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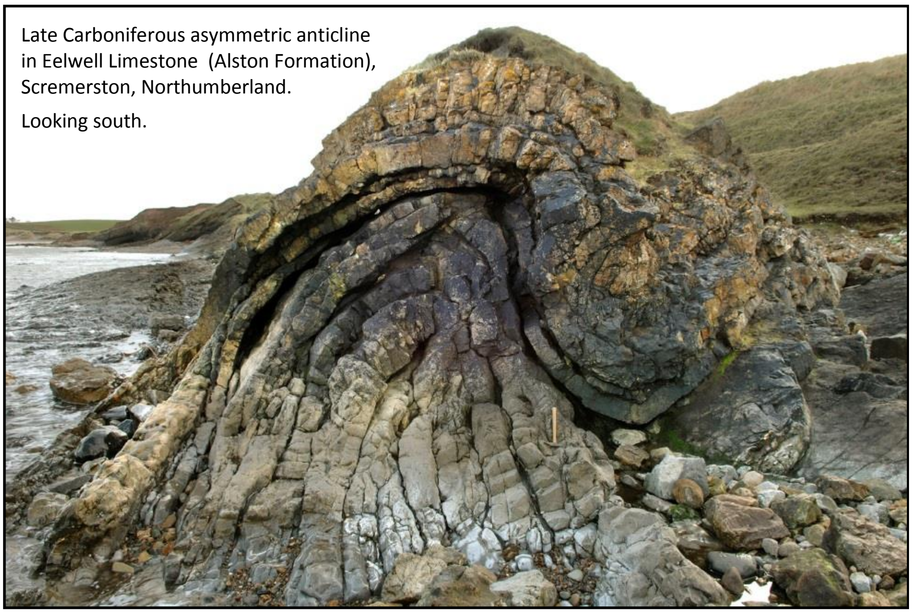
Tectonic synthesis and contextual setting for the Central North Sea and adjacent onshore areas, 21CXRM Palaeozoic Project

Energy and Marine Geoscience Programme

Commissioned Report CR/15/125



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Tectonic synthesis and contextual setting for the Central North Sea and adjacent onshore areas, 21CXRM Palaeozoic Project

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Keywords

North Sea, tectonics

Front cover

Late Carboniferous asymmetric anticline in Eelwell Limestone (Alston Formation), Scremerston, Northumberland. Looking south.

Bibliographical reference

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Foreword

This report is a published product of the 21st Century Exploration Road Map (21CXRM) Palaeozoic project. This joint industry-Government-BGS project comprised a regional petroleum systems analysis of the offshore Devonian and Carboniferous in the North Sea and Irish Sea. The tectonic synthesis presented here is supported by the emerging structural interpretations of seismic datasets from the offshore region and is readily integrated with published interpretations of Devono-Carboniferous tectonics onshore.

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Summary

This report is designed simply to provide a summary tectonic outline and contextual setting against which offshore seismic and well data relating to the Devono-Carboniferous evolution of the Central North Sea, Forth Approaches, and adjacent UK onshore region can be considered. This summary is intended to help better frame the questions that will arise during interrogation of that data; the findings that result from that analysis are presented elsewhere in the report series (Arsenikos et al., 2015; Kimbell & Williamson, 2015; Monaghan et al., 2015).

Apparently contradictory, wrench- or extension-dominated patterns of Lower Carboniferous basin development are recorded in the Forth Approaches, Quadrant 29, North Dogger and Silverpit basins of the Central North Sea, as well as the Midland Valley of Scotland (MVS) and Northumberland and Solway basins onshore. Partitioning Carboniferous deformation across inherited pre-existing Caledonian or Tornquist structures is likely to be an important control on the tectonic architecture developed in these regions during intervals of the geological record in the Carboniferous.

Onshore, spatially separate but contemporaneous domains of extension-dominated tectonics versus wrench-dominated tectonics explain the contrasting tectonic framework of the MVS/Forth Approaches region (wrench-dominated) compared with Northumberland Basin (classic ‘stags head’ structure). NE-SW trending Caledonian inheritance strongly controls the domain boundaries and the patterns of deformation created in each of these domains. Offshore, in the Devono-Carboniferous basins of the Central North Sea, the likelihood that strain is partitioned in a similar way across features inherited from the NW-SE Tornquist trend is proposed and examined. The data currently under consideration suggests that a NW-SE trending wrench-dominated domain is spatially associated with the region underlain by the Dogger Granite pluton; domains affected by extension-dominated tectonics appear to be arranged on either side of that feature, namely the Quadrant 29 and North Dogger basins to the NE, and the Silverpit Basin to the SW. Extension is expressed as a NE-SW directed stretch in both of these domains.

Patterns of broadly N-S trending fold axes need to be carefully assessed in terms of their structural setting, as folding cannot implicitly be linked with inversion/compression when partitioned strains are developed. Superficially similar features can develop in the MVS in dextral transpression, in north Northumberland buttressed around the Cheviot Granite in overall dextral wrench, and as superimposed late compressional folds in end-Variscan convergence, for example in the Boldon syncline of County Durham.

Offshore, similar inversion effects can be seen in the patterns of transpressive faulting associated with features such as the Murdoch Ridge, and with examples of superimposed NE-SW trending extensional faults active in the latest Carboniferous to early Permian.

Introduction

The 21CXRM Palaeozoic Project aimed to stimulate exploration of the Devonian and Carboniferous plays of the Central North Sea - Mid North Sea High, Moray Firth - East Orkney Basin, and in the Irish Sea area. The objectives of the project included regional analysis of the plays and building of consistent digital datasets, working collaboratively with the OGA, Oil and Gas UK and industry.

The report is adapted from a series of previously presented diagrams/slides, and the accompanying notes, and is designed simply to provide a summary tectonic outline and contextual setting against which offshore seismic and well data relating to the Devono-Carboniferous evolution of the Central North Sea, Forth Approaches, and adjacent UK onshore region can be considered. As a summary, it is intended to help better frame the questions that have arisen during interrogation of that data and accepts that the findings that result from that analysis are presented elsewhere in the report series (Arsenikos et al., 2015; Kimbell & Williamson, 2015; Monaghan et al., 2015).

The Carboniferous to Permian evolution of Northern Britain is typically presented in terms of N-S to NNW-SSE oriented extension during Dinantian times (Fraser and Gawthorpe, 2003), superseded by an episode of thermal subsidence during the late Carboniferous (Kimbell et al., 1989). Variscan inversion is arguably superceded, or even overlapped, by renewed N-S extension (Leeder at al., 1989, Timmerman, 2004) but these studies do not, taken in isolation, fit well with regional to plate-scale tectonic constraints. E-W shortening directions in northern England are highly discordant with the SSE to NNW direction of Variscan convergence in Britain (e.g. Sanderson, 1984; Woodcock and Rickards, 2003). Emplacement of large volumes of tholeiitic magma related to lithospheric extension (Timmerman, 2004) is apparently at odds with a significant episode of crustal shortening at this time.

De Paolo et al., (2005) propose an elegant solution to these apparent contradictions where the Carboniferous deformation is partitioned as a reactivation response to the interplay of the regional (up to plate)-scale Devono-Carboniferous stress régime and pre-existing Caledonian or Tornquist structures preserved in older rocks. Viable interpretation of the tectonic evolution of the Mid North Sea High area of interest should be considered within such a framework and is explored further here.

Slide 1: Tectonic setting for the UK and North Sea

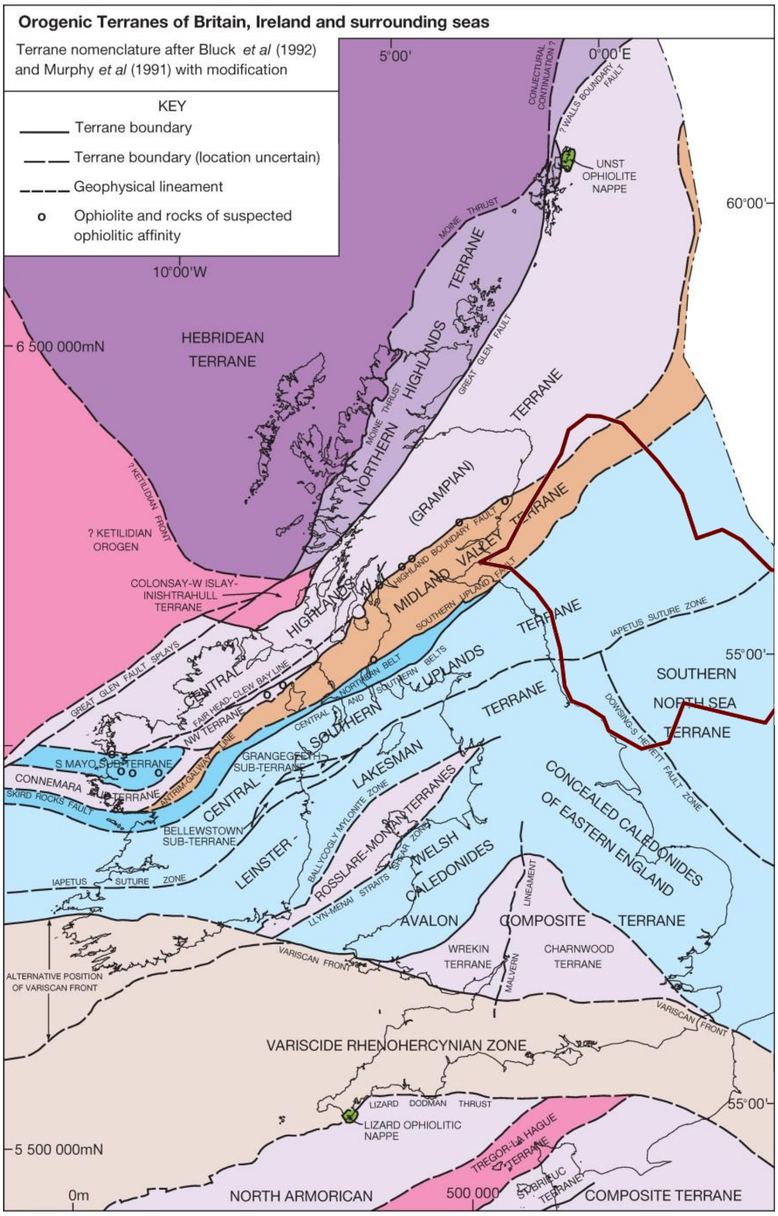


Figure 1. The essential elements of pre-Upper Palaeozic tectonic inheritance for the UK and surrounding areas are well understood in general. The pattern of underlying Caledonian and Tornquist trends will be a significant control on the subsequent patterns of Upper Palaeozoic structural development. The project area of Interest (AOI) is shown as the heavy outline. From UK Tectonic Map (BGS, 1996).

The tectonic setting for the Central North Sea study is reasonably well known in both UK and continental European terms and is typically presented in terms of N-S to NNW-SSE oriented extension during Dinantian times (Fraser and Gawthorpe, 2003), superseded by an episode of thermal subsidence during the late Carboniferous (Kimbell et al., 1989). Although there is some continuing debate over the projected traces and significance of the major crustal scale discontinuities that resulted from Palaeozoic Orogenies (Caledonian, Acadian, Variscan), (e.g. Pharaoh 1999), the general pattern is well understood (see for example the UK Tectonic Map, BGS 1996, Fig.1). The position of the offshore projection of the Iapetus Suture is arguable (though see Soper et al. 1992), but clearly transects the area of interest such that the northern 'Forth Approaches' area is placed well to the north of any putative trace for the Iapetus Suture.

The 'Mid North Sea High area' offshore NE England straddles, and lies above, the likely trace beneath Upper Palaeozoic strata of the both the Iapetus Suture and the fossil zone of Tornquist subduction coincident with the Dowsing-Hewett Fault Zone trend (Pharaoh, 1999, and references therein). This feature is related to and orientated parallel with, but should not be equated with, the Trans-European Suture Zone that marks closure of the Tornquist Ocean. The inherited tectonic framework for the area of interest therefore transforms from Iapetan Caledonian trends (NE-SW to ENE-WSW) in the north, to more NW-SE trends in the 'Tornquist zone' to the south (Pharaoh, 1999, and references therein).

The transition from Caledonian to Tornquist trends reflects the dominant sinistral transpression that was active in late-Caledonian times c. 400 Ma ago (e.g Dewey and Strachan, 2003) and a generalised clockwise rotation of trends of basement structures might be expected across the area of interest (*cf.* with the triangular form of the Midlands Microcraton).

Slide 2: Plate-scale context

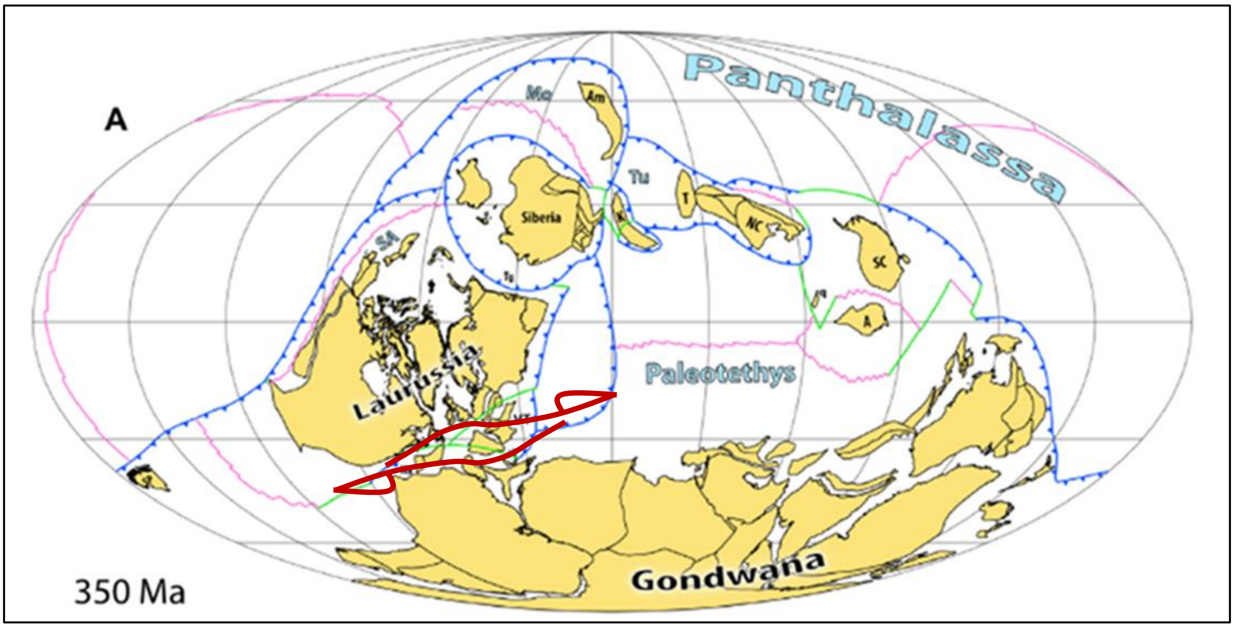


Figure 2. Plate-scale setting in the Devono-Carboniferous - snapshot at 350 Ma (after Domeier and Torsvik, 2014). Gondwana convergence with Laurussia is dextral at this time as shown by the red arrows superimposed; the UK, and thus the Mid North Sea High region, lies directly in this oblique convergence zone. Reproduced with permission of Elsevier from Geoscience Frontiers.

The time-sliced reconstructions of Domeier and Torsvik (2014) refine the earlier reconstructions of Scotese and McKerrow (1990) and highlight the dextral convergence of Gondwana and Laurussia throughout the late Devonian and Carboniferous (Fig. 2). Domeier and Torsvik (2014) also recognise the closure of the Ural Ocean by early Permian times that drives the 'European indentor' back in towards the Laurussian/Gondwanan convergence. At the plate tectonic scale, the of Domeier and Torsvik (2014) synthesis thus supports the plate-tectonic reconstructions of Coward (1993, see slide 3 below) and Maynard et al. (1997) for the Carboniferous of Greenland and Europe. Those earlier interpretations argued for early 'squeezing out' and later 'pushing back' of a 'European indentor' (i.e. Baltica) to explain the Carboniferous of Britain in a meaningfully wider context. A synthesis for the Central North Sea region should therefore start from this perspective.

Note that the Great Glen/Walls Boundary/Storstrommen structure that originally developed between Laurentia and Baltica in later Caledonian (Siluro-Devonian) times (Dewey and Strachan, 2003, and Fig. 3a) will still be expressed as an active structure within Laurussia during the Carboniferous (in the models of Coward and others, e.g. Coward 1993), but does not apparently affect these larger plate-scale reconstructions (e.g. Domeier and Torsvik, 2014).

Slide 3: Expulsion and insertion of Baltica, (after Coward,1993)

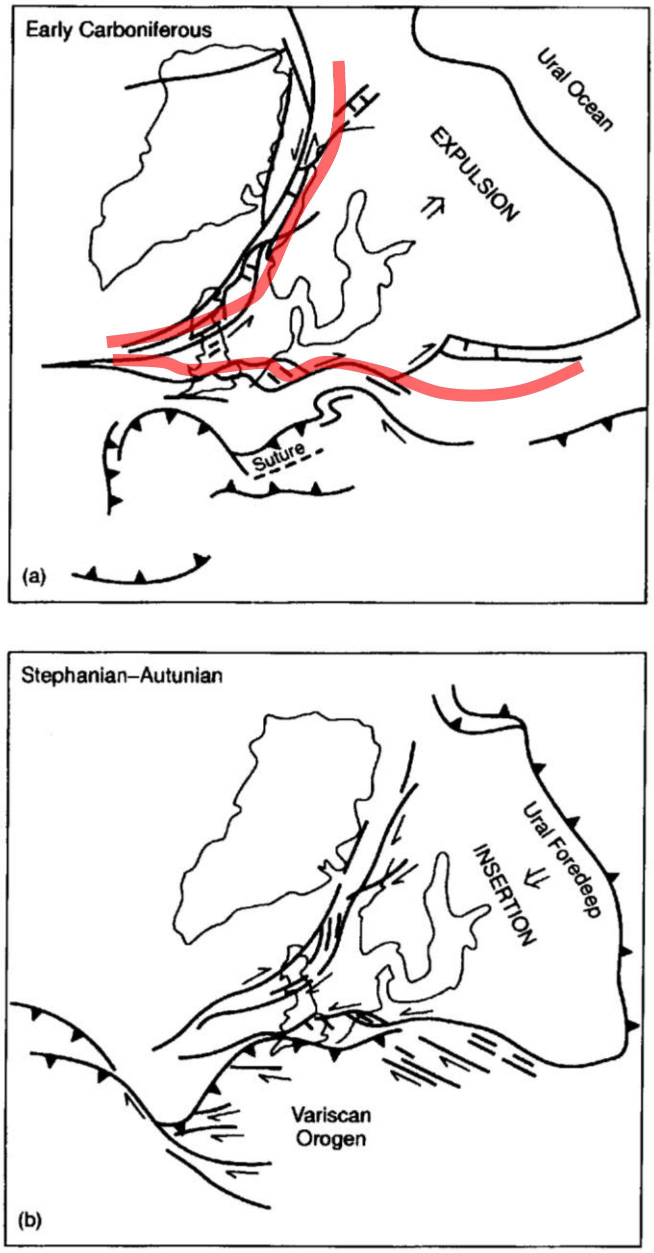


Figure 3. Plate-tectonic reconstructions for Greenland and Europe after Coward (1993) – Carboniferous to Early Permian. Reproduced with permission of the Geological Society, London.

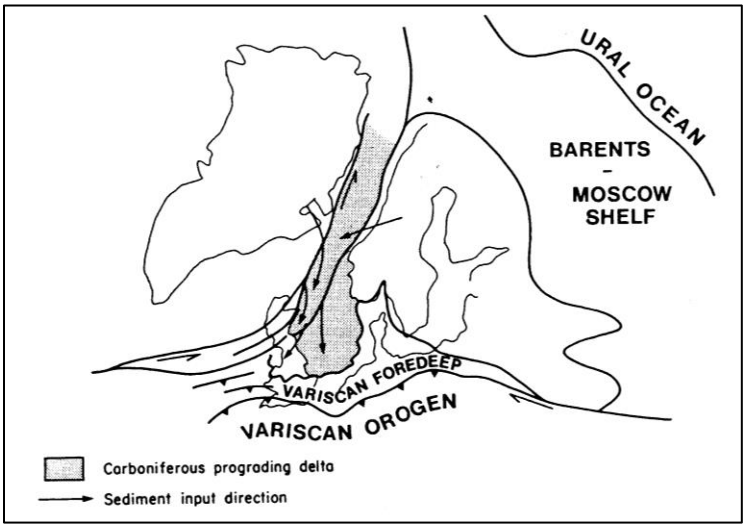
(a) the heavy red lines represent the foci of progressive development of the Variscan orogenic belt to the south in the early Carboniferous, with the Great Glen – Storstrommen shear zone active as an intra-Laurussia structure farther north.

(b) Interaction of Baltica-Siberia across the Ural Sea then comes into play, driving eastward movement of Baltica in the late Carboniferous (*cf*. Domeier and Torsvik, 2014).

In late Devonian - early Carboniferous times, the northern sector of the area of interest (Forth Approaches/Midland Valley of Scotland) was experiencing the last gasps of 'Caledonian' sinistral transpression that was switching over to a sinistral transtensional stress field as Baltica began to transition eastwards (*cf*. Dewey and Starcahan 2003, Coward,1993, and Fig.3a). The net stretch as Baltica departed was probably aligned approximately NNE-SSW (or NE-SW) by early Carboniferous times and continued thus until the latest Carboniferous when the regional stresses would have switched to dextral transpression as the movement of Baltica reversed direction (*cf.* Coward, 1993; Maynard et al., 1997).

In contrast, the southern sector of the area of interest (NE England and regions offshore) displays a range of structural styles throughout the late Devonian and the Carboniferous that are all consistent with dextral transtension (Coward, 1993; De Paola et al. 2005), implying that this sector was being influenced by the stress régime developed along the Variscan belt to the south (dextral at this time and as Baltica moved away; note right lateral stepovers inferred by Coward 1993, Fig. 3a). In late Carboniferous times, these stresses will have reversed as Baltica moved back westwards (Coward, 1993, Maynard et al. 1997), and a superimposed sinistral (transpressive?) regime should be anticipated, that may either have re-activated suitably orientated structures or generated new cross-cutting (early Permian?) faults (Fig. 3b).

It should be noted that the Coward (1993) and Maynard et al. (1997) reconstructions readily accommodate the observed middle Mississippian progradational delta systems and palaeo-topography observed in this project for the Central North Sea area. These delta systems would be fed by sediment distributary systems feeding axially along the developing rift between the Greenland and Scandinavian margins (Fig. 3c).



(c) The plate-scale reconstruction and developing rift model of Coward (1993), readily accommodates the middle Mississippian palaeo-topography and progradational delta sediment distribution systems identified in this project in the Mid North High Sea area of interest.

Slide 4: The strain partitioning model (de Paola et al., 2005)

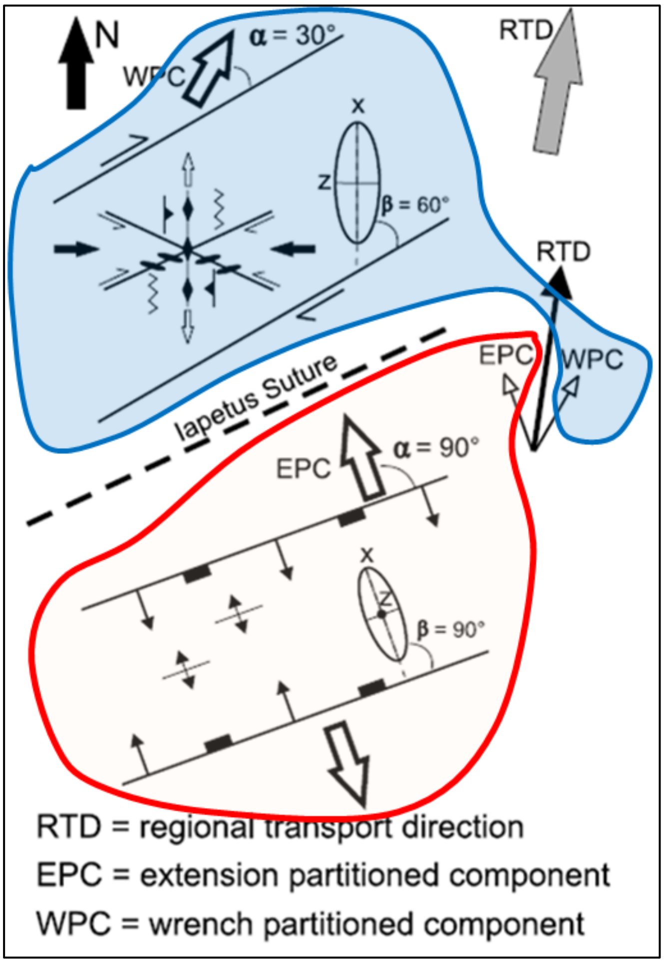


Figure 4. Wrench-dominated (WPC) and extension-dominated (EPC) components of deformation as expressed in the northeast of England onshore (after De Paola et al. 2005). Strain partitioning is argued by those authors to have been a reactivation response in the Carboniferous stress régime to inherited Caledonian structure and the Iapetus Suture Zone. Reproduced with permission of Elsevier from the Journal of Structural Geology.

From a field/outcrop perspective, and especially in regard to the Mid North Sea High (MNSH) region, it is very instructive to look at the interpretation of structural features relating to the Carboniferous onshore in NE England published by De Paola et al. (2005, Fig. 4). Note though that those authors focused specifically on the period around the time of emplacement of the Whin Sill (c. 297 Ma) in the earliest Permian. The model is readily applied more widely however.

In particular, the idea that strain has been partitioned into compartments where extension is dominant, adjacent to and contemporaneous with, compartments where wrench tectonics are dominant is an elegant solution to the long-standing conundrum of contrasting deformation styles that all occur within a relatively short span of geological time in spatially discrete and separate ‘compartments’, (and critically are associated with compressional features such as folds and thrusts). For the area of interest, such spatially separate but contemporaneous extension-dominated and wrench-dominated tectonic domains explain the contrasting MVS/Forth Approaches region (wrench-dominated) and Northumberland Basin (classic ‘stags head’ structure).

In the key summary diagram shown above (Fig. 4), the regional transport direction (**RTD,** relative to north) is consistent with the Baltica ‘departure direction’ and, it is reasonable to assume therefore, has been broadly applicable since early Carboniferous times (*cf.* Coward 1993), and possibly in the late Devonian as well. That regional (RTD) stretch is partitioned into:

A) NNW-SSE directed ‘pure’ extension (e.g. Northumberland Basin); and

B) ENE-WSW trending dextral wrench-dominated faulting, associated with folding/thrusting aligned on approximate N-S trends (e.g. the Holborn and Lemmington Anticlines in the Cheviot /Alnwick area (Shiells, 1963, and see following slide), and extending west to include features such as the Bewcastle Anticline in north Cumbria).

Slide 5: The field evidence (e.g. Shiells, 1963)

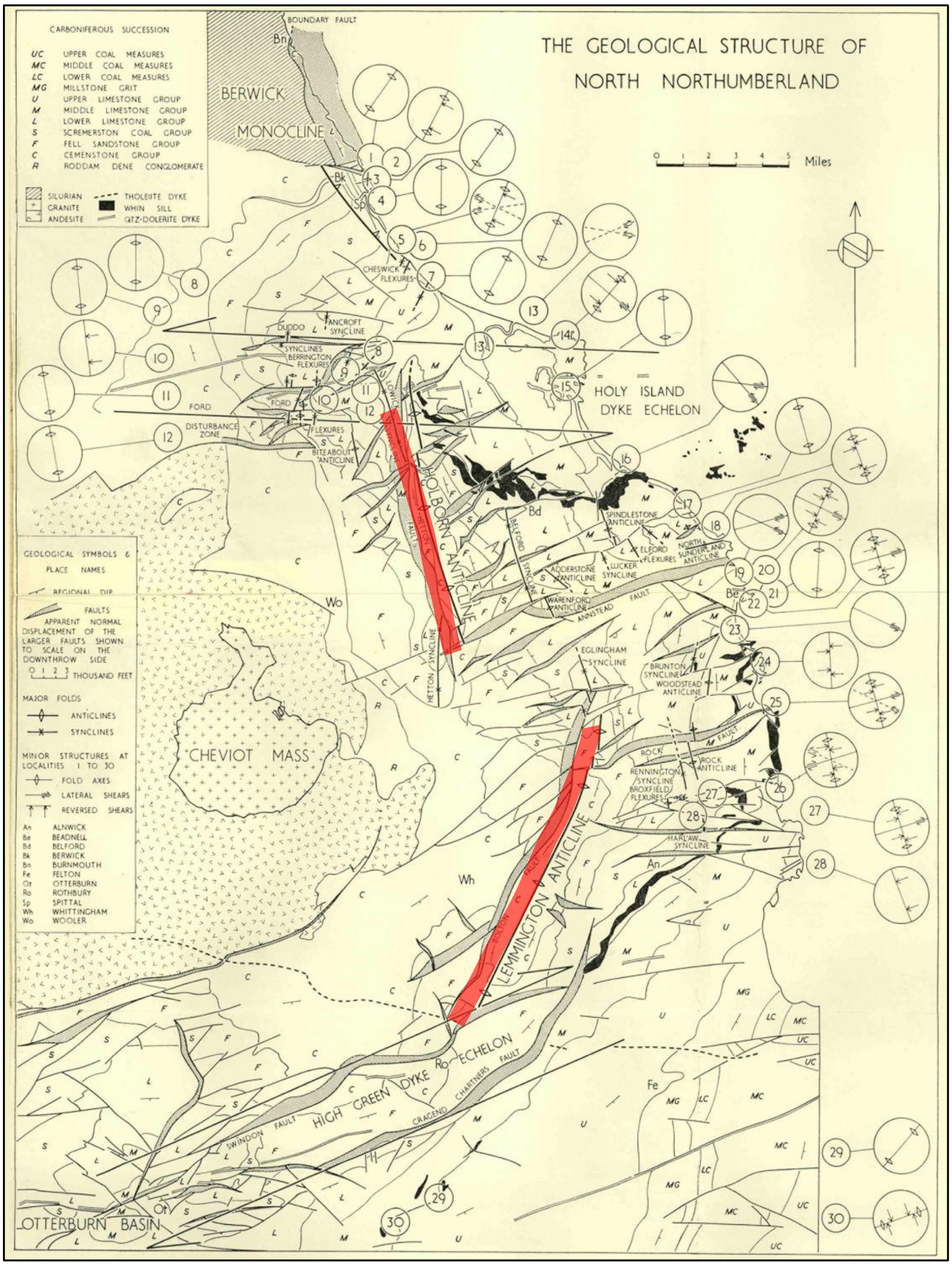


Figure 5a. The detailed and comprehensive mapping of Shiells (1963) highlights the prominent fold, and fold-thrust structures that developed in the wrench-dominated domain north of the Northumberland basin. The details of individual structures are less important here than the richness of the dataset. The pattern of folds suggests strongly that the Cheviot Pluton could have acted as a former, constraining the locus of folding (e.g. highlighted Lemington and Holborn anticlines). Reproduced by permission of the Royal Society of Edinburgh from *Transactions of the Royal Society of Edinburgh* volume 65 (1962-64), pp 449-481. The map is based in part on Crown Copyright Geological Survey Maps by permission of the Controller, H.M. Stationary Office.

Strain partitioning during a single and possibly protracted phase of regional stress (in this case dextral transtension) removes the necessity for an explicit link between inversion/uplift events and compression/transpression tectonics. Detailed mapping in NE England provides a very rich dataset of tectonic elements (folds, faults, thrusts etc.) that very strongly support the partitioned strain model of De Paolo et al. (2005), (e.g. Shiells 1963, Fig. 5a, and see summary in the BGS

Northern England Regional Guide (2010) Fig. 5b). The field data does clearly demonstrate contemporaneous and adjacent (but not superimposed) extension-dominated and wrench-dominated structural domains. Therefore, it should be expected that regional stress is partitioned/resolved in this fashion in the project area of interest along/across discontinuities that are inherited from pre-existing tectonic frameworks – in the Central/Mid North Sea/NE England case these are the old Caledonian and Tornquist 'trends'.

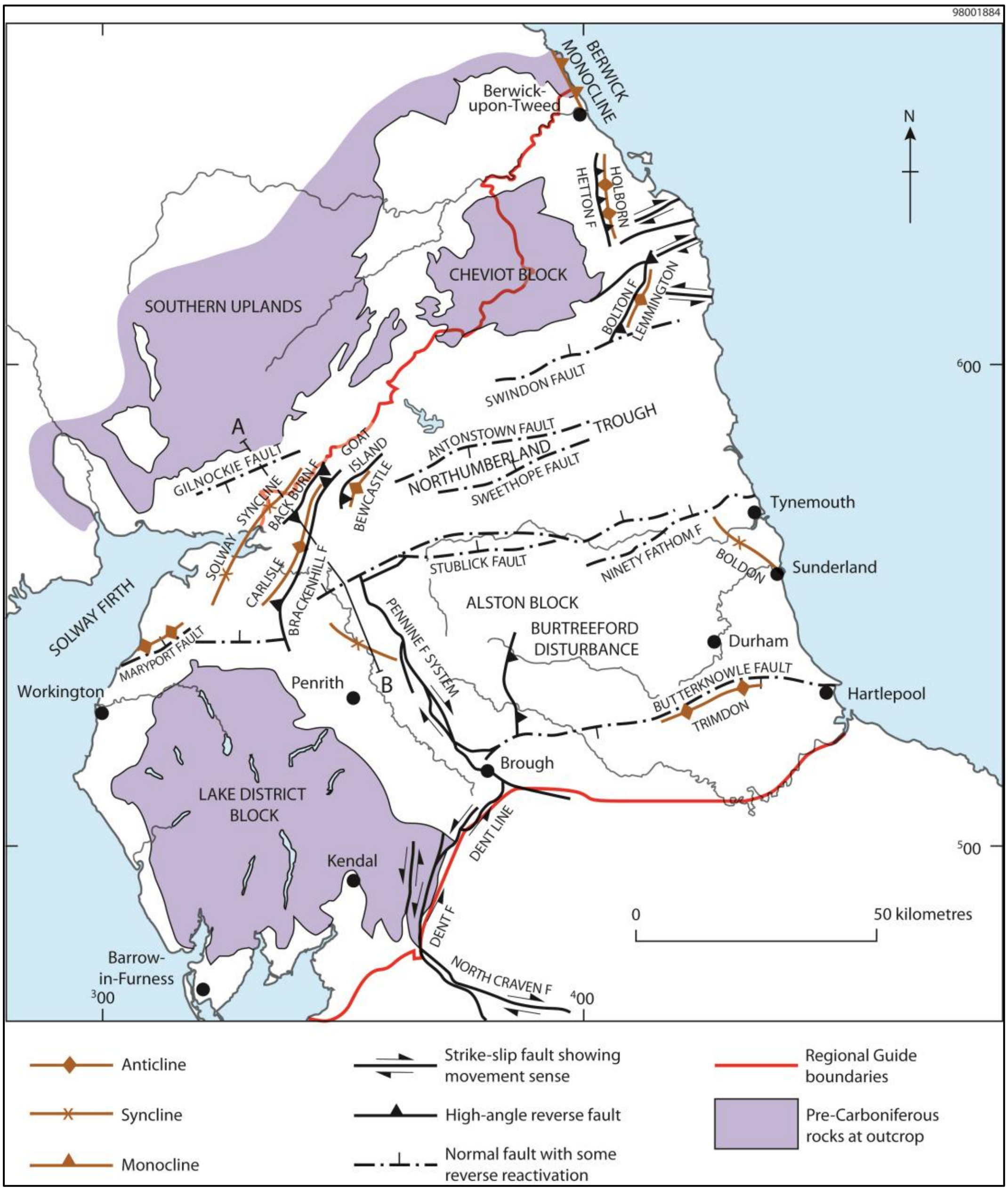


Figure 5b. The wider pattern of wrench- and extension-style structures identified across northern England, reproduced from the Northern England Regional Guide (BGS, 2010).

Slide 6: Strain partitioning applied in the offshore, 1a

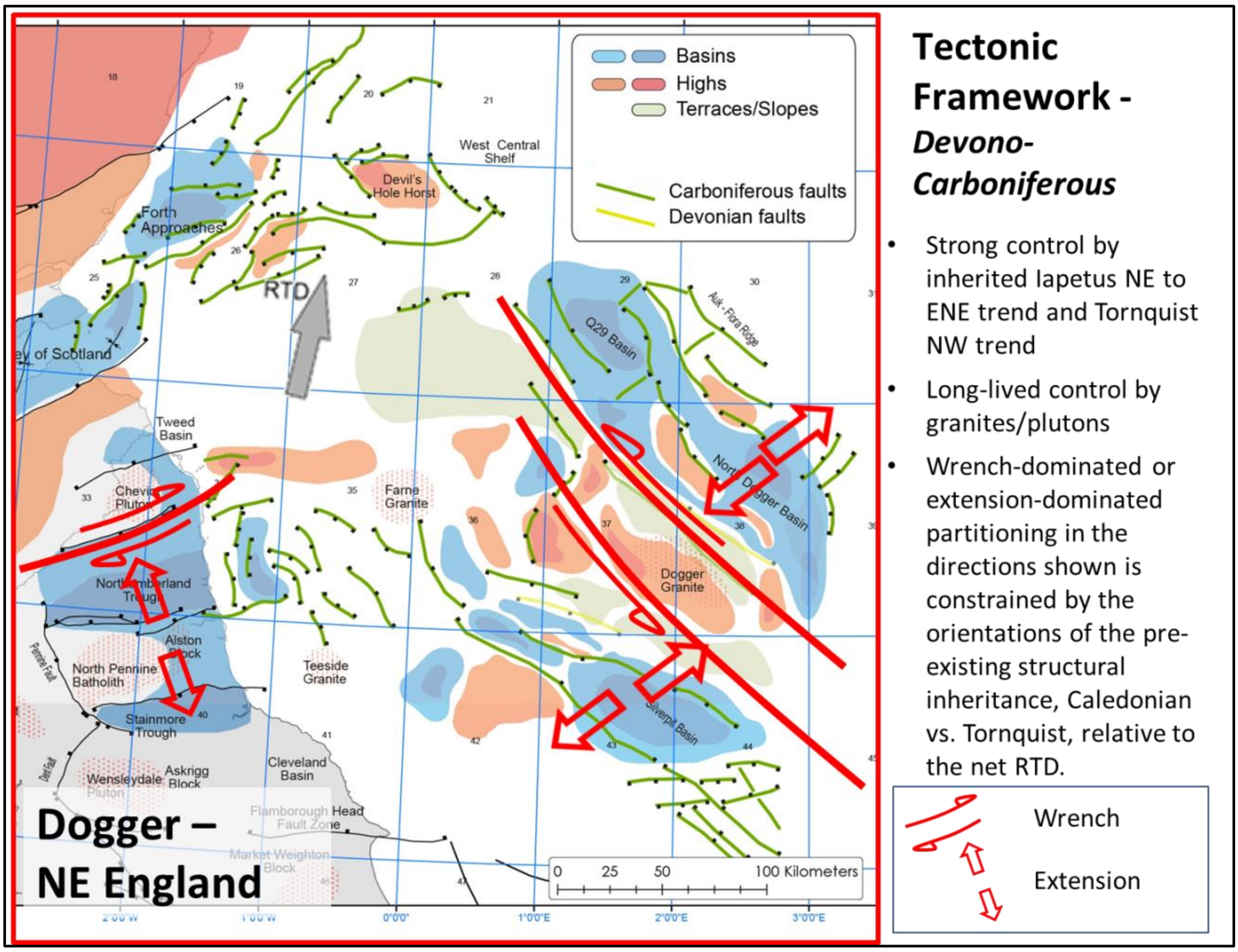


Figure 6. The heavy red ornament superimposed on the pattern of Basins,Highs and Terraces in the the project area of interest shows the expected trends of tectonic structures in anticipated wrench-dominated ot extension-dominated domains constrained by pre-existing trends inherited from Caledonian and Tornquist-related features beneath the Upper Palaeozoic.

A partitioned strain model is readily applicable to the NE England and offshore region including the Mid North Sea High where the relict NNW-SSE 'Tornquist trend' is expected to have influenced the developing tectonic framework in the Devono-Carboniferous. Applying the same RTD direction as resolved onshore (De Paola et al. 2005, and see red arrows on slide), and resolving extensional- and wrench-dominated stresses in relation to the NNW-SSE structural trends evident in the Dogger Bank region, means that we can anticipate being able to identify adjacent compartments that have experienced broadly contemporaneous NNW-SSE trending (sinistral) wrench-dominated structures (faults), or ENE-WSW directed pure extension in the Devono-Carboniferous while Baltica moved away. This is consistent with the emerging interpretation of seismic and well data from the region and is reported on further in other elements of the report series (Arsenikos et al., 2015).

Slide 7: Strain partitioning applied in the offshore, 1b

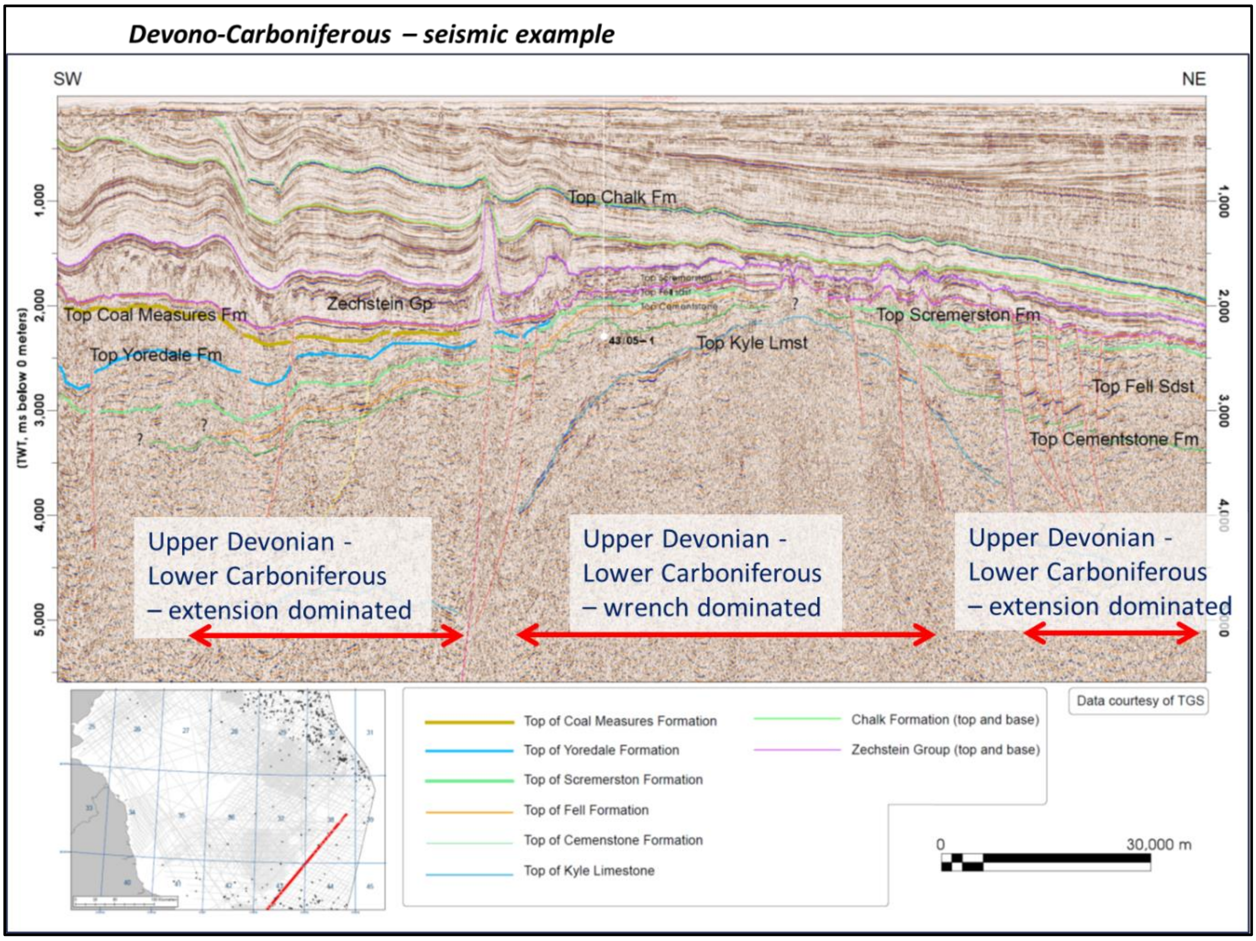


Figure 7. Preliminary assessment of NE-SW trending seismic line in the Mid North Sea High region, showing sub-division into possible extension-dominated and wrench-dominated domains.

As an example, a preliminary assessment of the seismic line figured above (Fig. 7) allows for a subdivision into extension-dominated domains in the south-west and north-east of the line, with a wrench-dominated domain in the central part of the line, lending support to application of the strain partitioning model (cf. De Paolo et al. 2005). The separate domains are divided across steeply-inclined faults. A detailed analysis of this seismic line is given in Arsenikos et al. (2015) and the area discussed in Kimbell & Williamson (2015).

Slide 8: Strain partitioning applied in the offshore, 2

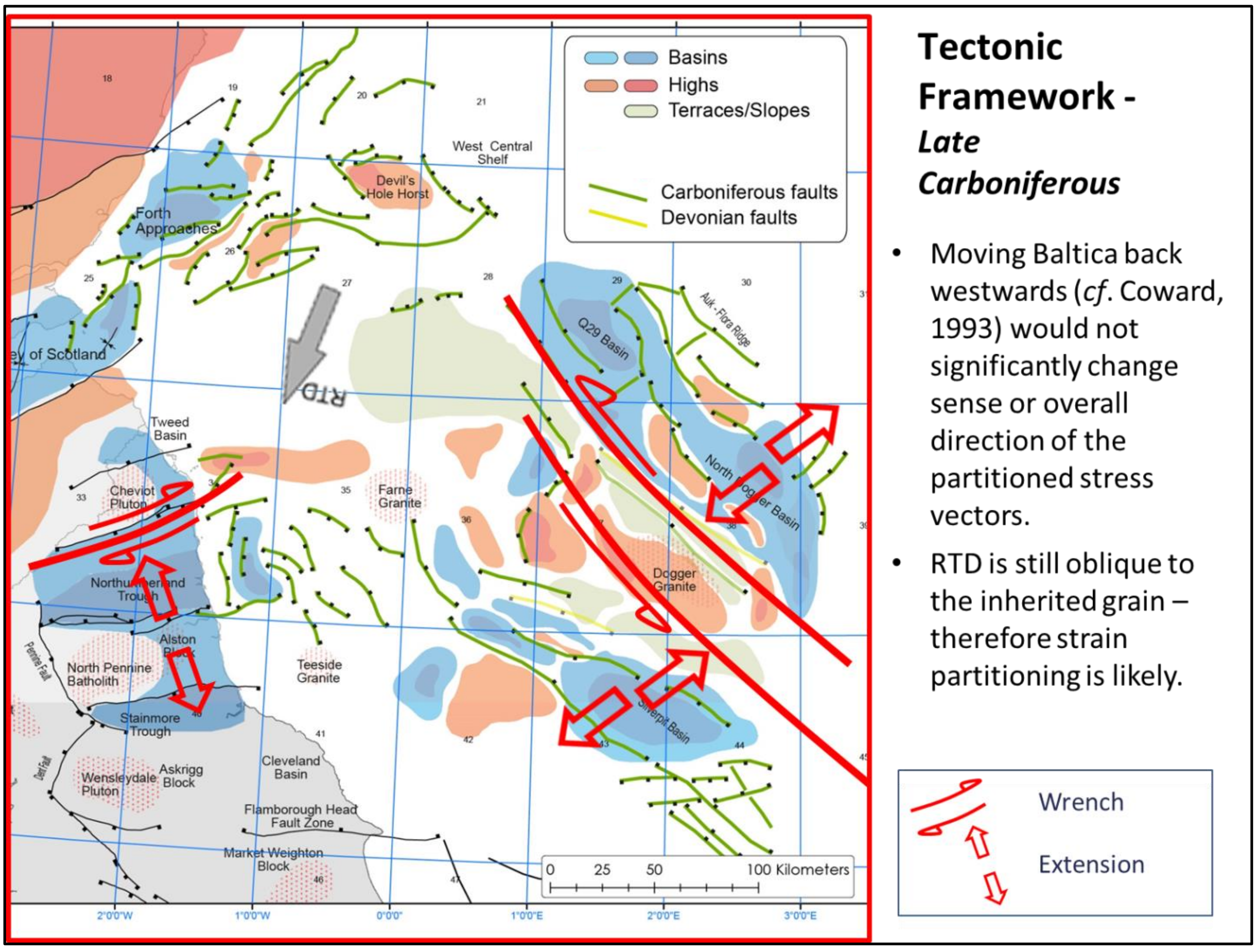


Figure 8. The anticipated Late Carboniferous configuration of wrench-dominated and extension-dominated domains in the Mid North Sea High region and NE England.

As Baltica moved back westwards in the late Carboniferous-early Permian there would be continued sinistral (re)working of wrench-dominated structures. Assuming a net direction similar to that proposed by Coward (1993), strain would have been partitioned on vectors little changed to those prevalent earlier in the Carboniferous. This would imply that inversion structures would be expected against discontinuities aligned at a high angle to the regional transport direction (RTD) and could feature in the seismic data.

Slide 9: Wrench-dominated strain in the Forth Approaches/MVS area, 1a

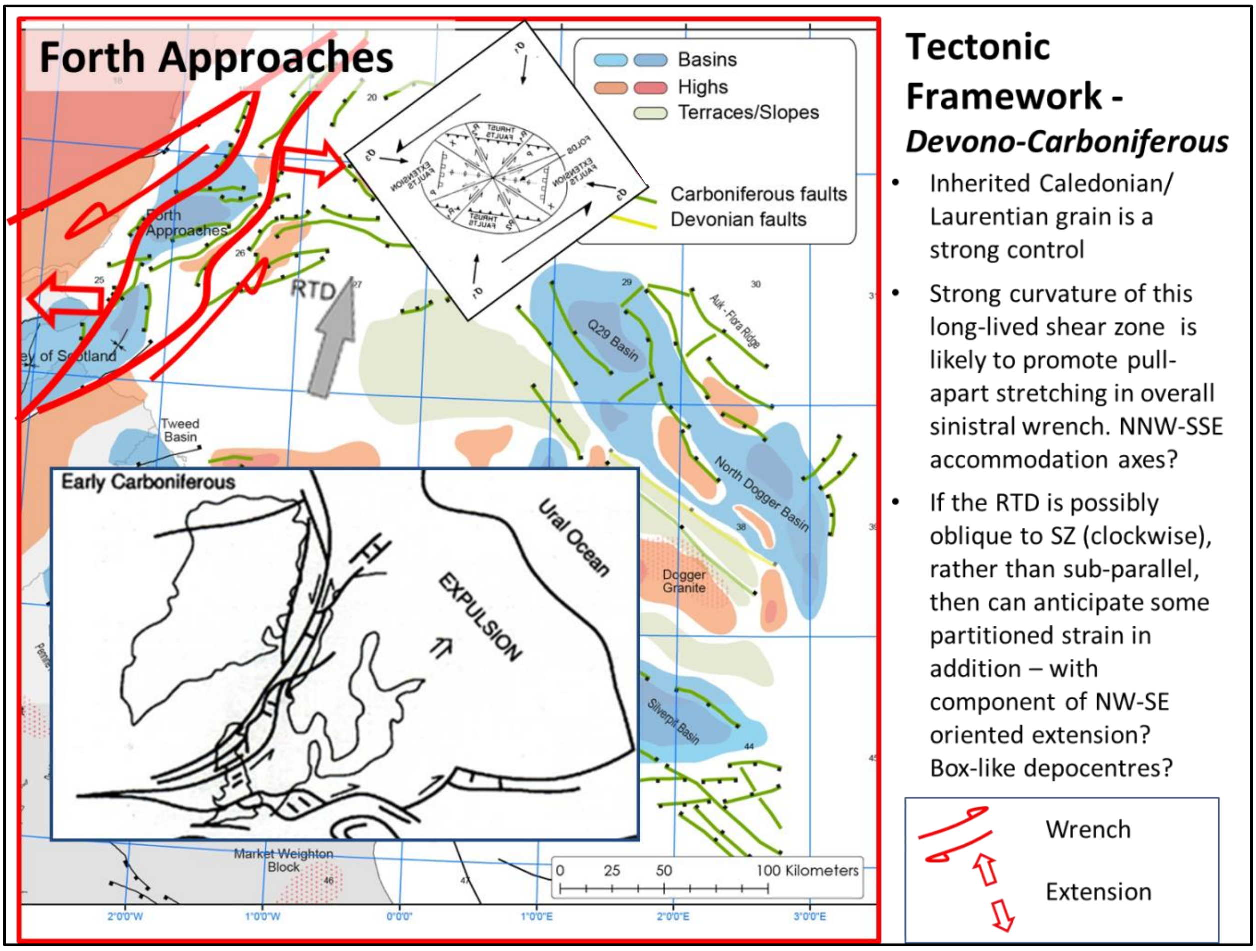


Figure 9. Preliminary assessment of anticipated wrench-dominated discontinuities in the Midland Valley of Scotland/Forth Approaches region.

In the Forth Approaches region and the Midland Valley of Scotland, the regional transport direction linked to Baltica translation was either close to, or slightly clockwise of, the Glen Glen/Walls Boundary/Storstrommen intra-Laurussia fault system throughout the late Devonian and much of the Carboniferous (cf. Coward, 1993; Dewey and Strachan, 2003).

On that basis we can expect to see sinistral wrench-dominated movements partitioned along the inherited Caledonian structures (e.g. the Great Glen, Highland Boundary and Southern Upland fault zones) in any detailed assessment of seismic and other data. The strong curvature of this system in the UK region probably promoted pull-apart stretching in the overall sinistral wrench, thus generating NNW-SSE oriented accommodation axes. Any contemporaneous partitioned component of NW-SE directed extension across this system (see inset arrows) would have promoted localised thickening patterns towards WSW-ENE oriented structures such as the Ochil Fault (*cf*. Rippon et al., 1996).

Local structural settings will likely constrain whichever of these is was allowable. In the relatively narrow confines of the Midland Valley buttressed by the Grampian Highland and Southern Upland terranes more easterly-directed extension might be anticipated, whereas more northerly-directed extension might feature in the less-constrained Forth Approaches region.

Slide 10: Wrench-dominated strain in the Forth Approaches/MVS area, 1b

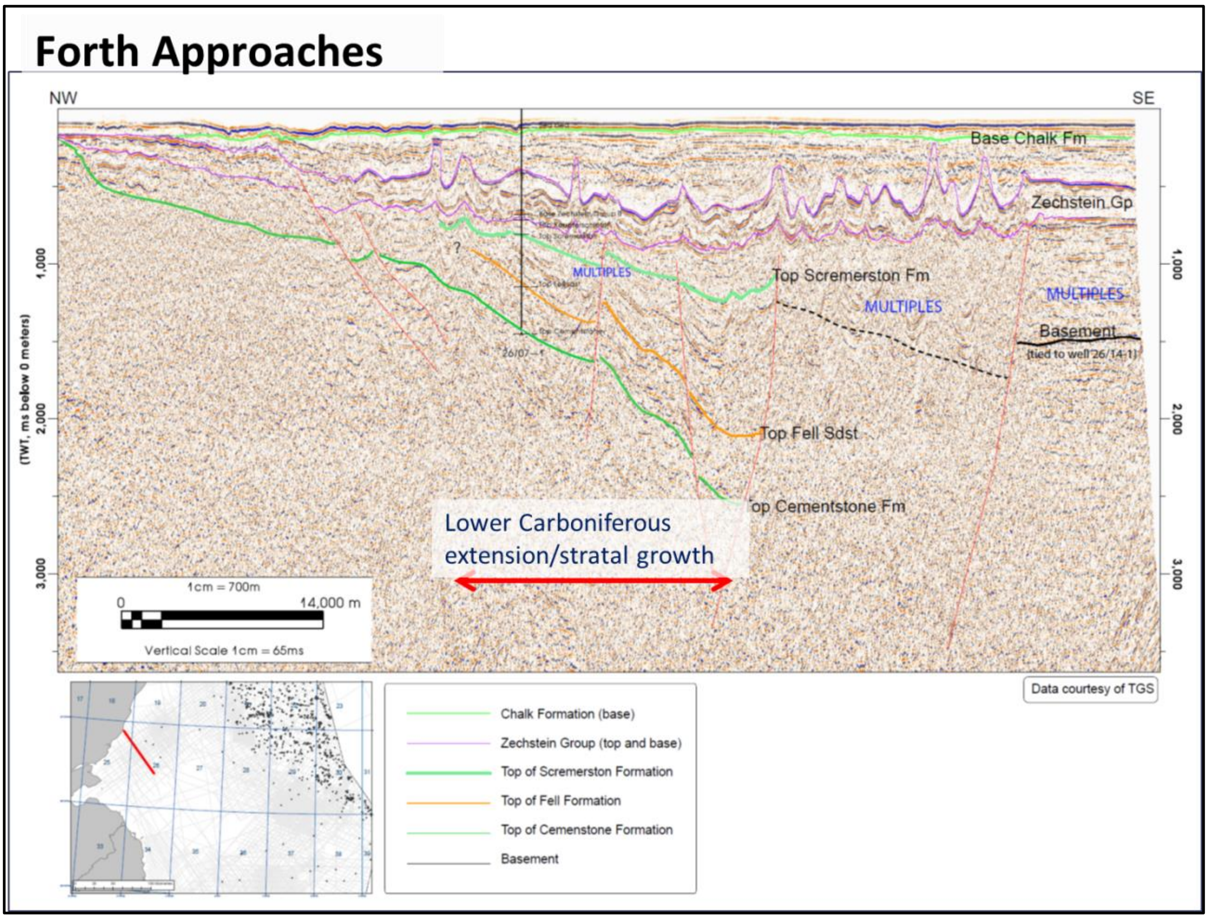


Figure 10. Preliminary assessment of NW-SE trending seismic line in the Forth Approaches region, showing prominent extension and stratal growth bound by steeping dipping (wrench?) discontinuities.

As an example, a preliminary assessment of the seismic line figured above (Fig. 10) lends support to a possible interpretation of extension and stratal growth where the bounding structures are steep and likely to have accommodated highly oblique strain. The preliminary interpretation shows marked stratal thickening towards the steeply-inclined faults recognised in the southern part of the seismic line interpretation. A detailed analysis of this seismic line is provided in Arsenikos et al. (2015).

Slide 11: End-Carboniferous Variscan encroachment

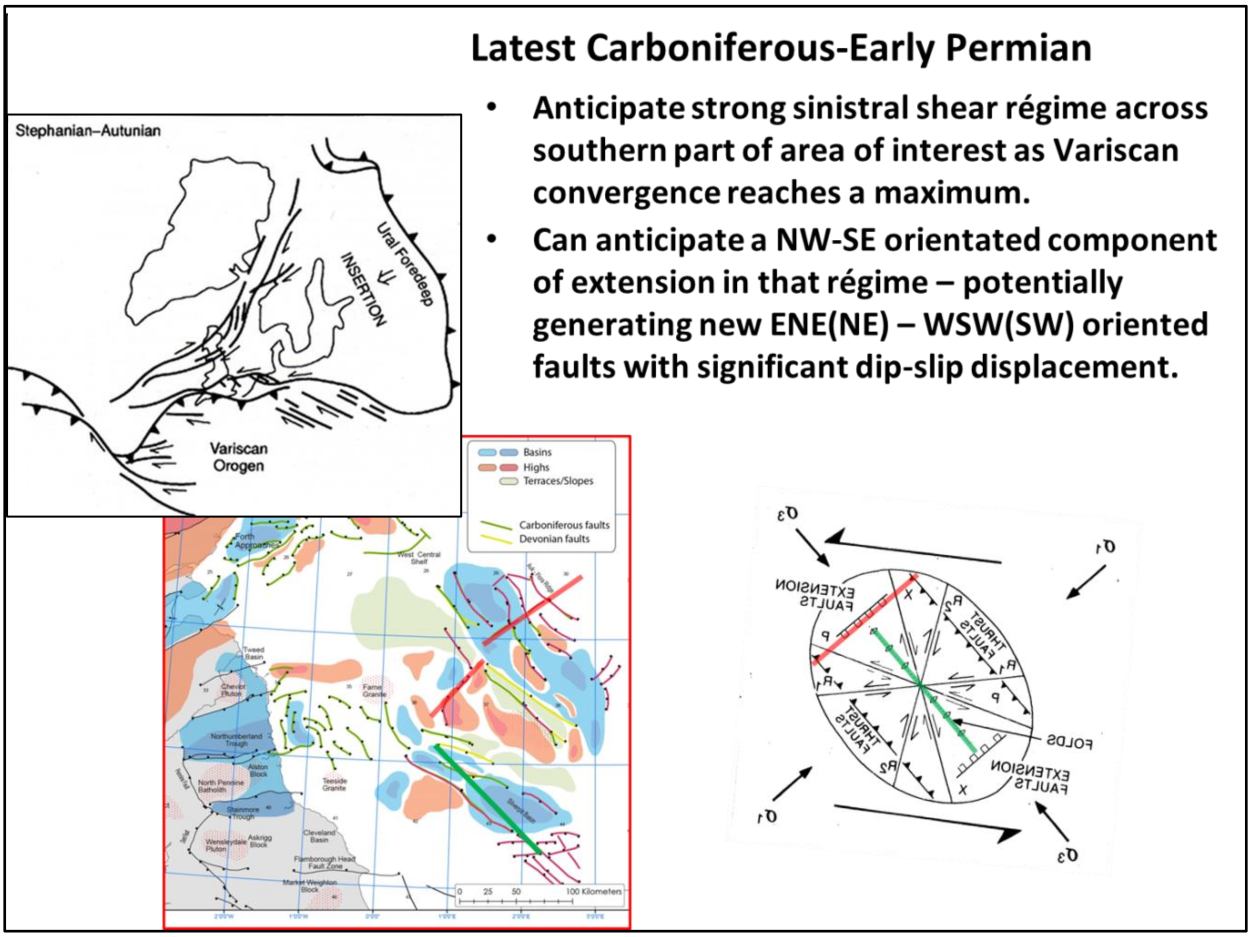


Figure 11. In latest-Carboniferous – Early Permian times we can anticipate a strong sinistral shear will be developed across southern part of area of interest, as Variscan convergence reaches a maximum. New ENE(NE) – WSW(SW) oriented faults with significant dip-slip displacement should be expected in such a regime (see purple highlight), given the likely NW-SE orientated component of extension.

As Baltica moved westwards in the late Carboniferous-early Permian, it resulted in the progressive northwards development of a strong sinistral shear régime across the southern part of the area of interest as Variscan convergence reached a maximum (Woodcock and Strachan, 2009).

It is likely that a NW-SE component of extension (*cf*. the sinistral strain ellipse above) was generated new cross-cutting NE(ENE)-SW(WSW) trending extensional faults in the latest Carboniferous-early Permian (see purple highlight above and Fig. 12).

NW-SE trending fold axes deforming the latest Carboniferous basin fill should be anticipated and are possibly represented by the Boldon Syncline of Co. Durham and related structures, and perhaps the Vale of Eden Syncline onshore, as well as the NW-SE trending compression structures observed in the Silverpit Basin and the Murdoch Ridge area – green highlight on North Sea in Fig. 11 above).

The NW-SE trending sinistral wrench faults active earlier in the Carboniferous might have experienced a measure of dextral oblique re-activation at this time.

Slide 12: Superimposed NE-SW trending faults

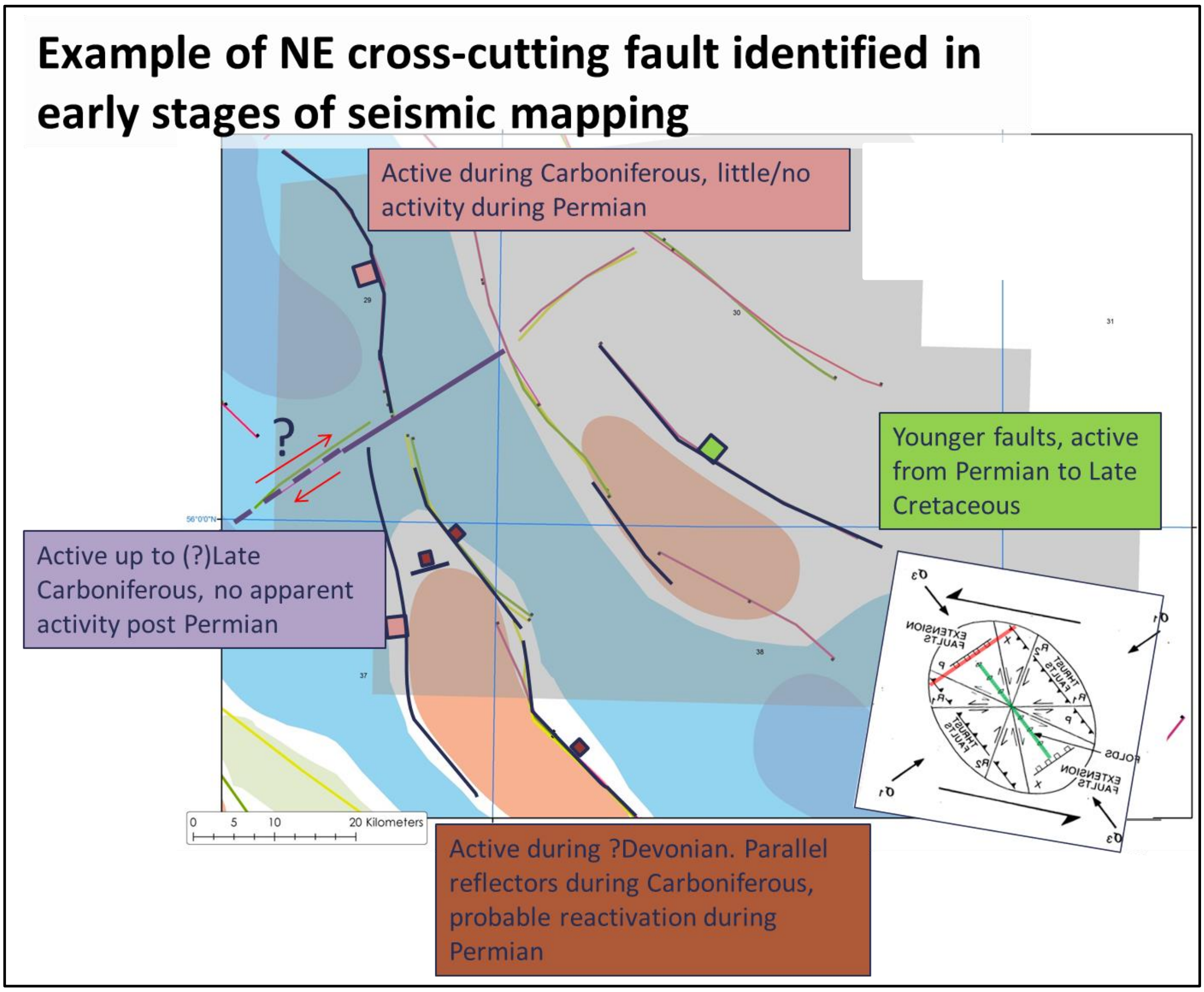
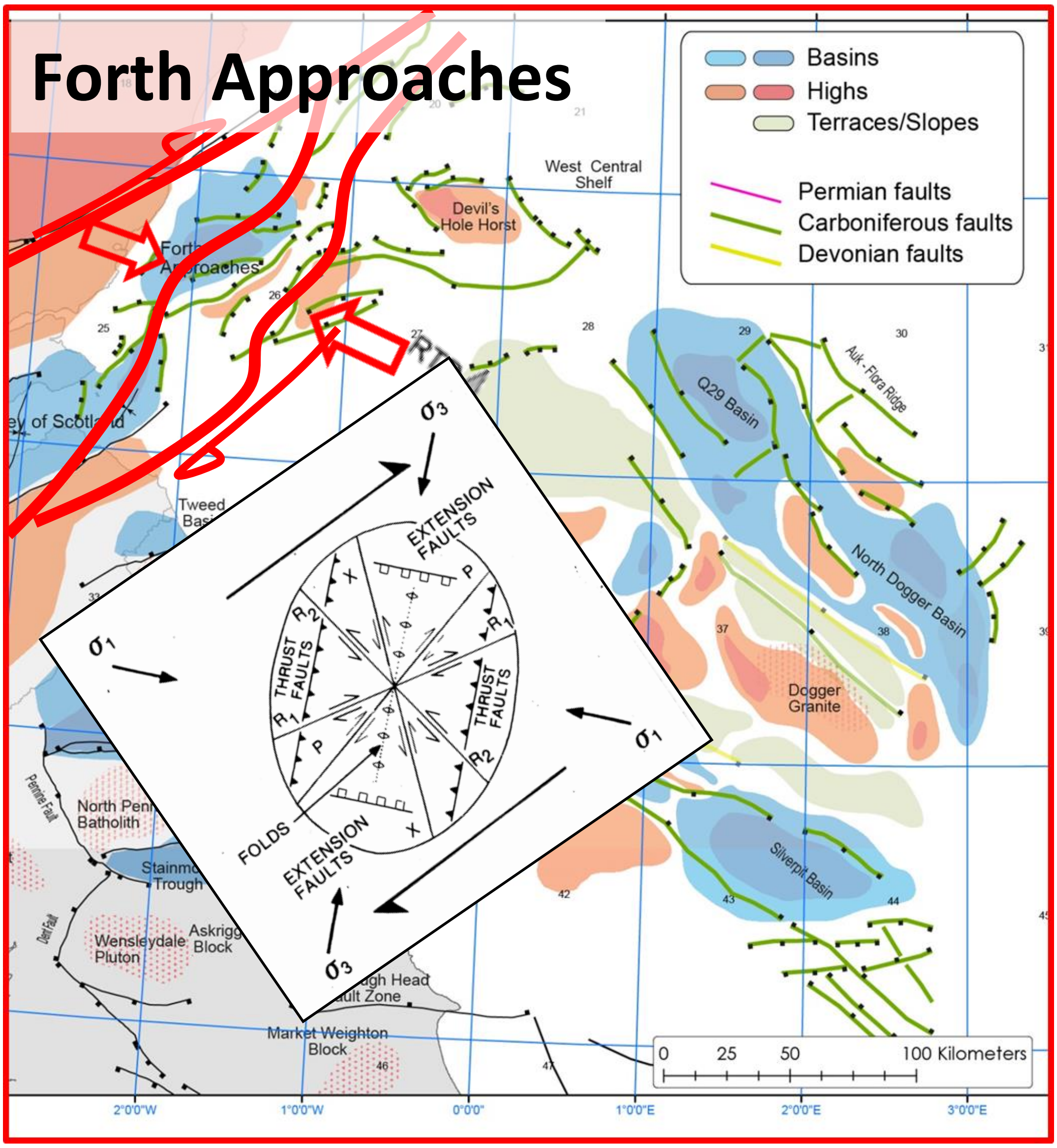


Figure 12. A preliminary assessment of new NE –SW oriented faults with significant dip-slip displacement (see purple highlight), identified in the early stages of the seismic mapping

As an example, a preliminary assessment of seismic mapping in the Central North Sea region demonstrates the cross-cutting superimposed style of the NE-SW trending late Carboniferous-Permian faults active in that region, cutting across earlier formed structures (see Arsenikos et al., 2015).

Slide 13: Dextral transpression in the Forth Approaches



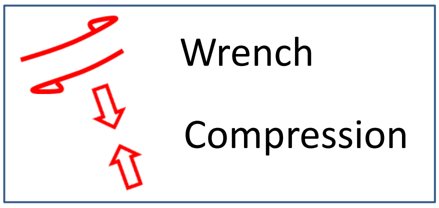


Figure 13a. Preliminary assessment of anticipated wrench-dominated discontinuities in the Midland Valley of Scotland/Forth Approaches region in the latest Carboniferous - Early Permian times. Dextral transpression by this timew will act to tighten and distort earlier-formed NNW-SSE axes of intra-basinal accommodation/ thickening.

During the latest Carboniferous to Permian the Forth Approaches/Midland Valley of Scotland region experienced strains consistent with overall dextral transpression (Underhill et al. 2008, and see Fig. 13a) which tightened and distorted earlier-formed NNW-SSE axes of intra-basinal accommodation/thickening. Such deformation is likely recorded in the distortion/deflection of Midlothian-Leven Syncline around the Pentland Fault/Pentlands block (see Fig. 13b).

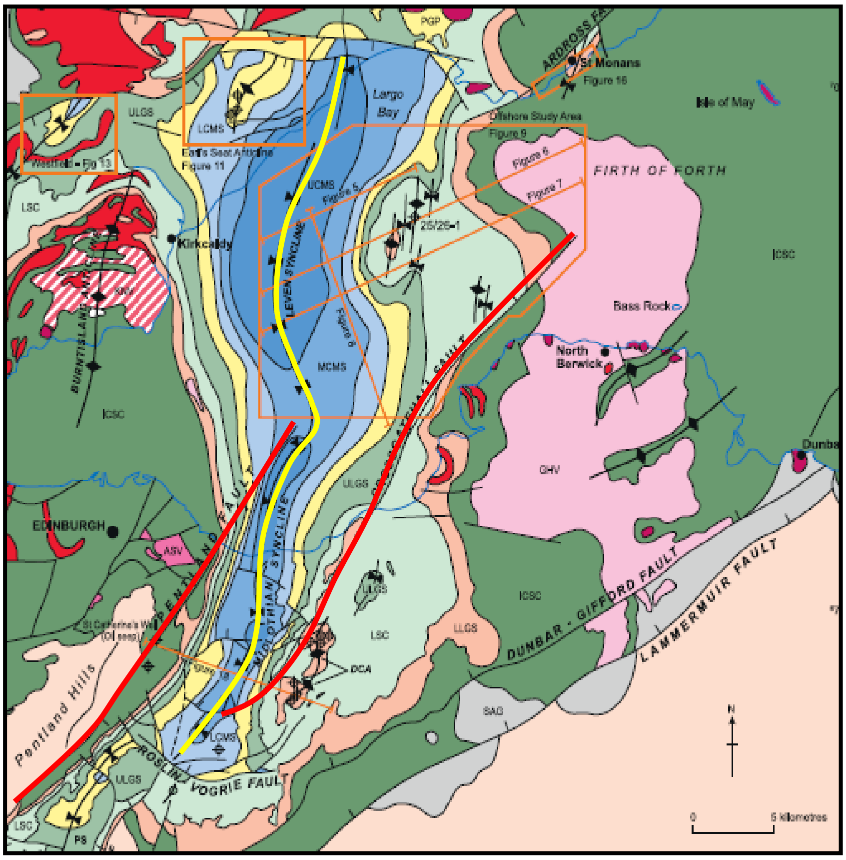


Figure 13b. Distortion of the Lothian Syncline (yellow highlight) around the Pentland Fault (red Highlight) and the Pentland Hills block of Devonian volcanic rocks. The Crossgatehall Fault is also highlighted (red), after Underhill et al., 2008. Reproduced with permission of Elsevier from Marine and Petroleum Geology.

Conclusions and lessons learned

- Pre-Lower Palaeozoic basement structures are a critical element in the tectonic framework for analysis of the Mid North Sea High and Forth Approaches project data.
- Granite batholiths and individual plutons are a likely additional strong influence in that framework.
- The framework of inherited pre-Upper Palaeozoic structures constrains patterns of strain partitioning, within a much larger-scale regional stress regime in the Upper Palaeozoic and early Mesozoic.
- Partitioning strain leads to the development of different tectonic signatures in adjacent compartments at the same time; extension-dominated vs. wrench-dominated domains.
- The patterns of domainal tectonics predicted by the strain partitioning model are supported by preliminary assessments of the interpreted seismic data.
- Detailed study at prospect level will further test the strain partitioning model and its impact on prospectivity.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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