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Tectonic synthesis and contextual setting for the Palaeozoic of the Moray Firth region, Orcadian Basin

Energy and Marine Geoscience Programme

Commissioned Report CR/16/039

Fault-bound Lower Devonian Sandstone, Dundarg Castle, New Aberdour. N-S faults bound westward-dipping sandstone that have an unconformable contact with Dalradian basement. Looking west.

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AG Leslie, AA Monaghan, S Arsenikos, M Quinn

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British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh, EH14 4AP

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Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB

Tel 028 9038 8462 Fax 028 9038 8461

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Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
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Requests and enquiries should be addressed to Alison Monaghan, 21CXRM Palaeozoic Project Leader, als@bgs.ac.uk.

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.

Rosie Fletcher (Chevron) is thanked for technical review of this report.

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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 Inner Moray Firth region, adjacent areas of the Orcadian Basin, and UK offshore regions 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., 2016; Kimbell & Williamson, 2016; Monaghan et al., 2016).

The pattern of Devonian and Carboniferous tectonics in the Moray Firth region will be strongly influenced by the underlying pattern of (N)NE-(S)SW tending Caledonian basement discontinuities transecting the region, in particular the expression of regional stress patterns along and across the trace of the Great Glen – Walls Boundary Fault Zone (GGFZ). Sinistral motion, on that very large-scale intra-Laurussian structure, is seen throughout most of the Upper Palaeozoic (Dewey and Strachan, 2003) but by the late Carboniferous, interaction of Baltica-Siberia across the Ural Sea foredeep had come into play, promoting dextral shear on the GGFZ (Coward, 1993; *cf*. Domeier and Torsvik, 2014).

In the Devono-Carboniferous, and under the influence of overall sinistral transcurrent motion on the GGFZ, E(SE)-W(NW) directed stretching should be anticipated in the Moray Firth region with N(NE)-S(SW) oriented extensional faults likely. Such structures would be similar in style to the patterns of faulting associated with the Devonian outliers observed onshore in Moray-Buchan, and also as described in the Helmsdale region (Underhill & Brodie, 1993). In addition to a strong 'basement' control from inherited Caledonian (N)NE to (S)SW features, there is likely also to be underlying control from any Caledonian plutonic complexes present (Kimbell & Williamson, 2016).

The present day pattern of Moray Firth faulting, established depocentres and intra-basinal highs, comprises a strong Mesozoic pattern of tectonic features (e.g. Andrews et al., 1990; Underhill 1991; Thomson and Underhill 1993) superimposed on older ('post-Caledonian') tectonic patterns established in the Late Carboniferous, most likely in response to the south-westwards movement of Baltica relative to Laurussia at this time (*cf.* Coward, 1993). Those regional stresses generated dextral shear in the GGFZ, coincident with strongly partitioned strain in the North Sea basin interior (Leslie et al. 2015). From Late Carboniferous times, N(NW) – S(SE) directed extension in the Inner Moray Firth region generated W(SW)-E(NE) trending extensional faults (e.g. the Banff and Wick faults).

This stress régime sets in place the framework of highs and lows preceding any Permian uplift and younger tectonics as the switch to the earliest Atlantic-opening stresses occurred. WNW-ESE directed extension, observed and dated in the Pentland Firth area (267+/-3 Ma, Dichiarante et al. 2015), will likely generate increasingly oblique (sinistral?) wrench on the Wick/Banff Faults from this time. Dip-slip components of movement are likely on the older (N)NE- (S)SW-trending structures inherited from the Caledonian, e.g. the Helmsdale/Strathconnon Faults, and perhaps the GGFZ; the latter may be too steep and fundamental a structure to actively respond in pure extension at this time.

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 only to provide a summary tectonic outline and contextual setting against which offshore seismic and well data relating to the Devono-Carboniferous evolution of the Moray Firth region, adjacent areas of the Orcadian Basin, and adjacent UK onshore region can be assessed. 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., 2016; Kimbell & Williamson, 2016; Monaghan et al., 2016). This report does not of itself set out to provide a full structural analysis of that data, simply to open up a number of possible scenarios for consideration.

The pattern of Devonian and Carboniferous tectonics in the Moray Firth region will be strongly influenced by the expression of regional (up to plate)-scale stress patterns along and across the trace of the Great Glen – Walls Boundary Fault Zone (GGFZ; Dewey and Strachan, 2003) and many other pre-existing Caledonian or Tornquist structures preserved in the older rocks of the region. By the late Carboniferous, interaction of Baltica-Siberia across the Ural Sea foredeep had come into play promoting dextral shear on the GGFZ (Coward, 1993 and cf. Domeier and Torsvik, 2014); the present day pattern of Moray Firth faulting, established depocentres and intra-basinal highs becomes apparent from this time,

Earliest Atlantic-opening stresses in the Permian generated WNW-ESE directed extension (267+/-3 Ma, Dichiarante et al. 2015), and would likely promote increasingly oblique wrench on the Wick/Banff Faults from this time onwards.

Slide 1: Tectonic setting for the UK and North Sea

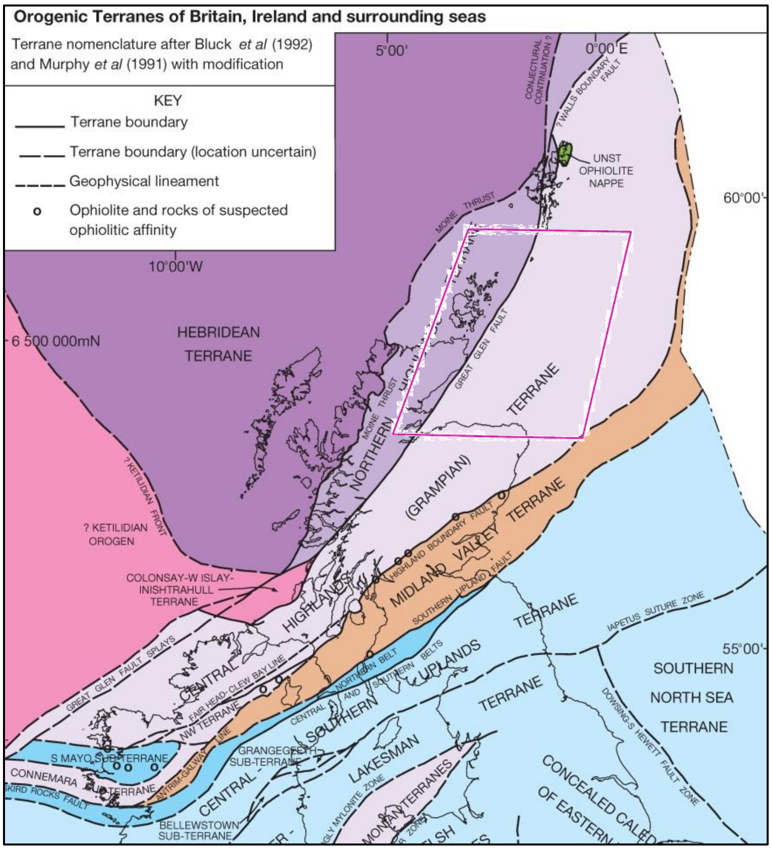

Figure 1. The essential elements of pre-Upper Palaeozoic tectonic inheritance for the UK and surrounding areas are well understood in general, including fragments of Iapetan ophiolite exposed in the Shetland Isles. The pattern of underlying Caledonian trends, in particular the GGFZ, will be a significant control on the subsequent patterns of Upper Palaeozoic structural development in the Moray Firth Region. The project area of Interest (AOI) is shown as the heavy outline. From UK Tectonic Map (BGS, 1996).

The tectonic setting for the Moray Firth region is reasonably well known in both UK and continental European terms, (see for example the UK Tectonic Map, BGS 1996; Figure1). The tectonic framework is typically presented in terms of the expression of regional (up to plate)-scale stress patterns along and across the trace of the Great Glen – Walls Boundary Fault Zone (GGFZ) and any other pre-existing Caledonian structures preserved in older (pre-Devono-Carboniferous) strata. Sinistral motion on this very large scale structure is seen throughout most of the Upper Palaeozoic (Dewey and Strachan, 2003) but by the late Carboniferous, interaction of Baltica-Siberia across the Ural Sea foredeep had come into play promoting dextral shear on the GGFZ (Coward, 1993; *cf*. Domeier and Torsvik, 2014).

Slide 2: Plate-scale context

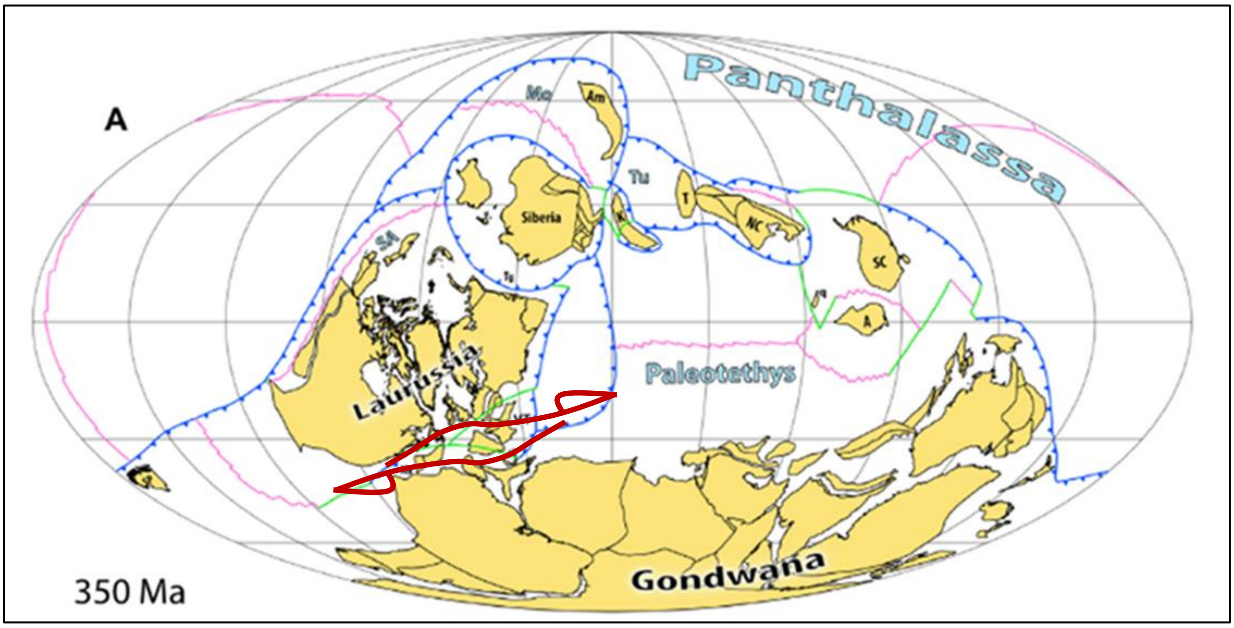

Figure 2. Plate-scale setting in the Devono-Carboniferous - snapshot at 350 Ma (after Domeier and Torsvik, 2014). Gondwana convergence with Laurussia is dextral at this time as shown by the red arrows superimposed; the UK lies immediately adjacent to this plate-scale oblique convergence zone. Reproduced 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 (Figure 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 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 Moray Firth region should therefore start from this perspective, paying particular attention to the expression of the regional stresses along and across the region transected by the GGFZ and its Caledonian continuation in East Greenland, the Storstrømmen shear zone.

Note that the Great Glen/Walls Boundary/Storstrømmen structure that originally developed between Laurentia and Baltica in later Caledonian (Siluro-Devonian) times (Dewey and Strachan, 2003, and Figure 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)

In late Devonian - early Carboniferous times, the Moray Firth region 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 Strachan 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 (red arrow on Fig. 3a) and continued thus until the latest Carboniferous when the regional stresses would have switched to dextral transpression as the movement of Baltica reversed direction (Fig. 3b, *cf*. Coward, 1993; Maynard et al., 1997).

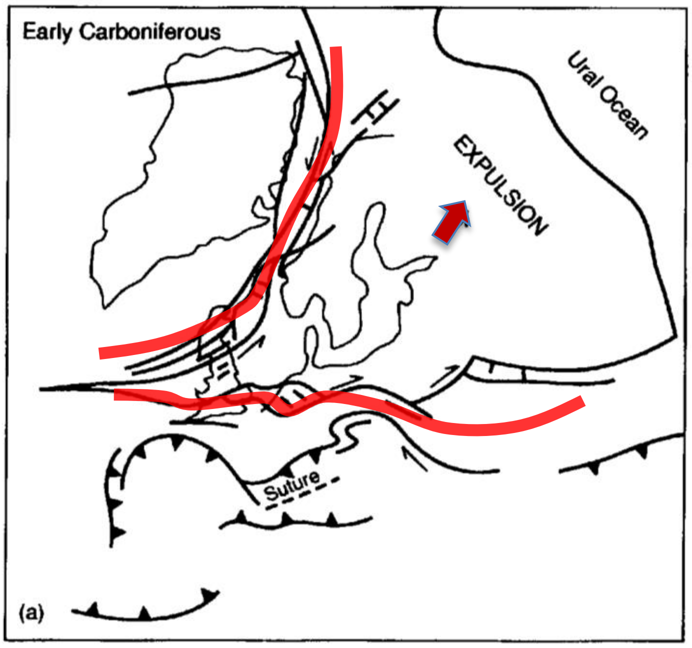

Figure 3. Plate-tectonic reconstructions for Greenland and Europe after Coward (1993) – Carboniferous to Early Permian. Reproduced with permission of the Geological Society, London.

Figure 3a. 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 – Storstrømmen shear zone active as an intra-Laurussia structure farther north.

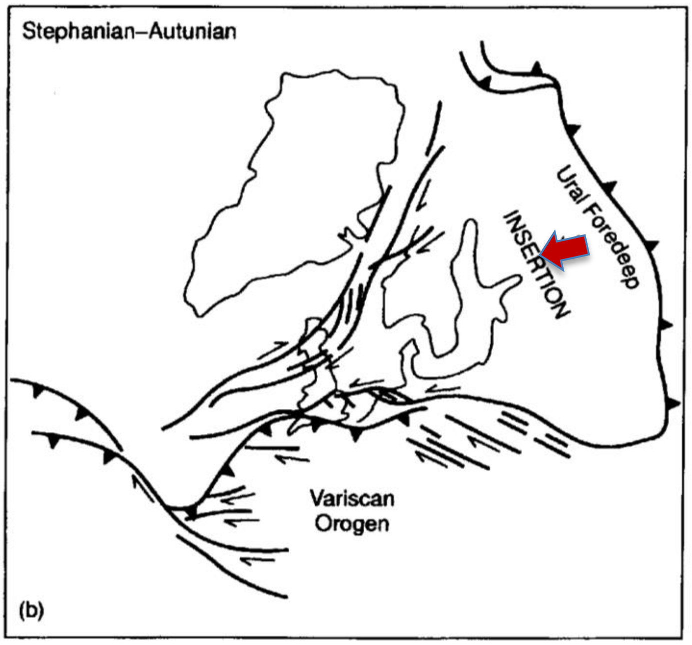

Figure 3b. Interaction of Baltica-Siberia across the Ural Sea then comes into play, driving eastward movement of Baltica in the late Carboniferous (*cf*. Domeier and Torsvik, 2014).

It should be noted that both the Coward (1993, Fig. 3c) 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 (Figure 3c). The Moray Firth region lies on the periphery of this system and Carboniferous deposition there may be significantly influenced by more parochial (Scottish Highlands) sources of detritus.

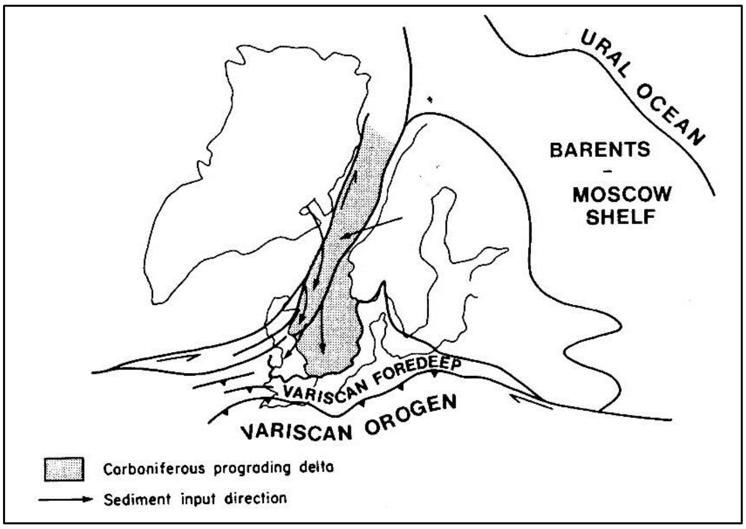

Figure 3c. The plate-scale reconstruction and developing rift model of Coward (1993), readily accommodates the middle Mississippian palaeo-topography and progradational delta sediment distribution systems identified in the Mid North High Sea area of interest.

Slide 4: Late Carboniferous tectonic framework

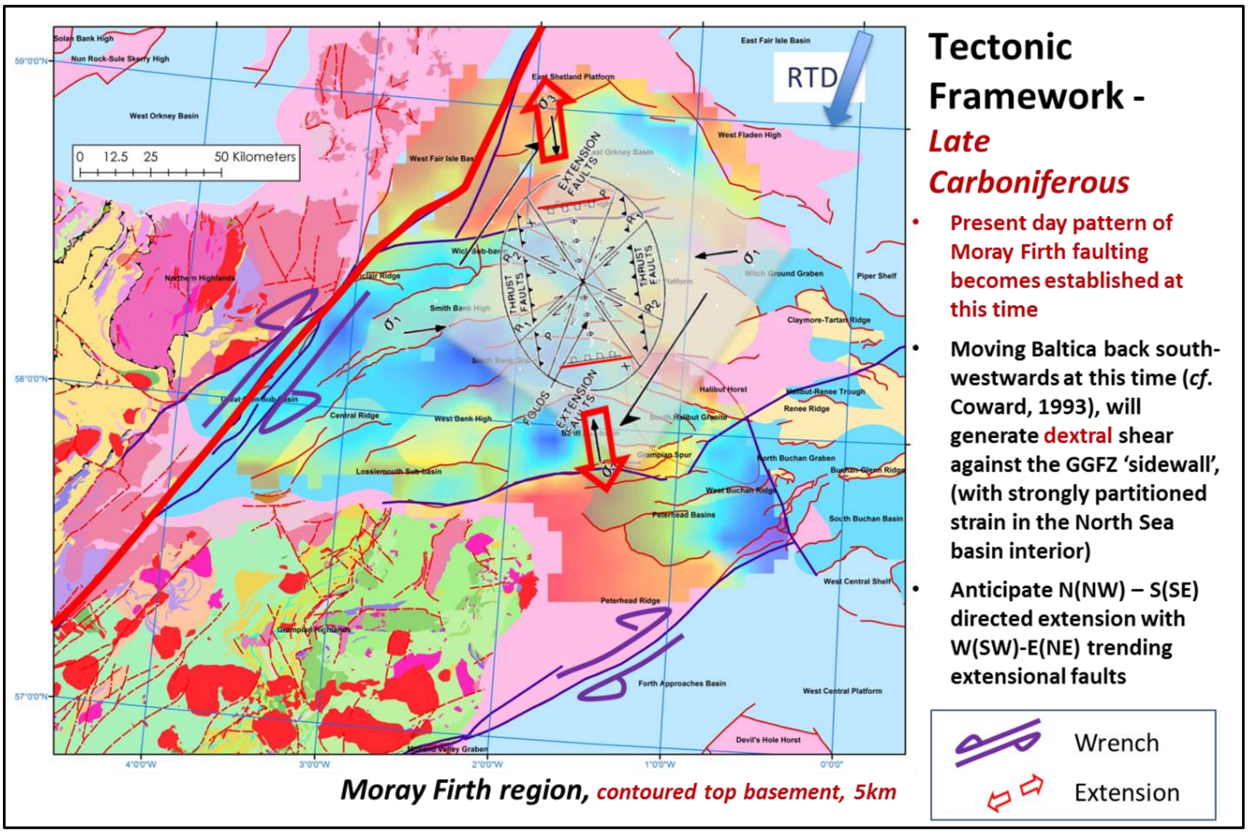

Figure 4a. The pattern and geometry of depocentres (blue shading), terraces (yellow shading) and structural highs (red shading) present in the Moray Firth region is kinematically consistent (see strain ellipse superimposed) with the NNW-SSE oriented maximum extension direction generated by dextral shear on the GGFZ (purple arrows). The Banff and Wick faults are aligned with the expected direction of normal faulting at this time.

In the late Carboniferous, the geology of the Moray Firth region becomes dominated by patterns of ENE-WSW trending major faults (Fig 4a) that effectively delineate the observed distribution of depocentres and (intra-)basinal highs at this time (Fig 4b, *cf.* Arsenikos et al., 2016). The ENE-WSW trending pattern of major faults (e.g. Banff and Wick faults) is entirely consistent with the maximum stretching direction at this time in the late Carboniferous when the GGFZ experienced dextral movement of the order of 6 -8 km, (e.g. Speight and Mitchell 1979). The challenge is then to determine whether or not elements of an older Devono-Carboniferous tectonic framework can be detected in the Moray Firth region beneath this strong tectonic overprint (but see Arsenikos et al., 2016).

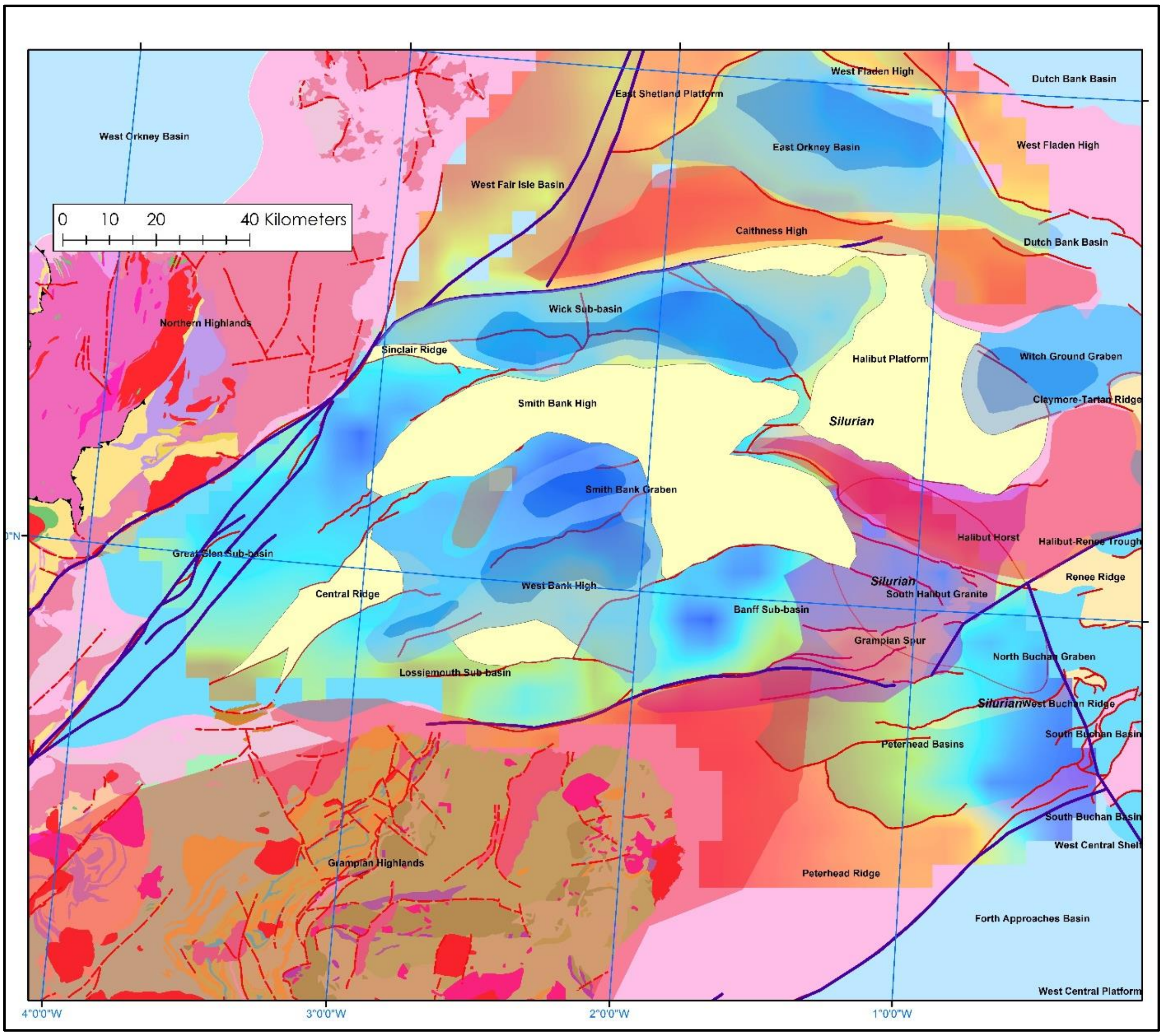

Figure 4b. The pattern of major Devono-Carboniferous structural elements in the Moray Firth region identified from the present data set (*cf*. Arsenikos et al. 2016); highs in red, terraces in pale yellow; basins in blue and sub-Permian basement on the Grampian Spur in purple. Principal faults including the Wick and Banff structures and elements of the Great Glen Fault system are highlighted in heavy blue lines. The onshore geology is taken from the BGS©NERC DigMap 1: 625 000 geology.

Slide 5: Permian and younger tectonic framework

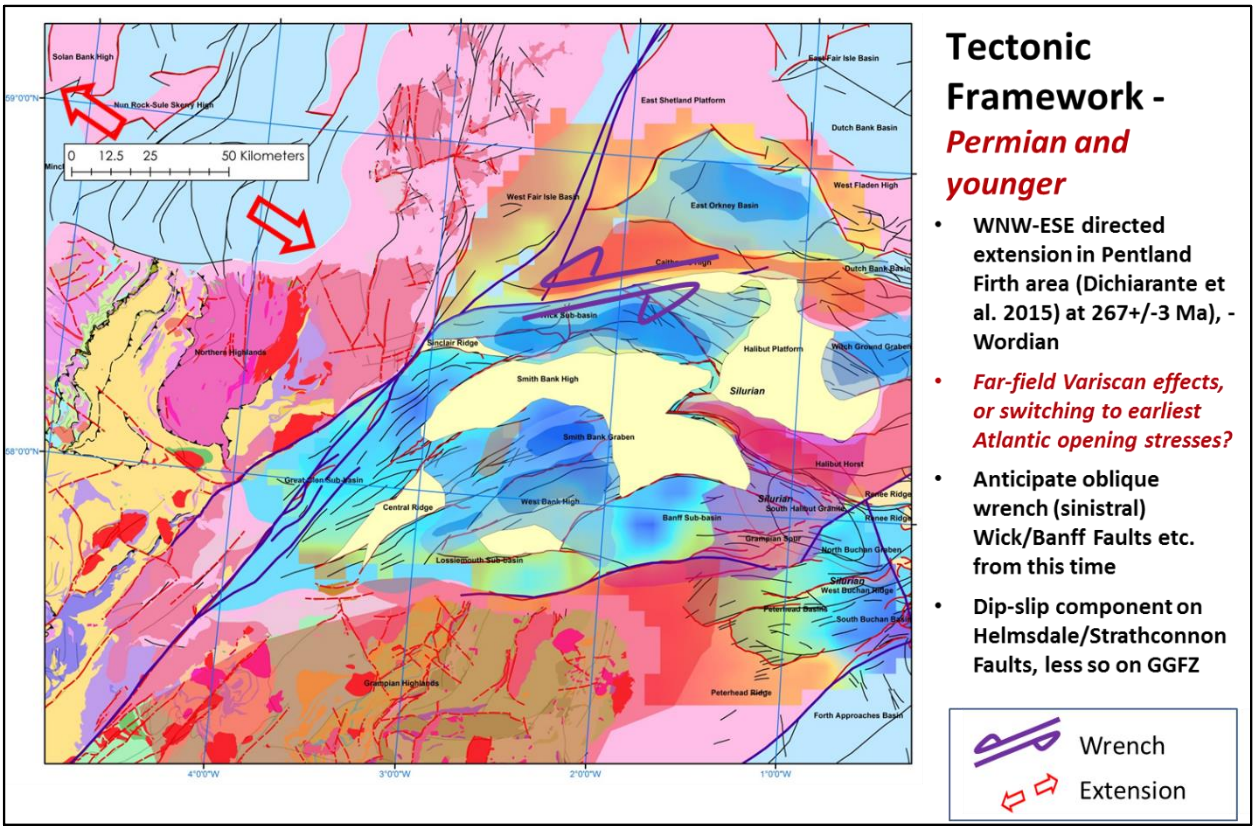

Figure 5. Observed and dated WNW-ESE directed extension in the Permian (red arrows, Dichiarante et al. 2015) will re-activate structures such as the Banff and Wick faults in sinistral oblique slip (purple arrows). The pattern of major Permian and younger structural elements in the Moray Firth region identified from the present data set (*cf*. Arsenikos et al. 2016); highs in red, terraces in pale yellow; basins in blue and sub-Permian basement on the Grampian Spur in purple. Principal faults including the Wick and Banff structures and elements of the Great Glen Fault system are highlighted in heavy blue lines; other faults offshore in finer linework. The onshore geology is taken from the BGS©NERC DigMap 1: 625 000 geology.

Dichiarante et al. (2015) have dated syn-tectonic mineralisation in the Wick region and documented an important phase of WNW-ESE directed extension (red arrows on Fig. 5) in the Pentland Firth area in Wordian time (c. 267 Ma). With the onset of what is likely to be an Atlantic-opening regional stress régime, important ENE-WSW trending faults structures in the Moray Firth region are likely to have been re-activated in (sinistral) oblique slip (purple arrows on Fig. 5), further emphasizing the current tectonic framework in the region. The extension observed and dated by Dichiarante et al. (2015) would also be geometrically consistent with far field Variscan stresses at this time (sinistral oblique convergence *cf*. Fig. 3b and Leslie et al. 2015); this scenario though perhaps less likely in the Moray Firth than the expression of Atlantic-opening effects should not be ruled out entirely.

Slide 6: Devono-Carboniferous tectonic framework

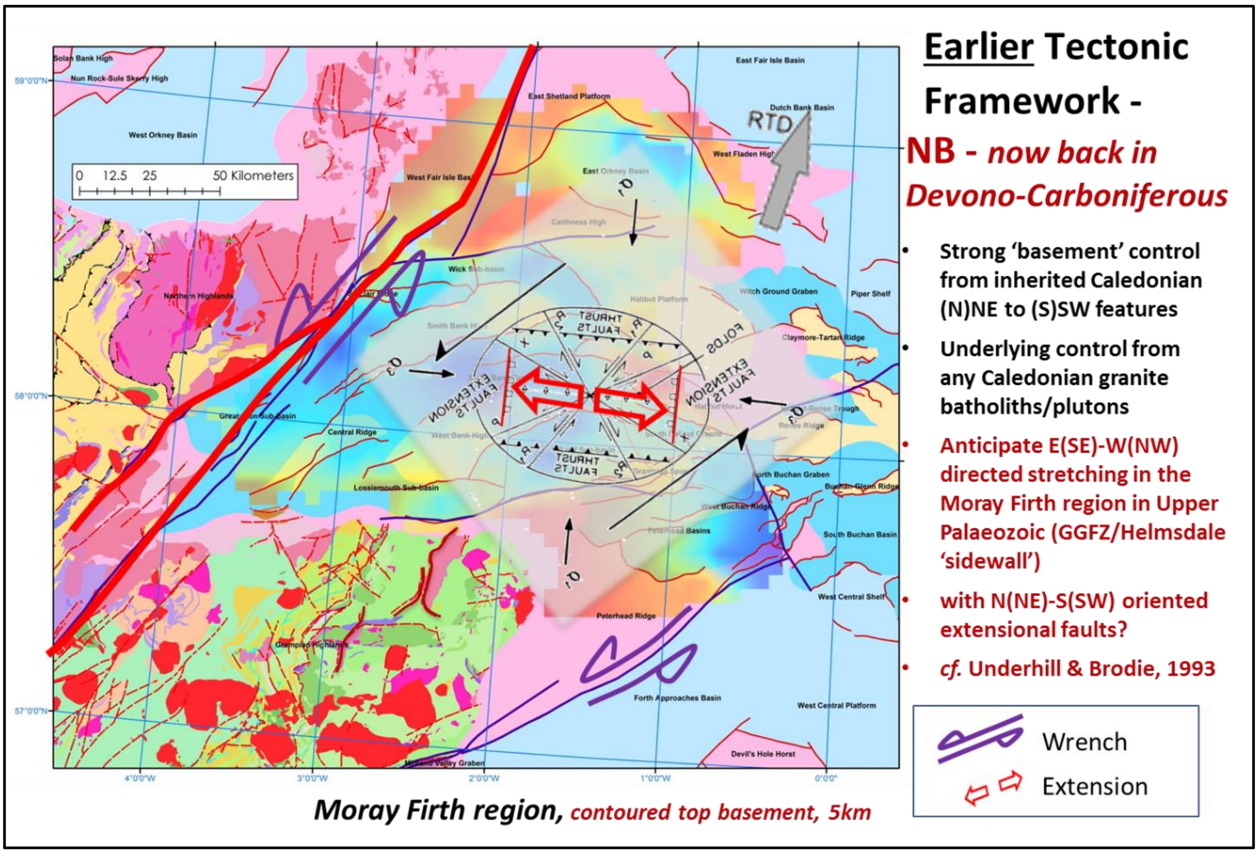

Figure 6. In post-Caledonian Devono-Carboniferous time, the GGFZ behaved as a sinistral strike-slip structure (Dewey and Strachan 2003), likewise the Highland Boundary Fault zone (purple arrows). The expected pattern of related fault structures is demonstrated in the strain ellipse superimposed, reversed to show sinistral shear patterns of discontinuities; a W(NW)-E(SE) stretching régime should be anticipated with broadly N-S oriented patterns of normal faults. The pattern of major structural elements in the Moray Firth region identified from the present data set (*cf*. Arsenikos et al. 2016); highs in red, terraces in pale yellow; basins in blue. Principal faults including the Wick and Banff structures and elements of the Highland Boundary Fault system are highlighted in heavy blue lines; other faults offshore in finer linework. The Great Glen Fault System (GGFZ) is highlighted in the heavy red line. The onshore geology is taken from the BGS©NERC DigMap 1: 625 000 geology.

If we now attempt to look beneath the latest Carboniferous to Mesozoic tectonic framework of the Moray Firth region, the pattern of Devonian and Carboniferous tectonics in the Moray Firth region will have been very strongly influenced by the underlying pattern of (N)NE-(S)SW trending Caledonian basement discontinuities transecting the region, in particular the expression of regional stress patterns along and across the trace of the Great Glen – Walls Boundary Fault Zone (GGFZ) (Figure 6).

In the Devono-Carboniferous, and under the influence of the then active overall sinistral transcurrent motion on the GGFZ (Dewey and Strachan, 2003), E(SE)-W(NW) directed stretching should be anticipated in the Moray Firth region with N(NE)-S(SW) oriented extensional faults also likely. Such structures would be similar in style to the patterns of faulting associated with the Devonian outliers observed onshore in Moray- Buchan (red highlights onshore on Figure 6), and as also described in the Helmsdale region by Underhill & Brodie (1993). In addition to a strong 'basement' control from inherited Caledonian (N)NE to (S)SW features, there is likely also to be underlying control from any Caledonian plutonic complexes present (Kimbell & Williamson, 2016). Note that the north-easterly extension of the Highland Boundary Fault zone is not known with certainty in any current dataset and can be interpreted in various ways; one possible scenario suggested by the lead author is shown here (Figure 6).

The present day pattern of Moray Firth faulting, established depocentres and intra-basinal highs, is thus superimposed on the older ('post-Caledonian') tectonic patterns in the Late Carboniferous, most likely in response to the south-westwards movement of Baltica relative to Laurussia at this time (Fig. 3b and *cf*. Coward, 1993).

Slide 7: Evidence for broadly N-S discontinuities in the Devono-Carboniferous

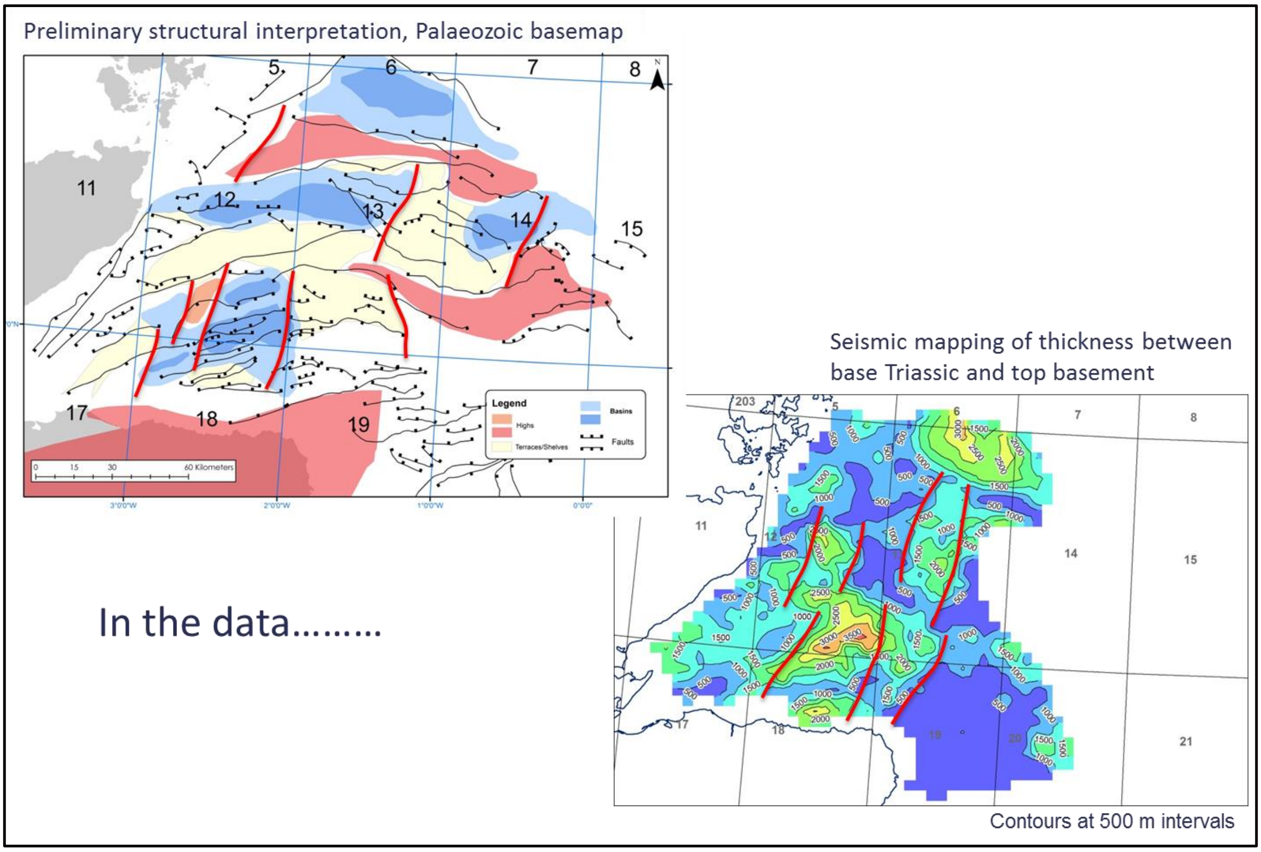

Figure 7. A preliminary assessment of broadly N-S trending fault-related discontinuities in the Moray Firth region from seismic data, and interpreted to be possibly of upper Palaeozoic age. The strong pattern of latest Palaeozoic to Mesozoic ENE-WSW trending faulting superimposed on this older framework makes clear delineation of this suspected trend challenging.

As an example, a preliminary structural assessment of the seismic data for the Moray Firth region lends support to a possible interpretation of broadly N-S oriented discontinuities that may indicate faulting in the Devono-Carboniferous (Figure 7). The strong patterns of ENE-WSW faulting developed from the late Carboniferous onwards does though mask these possible structures and makes their clear delineation difficult.

Conclusions and lessons learned

- Pre-Lower Palaeozoic basement structures, and basement blocks, will strongly influence tectonic development in the Moray Firth region of the Orcadian Basin.

- Granite batholiths and individual plutons are a likely additional strong influence in that framework (for example in the Inner Moray Firth, and in and around the Grampian High and Halibut Horst, *cf.* Kimbell and Williamson, 2016).

- The Great Glen/Walls Boundary Fault Zone forms a well-defined sidewall feature to the Moray Firth region, accommodating sinistral, and then dextral, shear in the Upper Palaeozoic (e.g. Dewey and Strachan, 2003; Speight and Mitchell, 1979; Underhill and Brodie, 1993).

- Devono-Carboniferous extension can be anticipated to have been expressed on broadly N-S faults.

- The present pattern of (intra-)basinal and depocentres in the Inner Moray Firth region will become well-established from late Carboniferous times onwards (*cf.* Arsenikos et al. 2016).

- Increasingly oblique (sinistral) movement is likely on ENE-WSW trending faults such as the Wick and Banff faults from the mid-Permian onwards.

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