The Eastern Extension of Southwest England under the Mesozoic Southern England Basin and its Variscan Dextral Translation

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January 2022

Abstract

A large positive residual Gravity Anomaly has been identified spanning the western parts of the Wessex Basin in Southern England and extending westwards to the Paleozoic outcrop. The northeastern margin of the Gravity Anomaly is well defined by a strong linear gravity gradient crossing the area from northwest to southeast. Available well data have shown that the area of the Gravity Anomaly has a number of associated geological features, making it distinct from the rest of the Basin. A change in metamorphic grade is seen, with higher grades over the Anomaly and marked changes in the lithologies, facies and stratigraphy of the Upper Paleozoic including a thick development of Permian basinal sequences. These Upper Paleozoic sequences appear to be similar to those seen at outcrop in Southwest England and are thought to represent their buried easterly extension. The northeastern linear margin of the Anomaly is thought to represent a deformation zone linking the fault zone of the Bristol Channel to the fault zones of the English Channel and France. The work described supports the suggestions of previous authors that such a boundary exists and is believed to be a Terrane boundary along which the Southwest England structural block was translated northwestwards during the Carboniferous, from its original position at the western end of the Rhenohercynian Zone of continental Europe, to its current position. The timing has not been precisely defined but is thought to have begun in the Namurian and continued into the Late Carboniferous.

Southwest Southern England

The area of study is located in the western part of the Southern England Basin and is shown in Figure 1. The oldest rocks outcropping are Devonian rocks in Southwest England and in the Quantock Hills

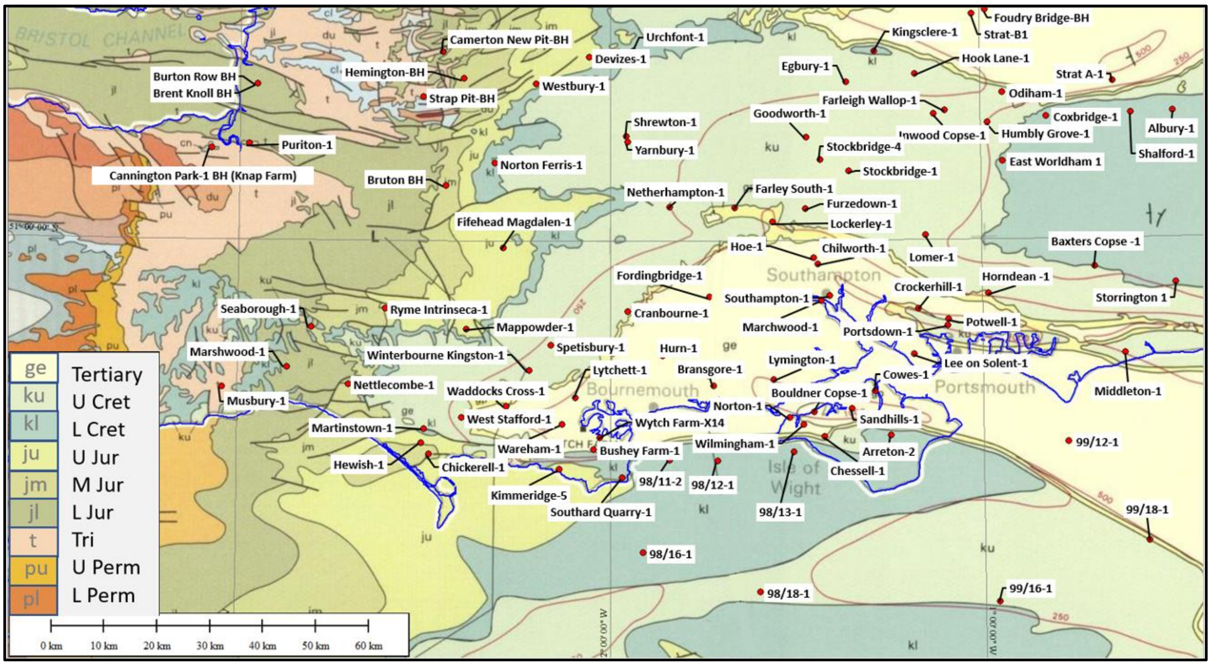

Figure 1 Bedrock 1:1 000 000 Geological Map reproduced with permission from the British Geological Survey. Well locations discussed in the text are also shown. Contains British Geological Survey materials © UKRI 1991.

to the north. A north-south trending belt of Permian rocks outcrop to the east of the older Paleozoics, with a progressively younger outcrop further east, eventually reaching the Tertiary beds of the Hampshire Basin.

Gravity Studies

Methodology and Database

A gravity modelling study has been carried out over Southern England, extending southwards into the English Channel. A publication providing a full description of this work is currently in preparation by the authors. Consequently, only a summary description will be given here. The purpose of the study has been to use gravity data in an attempt to assist an understanding of the deep geological structure. The approach has been to model the gravity effect of the post-Carboniferous sediments, then to strip away their gravity effect from the observed gravity values, revealing residual anomalies illustrating the gravity effect of deeper, less understood structures. This has involved the construction of fifteen profiles. The profiles are each 200km in length, with 25km spacing, and are located along north-south coordinate lines of the British National Grid, ranging from 275000m in the west to 625000m in the east. Of particular importance here are the profiles numbered 1 to 9 in Figure 2.

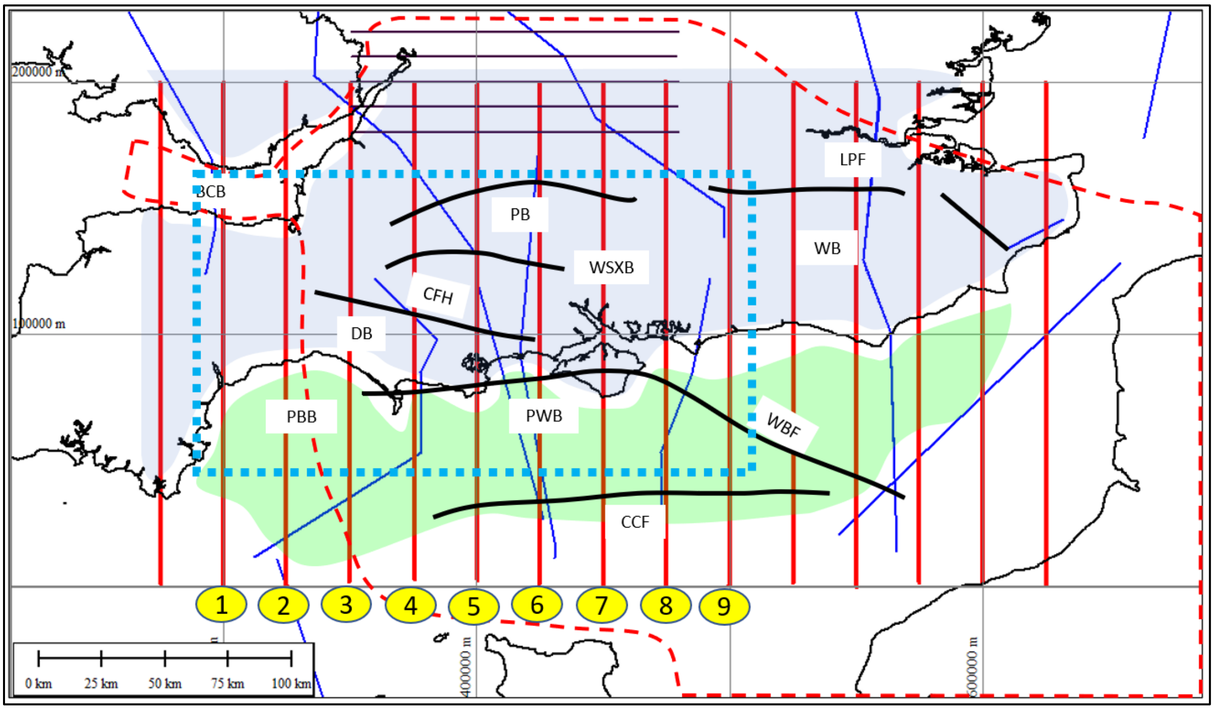

Figure 2 Map showing the distribution of source material used to construct the model profiles (fifteen N-S red lines). The blue dotted rectangle shows the area illustrated in Figures 5, 7 and 11. Profiles labelled 1 to 9 are shown in Figure 3. Main structural features are labelled as WSXB – Wessex Basin, BCB – Bristol Channel Basin, DB – Dorset Basin, CFH – Cranbourne-Fordingbridge High, PB – Pewsey Basin, PWB – Portland-Wight Basin, CCF – Central Channel Fault, WBF – Wight-Bray Fault, WB – Weald Basin and LPF - London Platform Faults. Blue shading onshore denotes areas where the BGS Atlas of Onshore Sedimentary Basins was used. For the green shaded area in the English Channel, structure maps downloaded from the OGA website were used. The area of the seismic interpretation of M Butler is shown by the red dashed outline. Guidance was also provided by the blue lines showing the locations of cross-sections published on various BGS 1:250,000 series sheets. The location of additional east-west profiles constructed across the Worcester Graben are also shown (black lines).

Published and unpublished structural information has been used to assist the construction of the profiles and the data sources are shown in Figure 2. Onshore in Southern Britain, various depth structure maps contained within the 'Atlas of Onshore Sedimentary Basins in England and Wales' (Whittaker, 1985) have been used. For the offshore area, the mapping of commercial marine seismic data, tied to wells drilled within the Channel, published by the Oil and Gas Authority (OGA) as well as the OGA and Lloyd's Register's English Channel Regional Geological Maps (OGA and Lloyd's Register, 2018) has been followed. The construction of the important Base Jurassic and Base Permo-Triassic horizons has blended two sources. Firstly, for a large part of Southern England, English Channel, Bristol Channel and Worcester Graben, an unpublished seismic interpretation by M Butler has been utilised. Secondly, depth maps published in the United Kingdom offshore regional report, 'The Geology of the English Channel' (Hamblin, et al., 1992) has been incorporated. Guidance for the profiles was also provided by a series of cross-sections published on various British Geological Survey (BGS) 1:250,000 series sheets (Bristol Channel, Chilterns, Thames Estuary, Portland, Wight & Dungeness-Boulogne). Their locations are also shown within Figure 2.

Profiles 1 to 9 are illustrated in Figure 3. The stratigraphic units used in the profiles are broad and general in nature; Cenozoic, Upper Cretaceous, Lower Cretaceous, Jurassic and Permo-Triassic. Such a general stratigraphic division is considered adequate for a regional gravity modelling study. This layering is paired with an estimation of layer densities. The density values were derived mainly from an evaluation of density logs run in 120 wells located across southern England and within the English Channel. In addition, published surface and subsurface density values were incorporated using, in particular, the comprehensive density review available in the BGS CD-ROM 'Regional Geophysics of Southeast England' (Busby, et al., 2006).

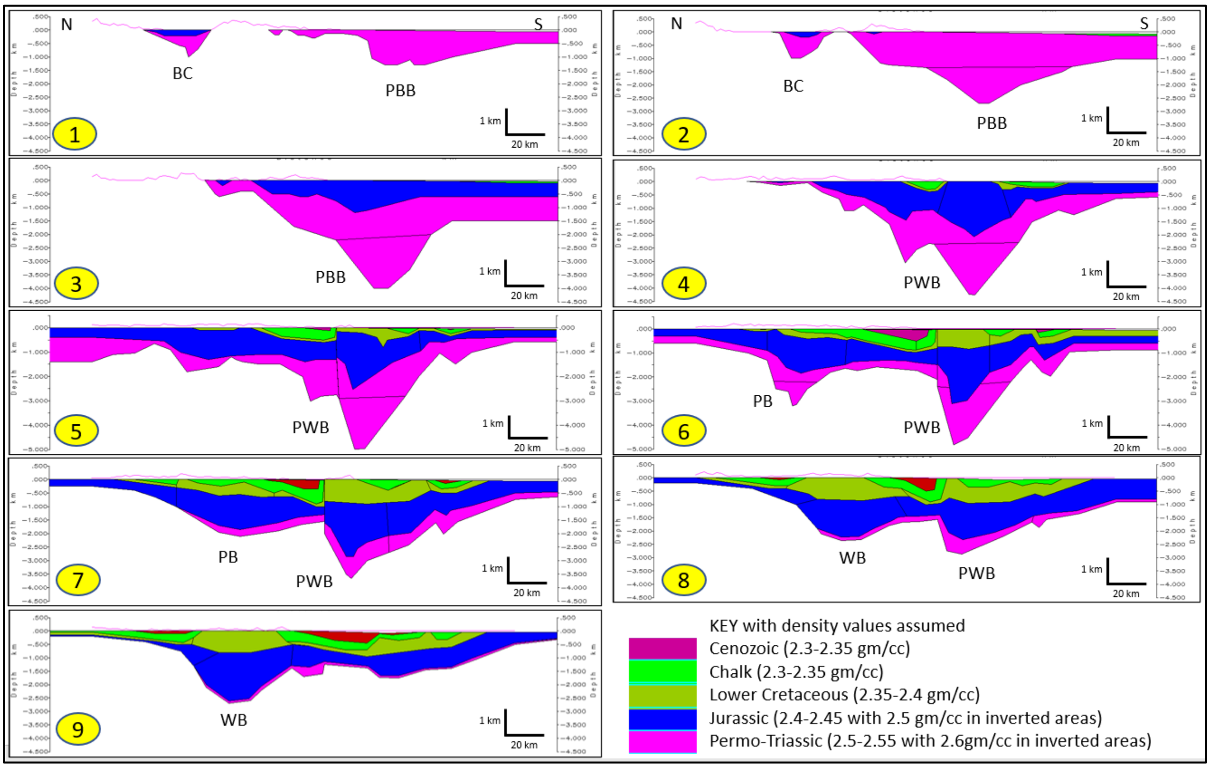

Figure 3 North-South modelled profiles numbers 1 to 9 crossing southern England and extending southwards into the English Channel. The profiles are 200km in length and the vertical scales extend from either 0 to 4.5km (numbers 1 -4 and 7 -9) or 0 to 5km (numbers 5 & 6). North is to the left and the sedimentary basins are labelled as for Figure 2

Results - Description of Gravity Anomalies

An example of one of the modelled profiles is shown within Figure 4. It illustrates the 2.5D polygonal model together with the observed and calculated gravity profiles. The observed data have been derived from the BGS 1:1 000 000 UTM Series of published gravity maps (Chacksfield & Edwards, 2006). The calculated profile has been derived using BGS 2.5D modelling software (Pedley, et al., 1993). The line starts just to the north of Bath on the Jurassic outcrop. It passes to the east of the

Mendips, crossing the chalk outcrop at the Dorset coast before continuing south into the offshore area and over the inverted Jurassic section of the Portland-Wight Basin. Further south, Cretaceous rocks outcrop, before Jurassic sediments are again found at the seabed at the southern end.

The estimated 3D gravity field of the model has been derived by gridding calculated values along all profiles. Subtraction of this estimated 3D field from the observed gravity values produces the residual gravity map of Figure 5. The residual map shows the predicted gravity effect of the pre-Permian sediments.

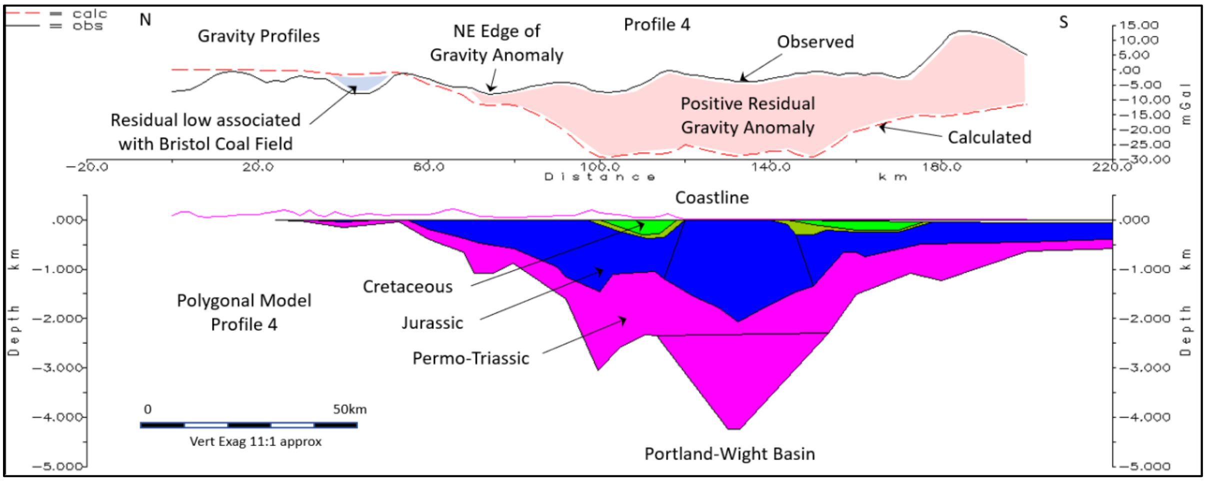

Figure 4 Example profile number 4 showing the observed and calculated gravity anomalies along the line. Assumed density values are Chalk and Lower Cretaceous 2.3 gm/cc, Jurassic 2.4 with 2.5 for the inverted section within the Portland-Wight Basin, and Permo-Triassic 2.5 with 2.6 for the deeper section below approximately 2km. The large calculated positive gravity residual anomaly (shaded red) extends over the southern half of the profiles with a maximum amplitude of approximately 30 mGal.

There are considered to be three main areas for potential errors within the gravity modelling procedure.

- The north-south 2.5D profiles offer only an approximation to the true 3D situation. However, good east-west structural continuity may be seen from profile to profile for the sedimentary basins. As such, the 'wavelength' of the basins is generally greater than the 25km profile spacing. Therefore, the merging of the 2.5D profiles into a 3D gravity field represents a reasonable approximation to the true gravity effect of the sediments. There is one exception, however, and this is for the area of the north-south trending Worcester Graben along the northern edge of the study area. Partly for this reason, a series of east-west gravity profiles have been constructed with locations as shown in Figure 2. Despite their different orientation, it was found that the results obtained from the east-west profiles could be merged satisfactorily with the results along the northern ends of the north-south profiles.
- Any inaccuracy in the depths and shape of the layers within each constructed profile will also contribute a potential error. It is hoped that the significant number of well ties used in conjunction with the large seismic dataset has minimised any errors within the structures modelled. However, the interpretation by M Butler differs from the OGA mapping for Base Jurassic and Base Permo-Triassic over local areas within the English Channel. The most significant difference occurs within the deep basin to the south of the Isle of Wight. Here, the differing interpretations result in a variation of the calculated gravity values by approximately 6 mGal. The deeper interpretation of M Butler has been followed here. In addition, the simplified polygonal structural form of the profiles will also contribute potential error, but this is considered insignificant for a regional study such as this.

- Density uncertainty probably affords a significant potential error. In order to try to quantify this uncertainty, a series of Monte Carlo gravity model simulations have been undertaken using Profile 5 as an example. The results show that the bulk of the calculated anomaly values lie within ±2mGal of the mean of the simulations. This does not rule out systematic errors within any of the density estimations, but it does suggest that anomalies of less than 2-3 mGal may be artifacts associated with possible density uncertainty.

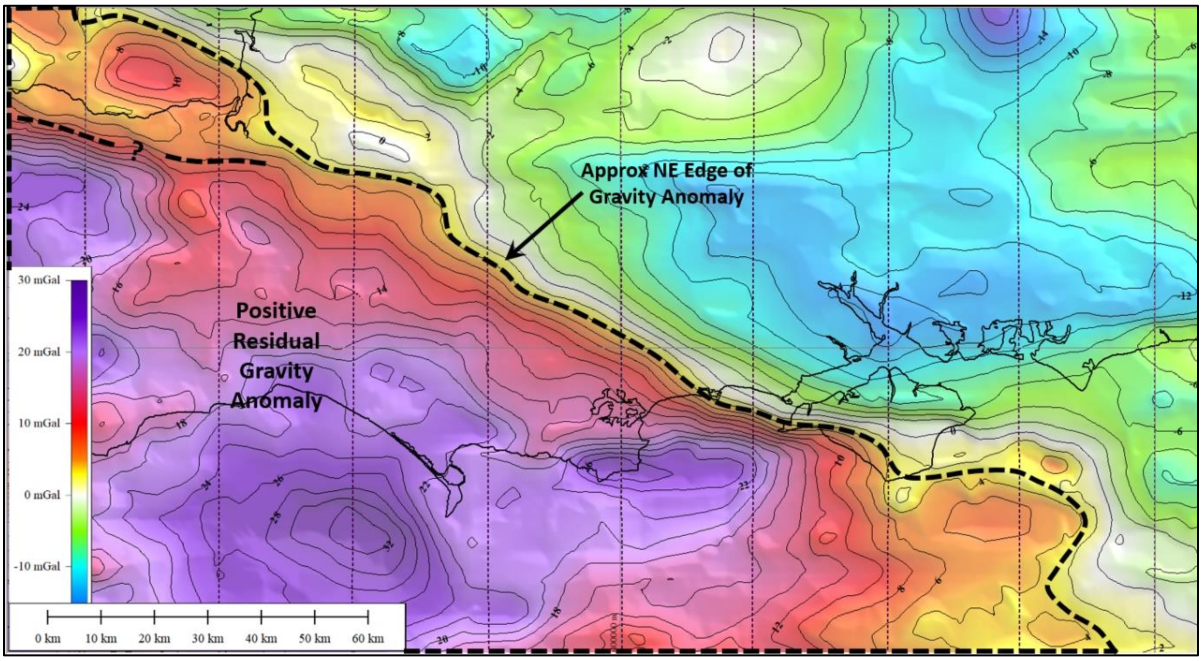

Figure 5 Residual Gravity Map. A large positive residual Gravity Anomaly lies within the southwestern part of the area with a strong northwest to southeast trending gravity gradient stretching from the Bristol Channel to beyond the Isle of Wight. The dotted north-south lines show the locations of the modelled gravity profiles (1-9).

The northeastern part of the residual gravity map of Figure 5 shows a series of low amplitude anomalies, typically of 5-10 mGal, within an area of generally low negative values between 0 and -12 mGal. Possible origins for these low amplitude anomalies will be discussed in a future publication. The most significant feature is the presence of a large positive anomaly extending across the southwestern half of the mapped area. This has high gravity values in excess of 10 mGal and reaching a maximum amplitude of approximately 30 mGal. The anomaly shows a marked northwest-southeast trending linear gravity gradient defining its northeastern edge and extending from the Bristol Channel to beyond the Isle of Wight. The presence of the residual gravity anomaly suggests the existence of denser rocks with the northwest-southeast gravity gradient defining the northeasterly boundary of the higher density section. The gradient approximately corresponds to the southern edge of the Midlands Microcraton (Butler, 2018).

Two other similar gravity stripping evaluations have been undertaken. Busby and Smith (Busby & Smith, 2001) undertook a 3D sediment stripping exercise. Their study covered south-eastern England and part of the English Channel but unfortunately did not extend as far west as the Isle of Portland. Nevertheless, they identified a positive residual anomaly, south and southwest of the Isle of Wight, with an associated northwest-southeast trending gravity gradient defining its northeasterly edge, very similar to that part of the Gravity Anomaly as shown in Figure 5.

Genc (Genc, 1988) undertook a 3D stripping exercise extending over the majority of England, Wales and the English Channel. The calculation of the gravity effect of the post-Carboniferous sediments was based upon one sediment layer above a pre-Permian basement and using a single depth-related density function. Despite the approximations inherent in this approach, the residual map produced by Genc shows a strong positive residual anomaly very similar in amplitude and location to the Gravity Anomaly of Figure 5. In particular, he identified the same strong gravity gradient along its northeasterly side. Spectral analysis suggested the source of the gradient to be deep, with a possible origin at two levels, 11 km and 30 km.

It is clear from the gravity work described here, and from the two earlier studies, that the large positive residual anomaly is a real and significant feature, probably deep-seated, and its associated northwest-southeast strong gradient represents an important crustal lineament requiring explanation. A possible origin is discussed within the geological sections below.

Geological Database

Sixteen wells have reached the Permian or older section in the area of the Gravity Anomaly. Unfortunately, there is very little information on these intervals besides the log suites and sample descriptions. Most wells do not have palaeontological or maturity studies over the Paleozoic intervals. A very limited geochemical study by GOAL (GOAL, 1986) was performed on wells with intervals of Culm facies. The only reported dating of the phyllites was carried out in the Wytch Farm X14 well where dates of 357my and 337my (Lower Carboniferous) were seen. In the Arreton 2 well on the Isle of Wight, radiometric dating of the metamorphosed sediments in the base of the well (Colter & Havard, 1980), suggests deposition in the Devonian, most probably in the Middle Devonian, with some evidence of inclusion of reworked older Lower Devonian sediments. The section also records several phases of later deformation in the Dinantian, Lower Namurian, Upper Westphalian and Stephanian (British Gas, 1974). The main deformation phase is thought to be in the Dinantian with the later three phases recording shearing, brecciation and mineral veining.

Well	Company	Date	Result	TD ft (md, tvdss)	TD Formation	Data Available			
						Logs	Dip	Dating	Maturity
Wells overlying Gravity Anomaly									
98/11-2	BG	1984	Gas Discovery	11391(-11319)	Devonian Phyllite	x	x		
98/12-1	Elf	1993	P&A, Oil shows	7661(-7542)	Permian	x	x		
98/13-1	Occidental	1991	P&A, Oil Shows	7830(-7711)	Permian	x	x		
98/18-1	Union	1983	P&A, Oil shows	8621(-7740)	Devonian Phyllite	x			
99/12-1	Exxon	1984	P&A, Dry	4000(-3881)	Devonian Metamorphics	x			
99/16-1	Texas Gas	1983	P&A, Dry	6692(-6573)	Devonian Phyllite	x			
99/18-1	Texas Gas	1984	P&A, Dry	4698(-4237)	Devonian Phyllite	x			
Arreton-2	BG	1974	P&A, Dry	9227(-9102)	Devonian Metamorphics	x		x	
Bransgore-1	BP	1986	P&A, Dry	5711(-5623)	Permian	x	x		
Bushey Farm-1	BGC	1981	P&A, Dry	6647(-6515)	Permian	x	x		
Chickerell-1	BP	1987	P&A, Oil Shows	7139(-7065)	Permian	x			
Hurn-1	BP	1986	P&A, Dry	6642(-5852)	Permian	x			
Lychett-1	BP	1991	P&A, Dry	6483(-5874)	Permian	x			
Mappowder-1	Carless	1982	P&A, Dry	8378(-7118)	Devonian Phyllite	x			
Marshwood-1	Cangeo	1974	P&A, Dry	6299(-5911)	Devonian	x			
Musbury-1	BGC	1986	P&A, Dry	4500(-4452)	L.Permian	x			
Nettlecombe-1	Berkley Pet	1972	P&A, Dry	7005(-6634)	Carboniferous-Culm	x			x
Ryme Intrinseca-1	Carless	1985	P&A, Dry	5991(-5327)	Devonian Phyllite	x			
Seaborough-1	Berkley Pet	1974	P&A, Dry	6294(-5953)	Carboniferous-Culm	x			x
Spetisbury-1	BGC	1984	P&A, Dry	8570(-6738)	Devonian Phyllite	x	x		
Waddocks Cross-1	BGC	1986	Oil Well	6035(-5878)	Permian	x	x		
West Stafford-1	Brabant	1994	P&A, Dry	6740(-5196)	Permian	x	x		
Wytch Farm-X14	BGC	1984	Oil Well	8861(-8832)	Devonian	x	x		

Figure 6 Wells Drilled on Gravity Anomaly reaching Permian or older

Many wells have reached the Paleozoic section away from the Gravity Anomaly and are listed in the Appendix. The wells generally have electric log suites, whereas the data from the boreholes (BH in the Table) are restricted to lithological descriptions.

The northeastern margin of the Gravity Anomaly is well defined geophysically. The available well data have shown that it has a number of associated geological features:

- Marked change in lithological characteristics, facies and stratigraphic sequences of the Upper Paleozoic over the Anomaly, as compared to the area to the east
- Change in metamorphic grade, with higher grades over the Anomaly
- Presence of Permian basinal sequences over the Anomaly

Marked Change in Facies and Stratigraphic Sequences

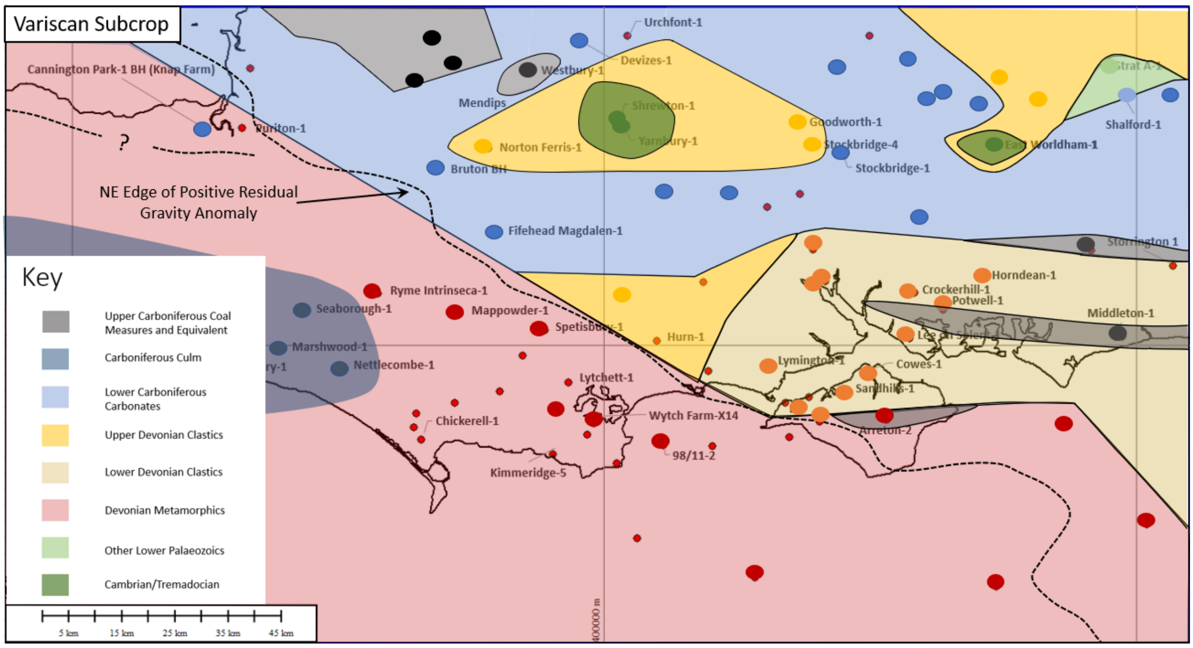

Figure 7 Variscan Unconformity Subcrop Map

In the Wessex Basin the Lower Paleozoic is represented by a thick section of Tremadocian rocks with a thin or absent post Tremadocian to Silurian sequence. A clastic sequence of indurated sands and shales, undated but thought to be of Lower Devonian age, are preserved in wells on, and adjacent to, the Isle of Wight. Elsewhere the Lower Paleozoic sequences appear to pass up unconformably into a Middle – Upper Devonian interval represented by a thick shale sequence, with coarser clastics seen to the north. No well has penetrated the transition from the Lower Devonian to the Middle – Upper Devonian and so the nature of the contact between the two intervals is unclear. The Upper Devonian clastics pass up conformably into the Lower Carboniferous carbonates, and this transition was seen in the Fifehead Magdalen 1 well (Carless Exploration, 1985) and Bruton borehole (Holloway, 1982). These carbonates are similar to those seen at outcrop in Wales and the Mendips to the north. In the Cannington Park borehole, further west, the Lower Carboniferous shelf limestones have Waulsortian reef facies associated (Whittaker & Scrivener, 1982). Where these reefal facies are seen, to the west in Ireland and to the east in Belgium, it is indicative that a shelf edge lies nearby.

No Namurian sediments are seen in any wells and this break in sedimentation is a regional phenomenon. Sedimentation recommenced in the Upper Carboniferous with Coal Measures sequences preserved in the Oxfordshire and Bristol Coalfields, to the north and northeast, and in the Westbury borehole. A non-marine red bed clastic sequence, poorly dated to the Westphalian, but possibly equivalent to the Upper Coal Measures interval, is locally preserved and has been encountered in Middleton 1, and possibly in the Baxters Copse 1 and Arreton 2 wells.

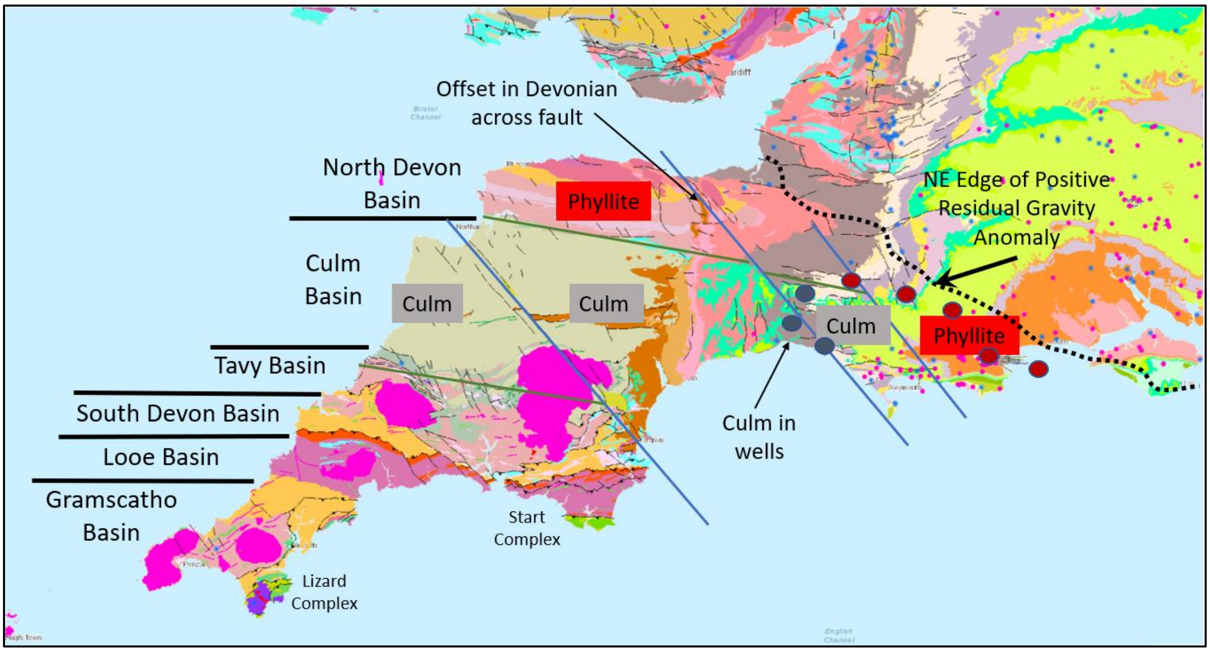

Figure 8 Structural Elements of Southwest England (Alexander & et al, 2019) The location of the northeasterly edge of the residual Gravity Anomaly is also shown. Contains British Geological Survey materials © UKRI.

In Southwest England the stratigraphic sequence is different. Sedimentation continued from the Lower Devonian to Upper Devonian and into the Carboniferous with no break. In North Devon, it was a dominantly marine sequence with the Lower Devonian represented by the Lynton Slates passing up into the Trentishoe Formation (Hangman Grits) of the Middle Devonian and the slates and sandstones of the Pickwell Down and Baggy Beds of the Upper Devonian (Brenchley & Rawson P, 2006). The Middle and Upper Devonian sandstones were derived from the north based on palaeocurrent and petrographic evidence (Tunbridge, 1986). In South Devon, basinal sequences dominate, with deepwater turbidites derived from the south. Further north, an intra-basinal high has been recognised over which shallow water carbonates were deposited (Hobson & Sanderson, 1983). The Devonian beds have been metamorphosed.

The Devonian section passes up conformably into the deepwater basinal sequences of the Lower Carboniferous in the Culm Basin. The Lower Carboniferous is represented by shales (Pilton Mudstones - Tournaisian) that pass up into cherts and shales (Codden Hill Cherts - Visean). Sandstones were first introduced into the basin in the Early Namurian, represented by the Arnsbergian aged Crackington Formation, but the sands are diachronous, and are younger to the north. Palaeocurrent data indicate axial transportation with currents flowing westwards. In the Late Namurian – Westphalian interval, clastic beds of the Bideford (Deltaic – Lower Coal Measures equivalent) and Bude Formations (Delta top – Middle Coal Measures equivalent) were deposited, reaching thicknesses of 3kms. Sediment transport directions in these beds show a switch of the sediment source to one in the north, accompanied by a decrease in the feldspar content of the sands. No sediments of Westphalian C to Stephanian age are seen.

The Upper Paleozoic sequences of Southwest England can be partitioned into a series of east-west trending tectonic zones with the North Devon Devonian phyllites and sandstones in the north, the Carboniferous Culm sequences in the centre and the South Devon Devonian phyllites in the south.

In the western part of the Southern England Basin, in the vicinity of the Gravity Anomaly, eight wells have reached the pre-Permian section. Five of the wells encountered phyllites; Ryme Intrinsica 1 (Carless Exploration, 1985), Mappowder 1 (Carless Exploration, 1985), Spetisbury 1 (British Gas, 1985), Wytch Farm X14 (British Gas, 1979) and 98/11-2 (British Gas, 1984). To the south and west, three wells encountered Culm sequences; Marshwood 1 (Canadian Geothermal Oil, 1974), Seaborough 1 (Berkeley Petroleum, 1974) and Nettlecombe 1 (Berkerley Petroleum, 1972). These sequences have been dated based on lithostratigraphic considerations. The Culm sequences seen are quite distinct from the contemporaneous Lower Carboniferous shallow water shelfal limestones seen to the north and east in the Mendips. No Upper Carboniferous section is preserved, and the intervals are overlain by Permian sequences. Further south, phyllites and higher grade metamorphics are seen in the offshore wells 98/18-1, 99/12-1, 99/16-1 and 99/18-1 and in the Arreton-2 well on the Isle of Wight.

Metamorphic Break

The wells over the Gravity Anomaly encountered phyllites and other metamorphosed rocks. The presence of the phyllites indicates the existence of sequences with a higher metamorphic grade as compared to the maturity of the sequences in wells drilled further to the northeast. This break and change in metamorphic grade seem to be coincident with the northeastern boundary of the Gravity Anomaly.

The phyllites seen in the wells are lithologically similar to those seen at outcrop in North Devon. Illite crystallinity studies on outcrops of the Devonian in Devon show that the phyllites are at the epizone metamorphic grade, although the Devonian of the Quantock Hills further east shows a slightly lower metamorphic grade (upper anchizone) (Kelm, 1986). The Illite data indicate low pressure metamorphism. Dating of the metamorphism of the phyllites in Devon gives ages of 337-357my (Late Visean to Early Namurian) (Shail & Leveridge, 2009). Radiometric dating of the phyllites in the Wytch Farm X14 and Arreton 2 wells record the same deformation phase, and these are thought to have formed contemporaneously with those of Devon during the Late Visean to Early Namurian.

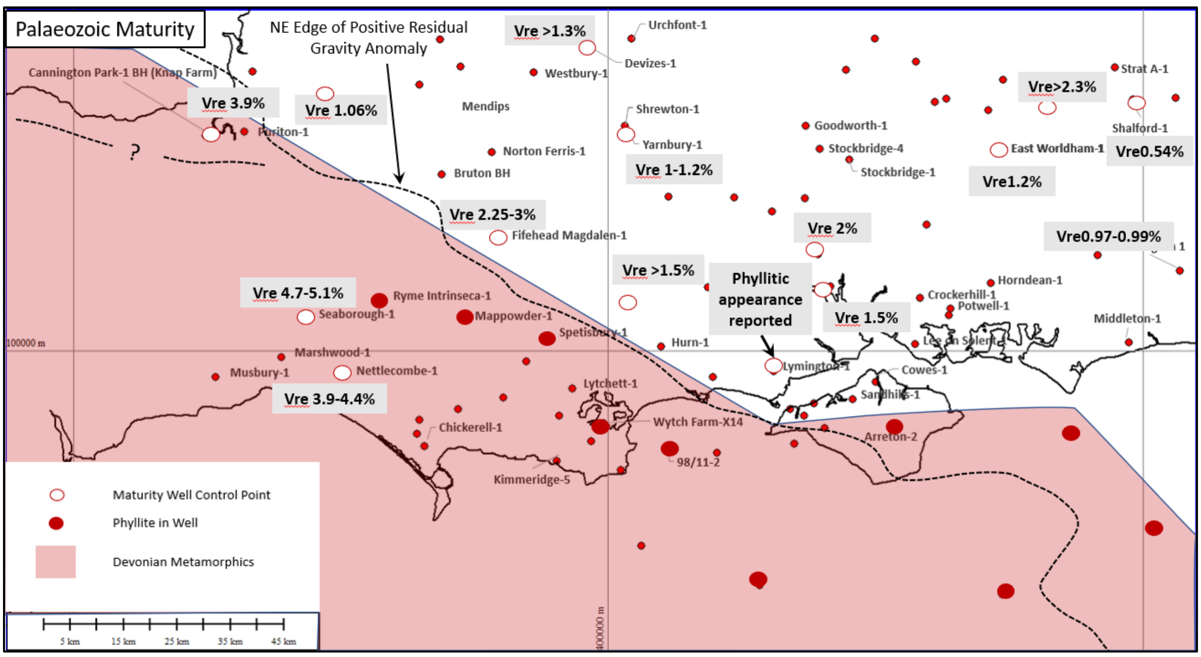

Figure 9 Paleozoic Maturity Map. The location of the northeasterly edge of the residual Gravity Anomaly is also shown.

Phyllite formation is thought to reflect regional metamorphism and to occur at temperatures in excess of 300°C (Columbia, 2019). Using the present geothermal gradient (27°C/km) of the UK, the 300°C isotherm would occur at depths of over 36,000ft (11,000m). To reach this level of metamorphism in North Devon, using only burial, 36,000ft (11,000m) of section would have had to be removed (based on the current geotherm). The same degree of burial and uplift is necessary to explain the metamorphic grade of the phyllites seen in the wells. It is extremely difficult to envisage a geological scenario that would accommodate this degree of burial and uplift, necessary to explain the metamorphic grade of the phyllites seen in the wells, without invoking higher temperature gradients.

Maturity studies on the Culm sequences in the Seaborough 1 and Nettlecombe 1 wells reveal vitrinite reflectance values of 3.9-5.1% (GOAL, 1986) and thus show a metamorphic break compared to the phyllites seen in wells to the north and east. Outcrop studies confirm that a similar maturity break is seen between the Carboniferous Culm sequences of the Culm Basin of Southwest England and the older Devonian phyllites of North Devon. Illite crystallinity studies show high diagenetic to anchizone grade in the Carboniferous as compared to epizone metamorphic grade in the Devonian (Kelm, 1986). The vitrinite reflectance values of 3.6-5.7% from the outcropping Culm sequences are in the same range as that seen in the wells (Cornford, et al., 1987). However, a relationship between the degree of deformation and the metamorphic grade is also seen, with some evidence of tectonic loading giving rise to maturity differences between Carboniferous units.

The lowest grade Upper Carboniferous rocks at outcrop have reached palaeotemperatures of at least 100°C. Work has demonstrated that to have reached this maturity, using the Carboniferous maturity gradients of the Southern North Sea and Northern Germany (with an implied temperature gradient of 40°C/km), the beds would need to have been buried to depths of 15-23,000ft (4,500-7,000m) (Cornford, et al., 1987). Using the estimated Culm thickness of around 10,000ft (3,000m) this implies that 13,000ft (4,000m) of uplift occurred during the Variscan events. The work by Cornford also showed that granite emplacement only had a local effect. There is some evidence of higher temperature gradients in the past, and work in the Carboniferous sections in Germany suggests gradients of 60-80°C/km (heatflow of 110-130 mW/m^2) during the Upper Carboniferous (Teichmüller & Teichmüller, 1986). Using these higher geothermal gradients for the Devonian phyllites at outcrop, would still imply significant burial with removal of up to 23,000ft (7,000m) of now missing Carboniferous section.

The current metamorphic grade of the rocks seen in the wells over the Gravity Anomaly infers significant burial and major uplift prior to the Permian burial. As in the situation in Southwest England, it is geologically difficult to reconcile these results using the current geothermal gradient. The similarity of the metamorphic grade to that seen to the west suggests a similar geological burial and temperature history.

Wells on and adjacent to the Isle of Wight, and in the immediately offshore areas have either direct evidence of phyllites (as in 98/11-2) or metamorphics (as in Arreton 2). Indirect evidence of high maturities is also present, with cleavage being seen in the Devonian of Sandhills 1 and the shales having a metamorphic appearance in the Crockerhill 1, Sandhills 1 and Cowes 1 wells. These wells show severe cementation and induration, with widespread veining and recrystallisation. This suggests that although the metamorphism and deformation is centred on the area of the Gravity Anomaly, its influence extends to adjacent areas. Results from wells adjacent to the Gravity Anomaly, to the east and north, show maturities that are higher than expected over a large area. The results at Fifehead Magdalen 1 show vitrinite reflectance values of 2.25-3%, with values of 1.1—1.6% in other wells in the neighbourhood (Figure 9). The results at Fifehead Magdalen 1 would suggest that the Lower Carboniferous has been uplifted 18,000ft (5,500m), but elsewhere the uplift could have been 13,000ft

(4,000m). These results point to the area of the Gravity Anomaly being buried under a thick sequence of Upper Carboniferous sediments prior to the Variscan phase of uplift and erosion.

Correlation of the Pre-Permian Section in Wells in the Wessex Basin

The beds encountered in wells over the Gravity Anomaly are very similar to equivalent intervals seen in outcrop in Southwest England and differ markedly from those intervals seen in the rest of the Wessex Basin. The change in the Upper Paleozoic facies and stratigraphy is quite distinctive and occurs across the boundary defined by the edge of the Gravity Anomaly. The phyllites seen in the wells are thought to be laterally equivalent to the Devonian phyllites seen at outcrop in North Devon. The Carboniferous sequences seen in the wells over the Gravity Anomaly, are thought to be a lateral equivalent of the sediments seen at outcrop in the Culm Basin of Devon. The similar metamorphic grade of the rocks in the wells to their equivalents in North Devon and the Culm Basin suggest a similar metamorphic history. This suggests a correlation between the two areas based on lithostratigraphic and metamorphic grade considerations.

The east-west tectonic partitioning of the Upper Paleozoic sequences seen at outcrop in Devon can be extended into the Wessex Basin (see Figure 8). The east-west boundary between the Devonian phyllites and Culm Measures, seen at outcrop in Southwest England, can be extrapolated to lie without significant offset between the phyllites seen in the Ryme Intrinsica 1, Mappowder 1, Spetisbury 1 wells and the Culm sequences seen in the Marshwood 1, Seaborough 1 and Nettlecombe 1 wells. Further east, the phyllites of the Wytch Farm X14 and the 98/11-2 wells seem to be offset southwards, but this can easily be accommodated when the wrench movement along the northwest-southeast trending strike-slip faults is considered (Dearman, 1963). Further south, the northern boundary of the metamorphosed Devonian follows the east-west trending structural lineament that crosses the Isle of Wight, running immediately to the north of the Arreton 2 well.

Variscan Deformation

The pre-Permian section of western southern England shows the effects of the Variscan Orogeny. Regional analysis reveals that three unconformities are associated with the Variscan deformation events: Namurian, base of the Upper Coal Measures, Late Carboniferous-Early Permian.

Deformation in Southwest England

The first phase of compressional deformation recognised in Southwest England, termed the D1 phase, has been dated to the Upper Tournaisian – Lower Namurian (Shail & Leveridge, 2009). Associated with this deformation was a regional metamorphic event dated to 325-345my (Visean-Early Namurian). The earlier formed Devonian-L. Carboniferous aged Trevone/Tavy Basin was inverted in the Lower-Middle Namurian (see Figure 8). Thick-skinned rather than thin-skinned tectonism is envisaged with earlier formed faults being reactivated as thrusts. In south Devon, movement was to the north and north-northwest, whereas in North Devon, movement was to the south (Hobson & Sanderson, 1983). There was widespread development of a slaty cleavage during this event.

Following these movements, sandstones were first introduced into the Culm Basin as shown by the Early Namurian (Arnsbergian) aged Crackington Formation. Palaeocurrent data indicate axial transportation with currents flowing westwards, but these data indicate that the sediment source changed with time, from the west in the Lower Namurian and from the north in the late Namurian.

Namurian Deformation Elsewhere in Southern England

The early Namurian phase of Variscan movements is marked in Southern England by late Dinantian (Visean) section being unconformably overlain by onlapping early Namurian (Pendleian) sediments. One of the reasons the unconformity may not be widely recognised in Southern England is that later Variscan erosion may have reworked these intervals and the Late Visean-Namurian section has been removed.

Namurian beds seem to be absent in wells throughout Southern England east of the Bristol Coalfield. The apparent Namurian absence below the Weald and Wessex Basins is based only on well data, and therefore may represent a sampling problem. However, all of the 59 wells that penetrated and reached the Lower Carboniferous show the Namurian to be missing. The absence below the coalfield in Kent has been demonstrated by extensive coal borehole records. This east-west zone of Namurian absence extends a distance of over 300kms and is clearly a regional event which is thought to be driven mainly by tectonic factors rather than by eustatic sea level changes. East of Kent, Namurian sediments are not seen in wells in Northern France and are only seen again in the vicinity of Namur in Belgium. There, early Namurian (Pendleian) age sediments onlap an unconformity that lies at the top of the Lower Carboniferous (Ramsbottom, 1978).

To the west, in the Mendips, no Namurian section is seen, but in the Bristol area, Namurian sediments are present again on the western side of the Bristol coalfield. Here, 1000ft of Namurian (Yeadonian-Arnsbergian) section onlaps and rests unconformably on Lower Carboniferous carbonates over the 'Bath Axis' (Kellaway & Hancock, 1983). The Namurian section in the Yate borehole contains reworked Tremadocian acritarchs, probably indicative of erosion of the Tremadocian rocks in the area of the later Worcester Graben. A similar situation is seen over the Severn Axis to the west, with Namurian (Yeadonian-Pendleian) beds resting unconformably on Lower Carboniferous Visean (Holkerian) carbonates. Further north, no Namurian aged sediments have been encountered in the Forest of Dean or Newent Coalfields. In South Wales, the age of the Lower Carboniferous subcrop beneath the Namurian is older to the east towards the Severn Axis and this is coincident with a younger onlap of the Namurian. Overall, the Namurian thins to the east, west and north away from the Swansea area, but the available data show that the long-lived northeast-southwest trending structural lineaments in South Wales were active at the time (Owen & Weaver, 1983).

Later Variscan Movements

A second phase of Variscan movements is seen in Southwest England and is dated to the Westphalian. It represents the first deformation of post-Namurian sediments and is termed the D2 event (Shail & Leveridge, 2009). It involved the inversion of the Culm and North Devon Basins, widespread thrusting and the creation of east-west trending folds and a crenulation cleavage. The folds are often coaxial with D1 folds but there can be anticlockwise rotation of up to 30°. The youngest rocks deformed are of Westphalian C age. The K-Ar deformation dates group around 305±5my (Late Westphalian – Early Stephanian) in North Devon, but this is suggested to represent the timing of uplift rather than the date of peak metamorphism (Warr, 1991).

These compressional convergent movements of the Late Carboniferous were replaced by a north-northwest-south-southeast extensional regime that persisted through much of the Early Permian (Shail & Leveridge, 2009). During this period, granites were emplaced (274-293my) (Brenchley & Rawson P, 2006). Northwest-southeast trending dextral wrench faults affect the granites and have evidence of later Tertiary movement (Dearman, 1963).

Variscan deformation characterises the southern margin of the Carboniferous outcrop in South Wales (Owen & Weaver, 1983). This zone of deformation then continues to the east through the Mendips, forming the southern margin of the Bristol coalfield (Kellaway & Hancock, 1983). The first evidence of the later Variscan tectonism is represented by the Pennant Sandstone. This is a thick, lithic sandstone derived from the south, and deposited in the South Wales and Bristol areas during the early Bolsovian (Westphalian C), reflecting uplift of a major sediment source to the south. As during the Namurian, subsidence was strongly influenced by the presence of long-lived lineaments such as the Severn Axis and Vale of Neath Disturbance.

The main phase of deformation is thought to have occurred in the Bristol – South Wales area during the late Stephanian – Early Permian and was dominated by west-northwest - east-southeast trending thrusts and folds. The structures are compartmentalised by the northwest-southeast cross-faults that were later reactivated (Owen & Weaver, 1983).

In the subsurface of Southern England, evidence of post Lower Carboniferous deformation can be clearly demonstrated based on dipmeter data. However, the stratigraphic control does not allow the timing to be precisely defined. Unfortunately, the seismic data have rather poor resolution of the Upper Paleozoic structuring due to the steep dips below the Variscan unconformity and the generally poor energy penetration to these depths. Both the well and seismic data do show a predominantly east-west to northeast-southwest structural orientation, a fabric that was later reactivated in the Mesozoic. In order to explain the observed maturity data, the whole area must have been deeply buried and then uplifted during the later Variscan orogenic events.

In the Bristol Channel, seismic mapping has shown the presence of a zone of deformation running along its axis which was active during the Variscan (Miliorizos, et al., 2004). It is thought that the northeastern margin of the Gravity Anomaly represents a deformation zone which links to the Bristol Channel deformation zone and marks its continuation south-eastwards to the English Channel.

Permo-Triassic Sequences of Southern England

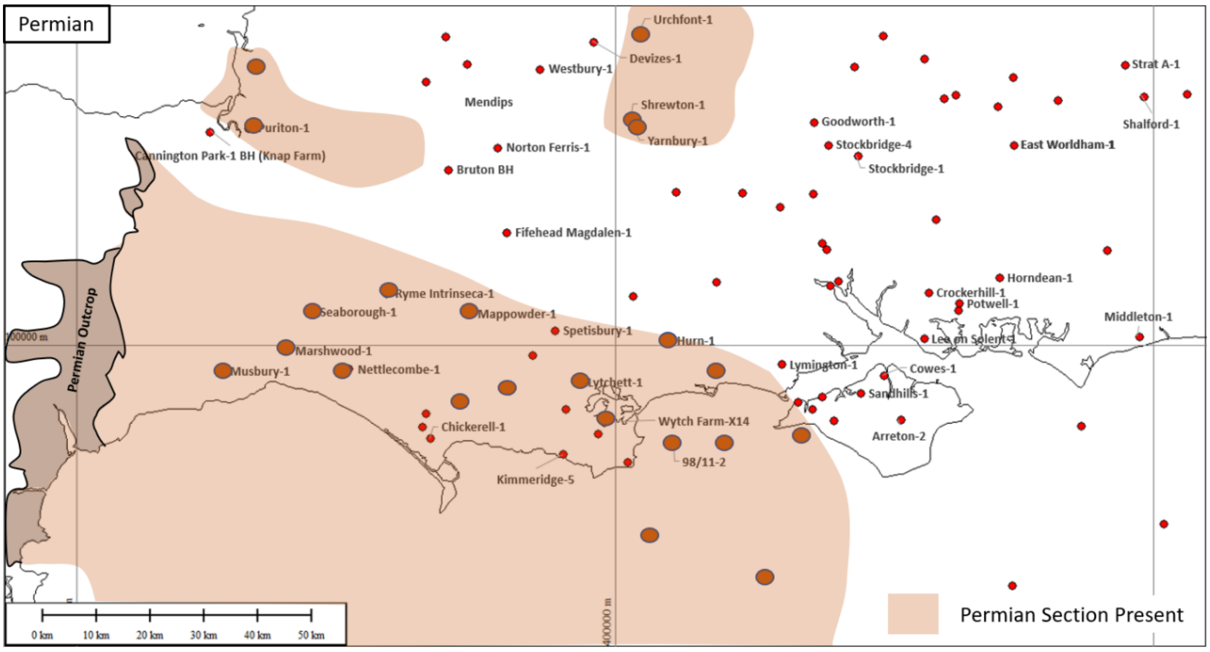

Figure 10 Map of Permian Distribution

Along the south coast of Devon and west Dorset a thick sequence of Permo-Triassic rocks is seen at outcrop, representing a post orogenic deposit. At the base, poorly dated conglomerates and breccias, thought to be of Lower Permian age, are unconformably overlain by a sequence of sandstones which in turn pass up into thick shales of the Aylesbeare Group (Gallois, 2019). This low energy environment is punctuated by occasional sand influxes of which the Sherwood Sandstone is the best developed. The sandstone is underlain by the Budleigh Salterton Pebble Beds, which mark the base of the Triassic. These coarse clastics pass up into the shales and evaporites of the Mercia Mudstone succession. The shales of the Triassic Mercia Mudstone have many of the same characteristics as the shales of the older Aylesbeare Group.

Although well-known at outcrop, thick Permian sequences are only seen in the subsurface of Southern England in wells drilled on the Gravity Anomaly. In those wells, the Permian is characterised by the rather monotonous Aylesbeare Mudstone which, in place, overlies a basal conglomerate or breccia. The basal breccia/conglomerate in the wells has clasts of phyllite and igneous material.

The well data show that the Permian thins towards the northern and eastern edges of the Gravity Anomaly. The thickest sequence of Permian has been proved in the offshore well 98/11-2 where 4,800ft (1,460m) of Permian Aylesbeare Mudstone, with no basal breccia, were drilled before the Devonian phyllites were encountered. This interval is far thicker and finer grained than measured outcropping sections further west, and may represent equivalents of the coarser grained clastics seen for example in the Musbury-1 well (British Gas, 1986), where sandstones are developed above the basal breccia unit.

In wells east and northeast of the Gravity Anomaly, the Permian section is either thin or absent. A small pocket of Permian is developed in the Urchfont and Shrewton wells, which seems to extend to the east based on seismic interpretation (Whittaker, 1985), but in other wells the Triassic directly overlies the Paleozoic. To the north, Permian sediments appear to be present within the Central Somerset Basin.

The Permo-Triassic section is clearly a post orogenic deposit with the thickest Permian sections developed over the area of the gravity high, indicating that subsidence was significant in this area during the Permian. Regionally, the stratigraphy shows that the Permo-Triassic oversteps and onlaps the Variscan Basement. However, the major phase of overstep begins in the Triassic with the Triassic Sherwood sandstone/Budleigh Salterton basal conglomerate. A similar pattern of progressive overstep with time onto Variscan aged palaeohighs is seen all around the Southern England Basin, with prominent highs such as the Mendips, Paris Plage Ridge, and the eastern edge of the Wessex Basin (Solent – Swindon line) only being finally covered in the Late Triassic-Early Jurassic.

Timing of the Emplacement of the Southwest Block

Numerous authors have pointed out the similarity of the geology of Southwest England to the Rhenohercynian Zone of Central Europe (Brenchley & Rawson P, 2006; Holder & Leveridge, 1986; Franke, et al., 2017). The offset between the two areas can be accommodated by 400 kms of dextral movement along the Bristol Channel - Pays de Bray fault zone (Woodcock, et al., 2007). Other authors have also commented on the abrupt geological changes across the Bristol Channel (Holder & Leveridge, 1986; Woodcock, et al., 2007) between Southwest England and South Wales:

- The Middle Devonian unconformity seen in Avon and South Wales, marking the timing of Acadian deformation, is not seen in Devon and Cornwall and there is no break in sedimentation
- Marine sedimentation dominates Devonian deposition in the southwest whereas non-marine clastics are encountered in Avon and Wales
- In the Lower Carboniferous, shelfal carbonates are seen at outcrop in Wales and the Mendips and in the subsurface at the Bruton, Fifehead Magdalen and Cannington Park wells whereas deepwater shale sedimentation occurs in the Lower Carboniferous of Southwest England

- Sedimentological studies have shown that a sediment source in the Bristol Channel area was active during the Devonian and Carboniferous, shedding sediments to the north in Wales and to the south in Southwest England (Tunbridge, 1986)

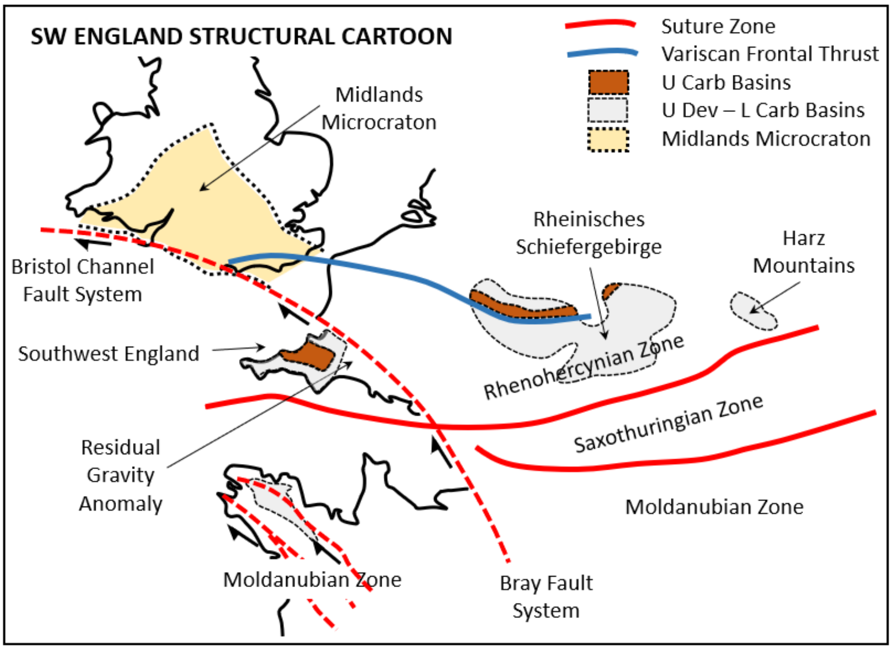

Figure 11 Structural Cartoon of Southwest England

The marked geological changes, detailed above, across the northeastern margin of the Gravity Anomaly are similar to some of the changes seen across the Bristol Channel. The lineament is thought to represent the subsurface trace of a major fault system that links the Bristol Channel deformation zone to the south coast of England and the Pays de Bray Fault zone of France. This deformation zone is thought to represent a Terrane boundary forming the northeastern limit of the Southwest England continental block which was translated along this zone in the Carboniferous (Holder & Leveridge, 1986; Woodcock, et al., 2007). It also marks the junction with the Southern England - Midlands Microcraton (Butler, 2018). The timing of dextral movement along this fault zone cannot be defined with precision, but a late Visean-Namurian initiation age is thought likely, with reactivation into the Late Carboniferous.

Acknowledgments

This study has been undertaken as part of the Beneath Britain joint initiative between UKOGL (UK Onshore Geophysical Library) and the Department of Earth Sciences at Oxford University.

We would like to thank Malcom Butler for many fruitful discussions which have helped us to develop the ideas presented here and, in addition, for allowing the use of his seismic interpretation of southern England and the English Channel.

We wish to thank Bernard Cooper, Dave Shaw, Andy McGrandle and Malcolm Butler for their many helpful comments and suggestions made on an early version of this paper. Any remaining errors or shortcomings are the responsibility of the authors.

Approval for use of the BGS GRAVMAG Interactive 2.5D Gravity and Magnetic Modelling software is gratefully acknowledged. The surface geological map of Figure 1 and 8 is reproduced with the permission of the BGS.

Appendix – Wells Drilled East of the Gravity Anomaly

Well	Company	Date	Result	TD(md,tvdss)	TD Formation	Data Available			
						Logs	Dip	Dating	Maturity
Wells away from Gravity Anomaly									
Chilworth-1	Amoco	1983	P&A, Dry	6200(-6036)	Devonian	x	x		x
Cannington Park-BH	IGS	1976	P&A, Dry	3783(-3651)	Devonian			x	x
Cranbourne-1	BP	1972	P&A, Dry	6696(-6506)	Devonian				x
Fifehead Magdalen-1	Carless	1985	P&A, Dry	4492(-4220)	Devonian	x	x	x	x
Shrewton-1	IGS	1979	Stratigraphic	9824(-9356)	Ordovician	x	x	x	x
Baxters Copse-1	Conoco	1983	P&A, Oil Shows	7762(-7517)	Devonian	x	x		
Chessell-1	Brabant	1996	P&A, Dry	7242(-6445)	Devonian	x	x		
Goodworth-1	Amoco	1987	Oil Discovery	7005(-6756)	Devonian	x	x		
Hoe-1	Amoco	1982	P&A, Dry	5800(-5656)	Triassic	x	x		
Horndean-1	Carless	1983	Oil Discovery	6004(-6362)	Devonian	x	x		
Lymington-1	Brabant	1992	P&A, Dry	5692(-5333)	Devonian	x			
Marchwood-1	IGS	1979	Stratigraphic	8480(-8445)	Devonian	x	x		
Potwell-1	Carless	1985	P&A, Oil Shows	6984(-5388)	Devonian	x	x		
Southampton-1	IGS	1981	Stratigraphic	5994(-5958)	Devonian	x	x		
Stockbridge-1	Amoco	1984	Oil Discovery	6153(-5779)	L.Carboniferous	x		x	
Stockbridge-4	Amoco	1986	Appraisal Well	8421(-6923)	Devonian	x			
Wilmingham-1	Sun	1984	P&A, Dry	5980(-5930)	Devonian	x	x	x	
Middleton-1	Pennzoil	1971	P&A, Dry	6982(-6962)	Carboniferous	x	x		
Lomer-1	Carless	1985	P&A, Oil Shows	6940(-6362)	Devonian	x	x		
Sandhills-1	BG	1982	P&A, Oil Shows	4799(-4709)	Devonian	x	x		
Cowes-1	Sun	1983	P&A, Dry	5858(-5598)	Devonian	x	x		
Crockerhill-1	Carless	1986	P&A, Dry	7039(-6326)	Devonian	x	x		
Bruton-BH	IGS	1982	P&A, Dry	1263(-947)	L.Carboniferous			x	
Netherhampton-1	Shell	1985	P&A, Dry	5361(-5106)	L.Carboniferous	x		x	
Norton Ferris-1	Carless	1985	P&A, Dry	2510(-1831)	Devonian	x	x		
Puriton-BH	Bridgewater Colleries	1910	P&A, Dry	2072(-2030)	Permian				
Yarnbury-1	Carless	1985	P&A, Dry	5511(-4992)	L.Ordovician	x		x	

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