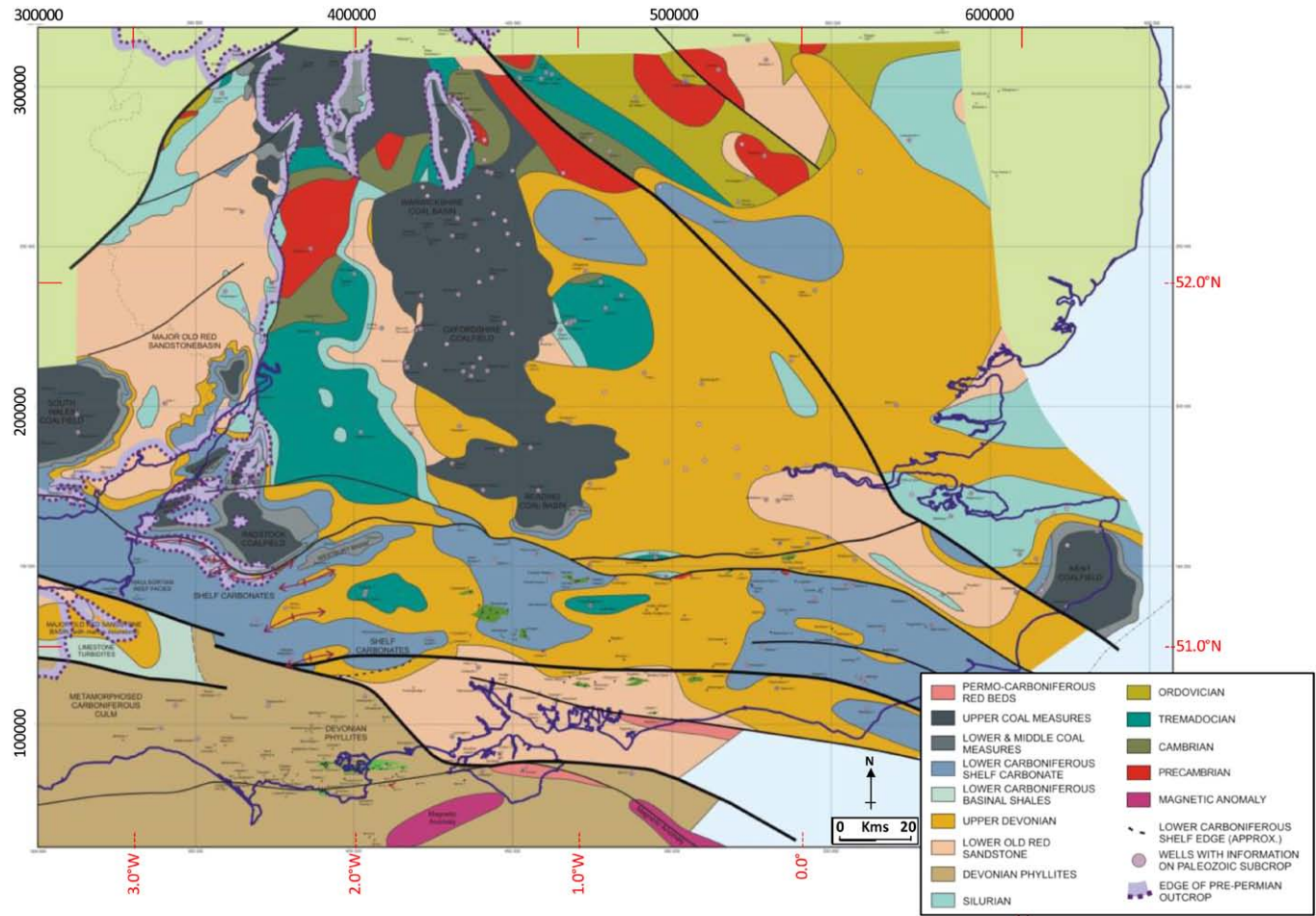


Fig. 15. Map showing the interpreted subcrop to the Variscan Unconformity, based on well, seismic and outcrop information and relying on previous work by Smith (1985), Pharaoh *et al.* (1991, 2011) and Smith *et al.* (2005) for the NE parts.

into a series of broad folds orientated almost north–south. Changes in thickness of the Tremadoc sequence identified on seismic lines in the area are likely to be due, in large part, to later erosion rather than original deposition, since the top of the unit is always an unconformity surface. The Silurian package characteristic of the post-Shelveian Unconformity sequence can be seen to be folded in the same way where it occurs in small outliers beneath the Variscan Unconformity just to the NW of Cooles Farm-1. The orientation of the syncline in the ORS of Figures 9 and 10 has a similar north–south trend, which would suggest this regional-scale folding to be of Acadian age.

Unfortunately, lines IGS79-01 and IGS79-02, at right angles to it and with poor data quality, provide the only deep data in the area, being recorded to 12 s TWT, but there are several long lines immediately east of it that were recorded to 4 s TWT in the mid-1980s and reprocessing of these might help in understanding the structural picture.

Variscan Unconformity subcrop map

Interpretation of the available seismic, well and outcrop data has enabled the construction of a map of the subcrop underlying the Variscan Unconformity (Fig. 15), which is a diachronous erosional surface overlain by rocks ranging in age from early Permian to late Trias, and, in the eastern Mendips, as young as Inferior Oolite (Woodward 1894), although older Mesozoic rocks may have been removed post-Trias. This mapping has, again, made use of the previous work undertaken by Smith (1985), Smith *et al.* (2005) and Pharaoh *et al.* (2011), and the data points of Molyneux (1991), on the areas to the NE of the seismic coverage. This is considered to be a more accurate representation than the Acadian subcrop map (Fig. 11) because of the availability of considerably more data. However, it is subject to change in the Oxfordshire Thrust Belt, because of the complexity of the structures, and in areas where there is little seismic coverage. Based on well penetrations and limited seismic evidence, the subcrop in the area south of the Variscan Front but north of the inferred boundary of the Variscide Rhenohercynian Terrane is interpreted as consisting of mainly Upper Devonian and Carboniferous Limestone, with a number of erosional windows through to the pre-Acadian Lower Paleozoic rocks. Indications are that these rocks were subjected to open folding and thin-skinned thrusting similar to that seen in outcrop in the Mendip Hills. The present-day limits of the Variscan Unconformity are shown on the map (it is present on the dotted side of the grey shaded line in Fig. 15), beyond which the basal Permo-Trias has been eroded and pre-Permian rocks outcrop.

Conclusions

Study of the released seismic and well data over the MMC shows that it is possible to correlate seismostratigraphic sequences over large parts of the area. These sequences appear to continue southwards across much of southern England and suggest that the southern margin of the MMC should be taken at a line running from north Dorset to the Isle of Wight, rather than at the northern margins of the Wessex and Weald basins (the Variscan Front). Where available, seismic data reveal considerable tectonic activity across the MMC prior to the Shelveian, Acadian, Symon and Variscan unconformities, and indicates that the MMC has not always been a stable block. This review gives a general indication of the history of the area during Paleozoic times but it is hoped that the availability of released seismic and well data through UKOGL will encourage more detailed studies.

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