Carboniferous petroleum systems beneath the Central North Sea

1. Abstract

Interpretation of recent long-offset seismic data augmented by potential field modelling has revealed a Devono-Carboniferous basin architecture beneath the Central North Sea that exhibits many features in common with the contemporary basins of northern England and southern Scotland (Milton-Worssell *et al*. in press).

Potential source rock intervals within Dinantian and Westphalian-age coal measures remote from the traditional Central Graben Jurassic source kitchen are confirmed by deep Central North Sea wells. The maturity of these potential source rocks is supported by the occurrence of prominent gas chimneys in the Mesozoic and Tertiary strata of southern Quadrant 29, up to 50 km south-west of the Jurassic source kitchen (Hay *et al*. 2005).

2. Middle Devonian to Lower Carboniferous basin architecture

Seismic interpretation has provided indications that many of the basement controls that defined the architecture of the onshore UK Lower Carboniferous basins operated across much of the UK Central North Sea also (see section 5). In the south-east Central North Sea (Fig. 1), Mid North Sea High structural elements have been interpreted that are comparable with the Askrigg Block and Stainmore Trough. The up-thrust Auk-Flora Ridge intra-basinal basement block resembles the Pentland Hills inlier within the Midland Valley of Scotland and the Cross Fell inlier in northern England.

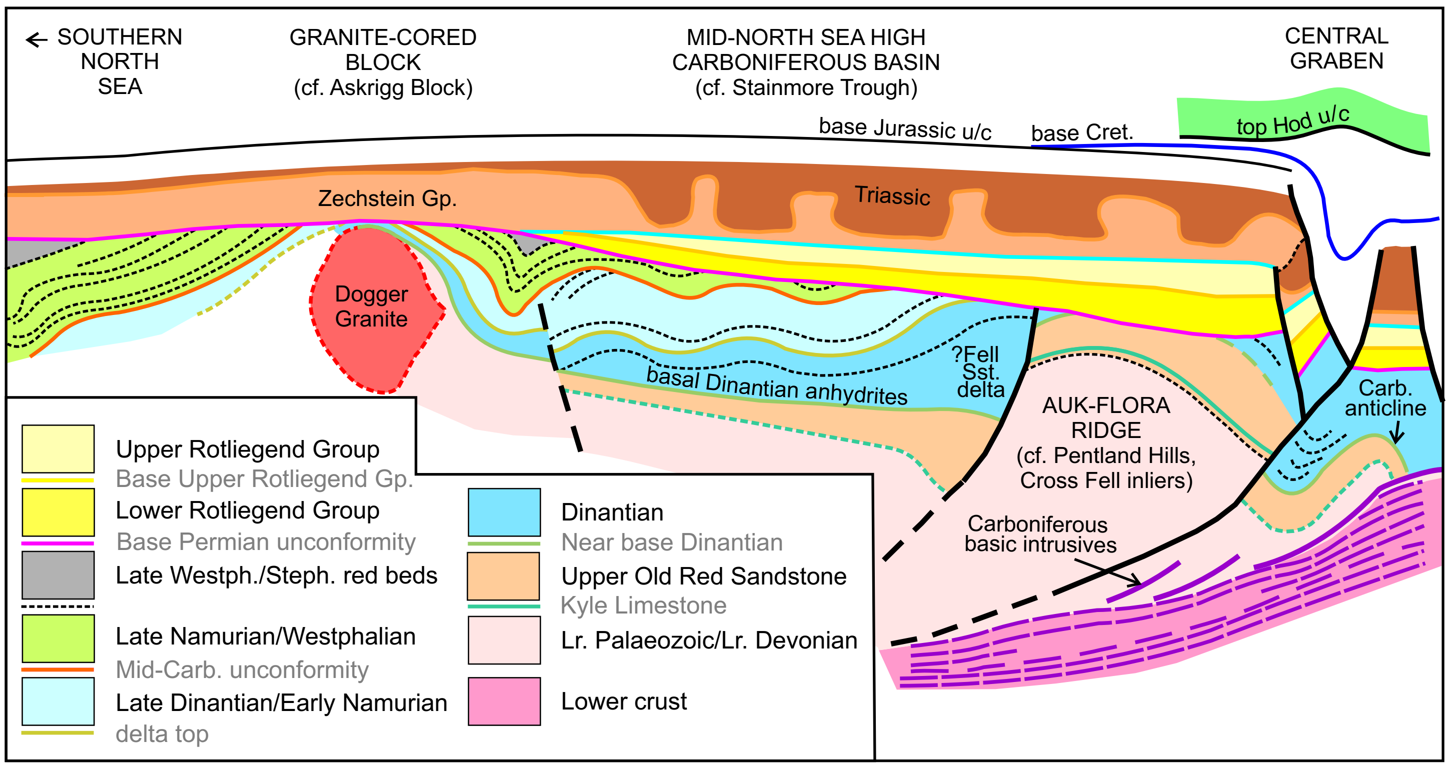
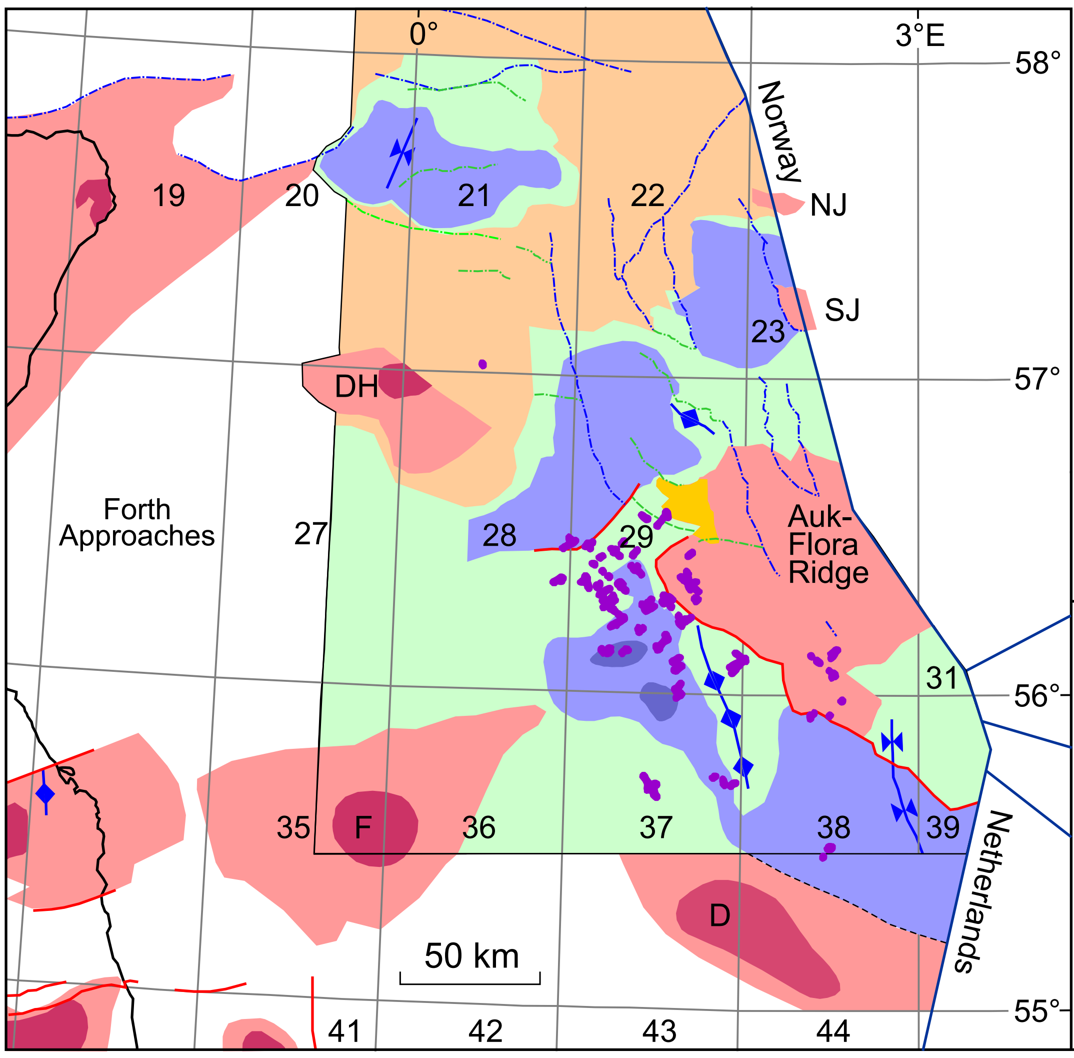


Fig. 1 Schematic profile showing generalised structural and stratigraphic relationships across the Mid North Sea High, from south of the Dogger Block to the Central Graben. The Mid North Sea High Carboniferous basin includes coal-measure source-rock intervals equivalent to those in the Scremerston Coal Group of northern England.



Preliminary results of seismic interpretation augmented by potential field modelling are presented in Fig. 2. In addition to Lower Carboniferous basins proven by drilling on the eastern Mid North Sea High and in northern Quadrant 21, undrilled Lower Carboniferous basins have also been interpreted in Quadrants 28 & 29. These are the regions that are the most likely to contain significant volumes of coal-measure source rocks within the sub-Permian section. The Quadrant 29 basin occurs adjacent to a region of numerous gas chimneys within the post-Permian section inferred from older 2D seismic data such as that illustrated in Figure 3 - it is the most likely source kitchen for this gas.

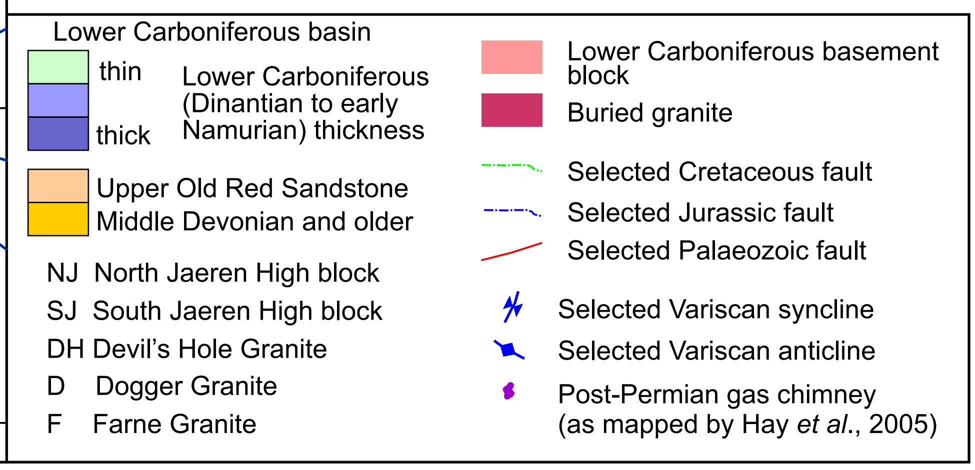


Fig. 2 Lower Carboniferous basin configuration in the Central North Sea, based on the seismic interpretation

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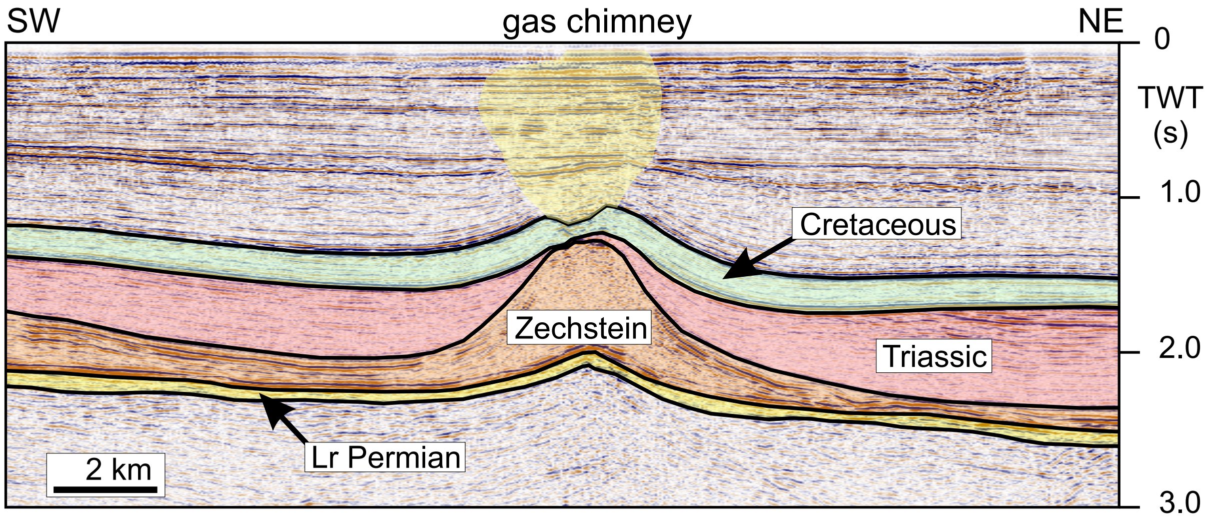
Fig. 3 Example of gas chimney above Zechstein salt diapir in Quadrant 29.
Seismic data courtesy of WesternGeco



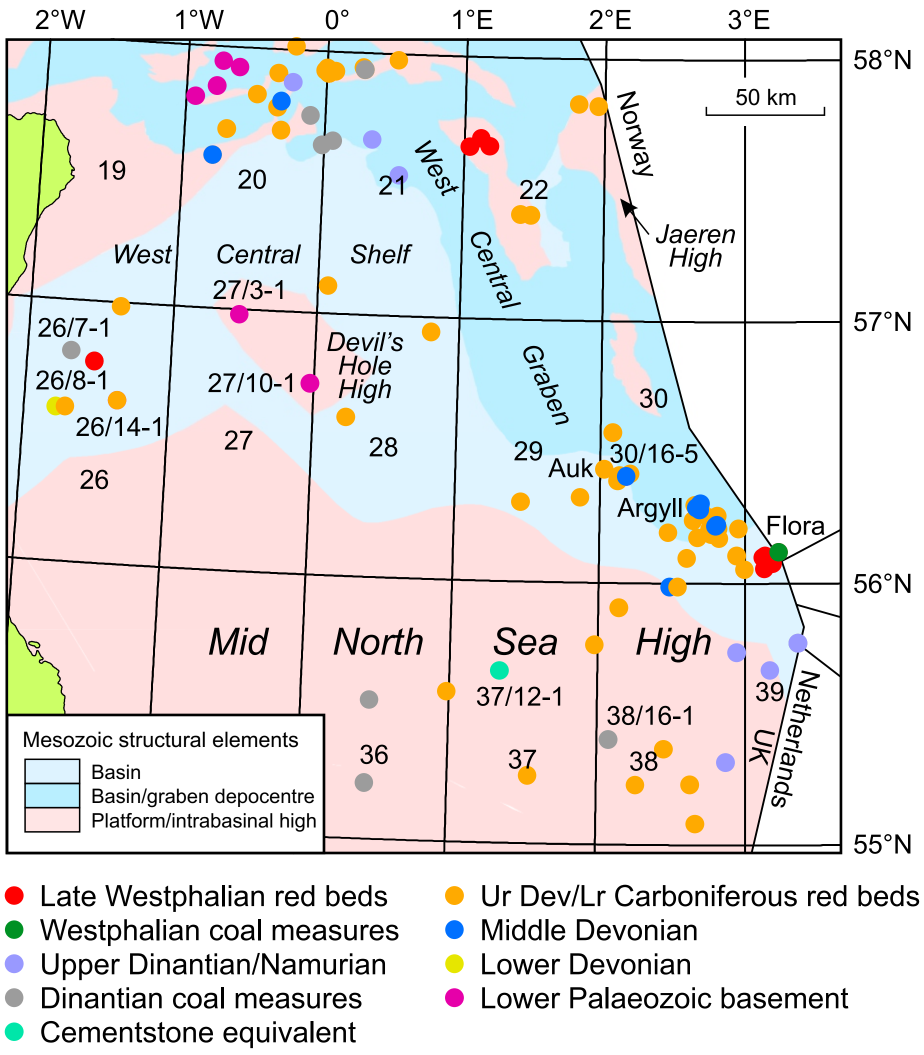


Fig. 4 Pre-Permian stratigraphy recorded in Central North Sea wells

3. Highlights of deep Central North Sea wells

- 2 Devil's Hole High wells and 30/16-5 drilled Lower Paleozoic basement of Scottish Southern Uplands affinity
- 6 Auk-Argyll area wells drilled Middle Devonian, Kyle Gp. shallow-marine limestones, evaporites and mudstones
- 76 wells proved Upper Devonian continental red beds directly beneath a regional base Permian unconformity
- 5 Mid North Sea High wells drilled Lower Carboniferous strata of Northumberland Trough (N England) affinity - the High was not a uniformly positive pre-Permian feature
- 26/7-1 drilled 1,090 m of Lower Carboniferous coal measures of Midland Valley of Scotland affinity
- These coal measures are overlain by red beds ascribed to the Westphalian - if so confirming an extension of an intra-Namurian Midland Valley of Scotland unconformity into the offshore area
- 6 Flora area wells proved Late Carboniferous sandstone units separated by volcanics, unconformably overlain by Lower Rotliegend Gp argillaceous and volcanic strata
- Another unconformity separates Lower Rotliegend and Upper Rotliegend Group strata at Flora

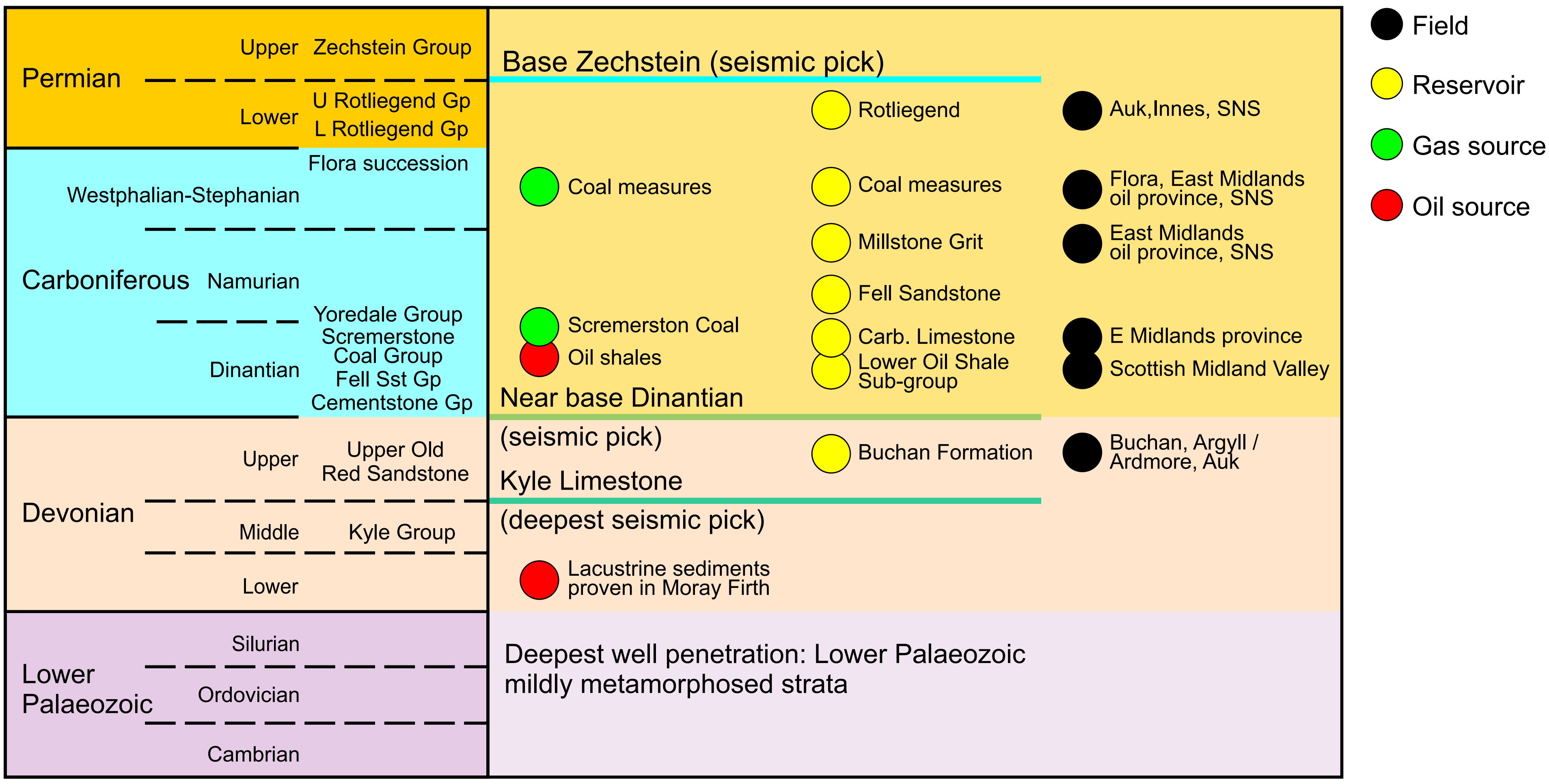


Fig. 5 Summary of Permian and pre-Permian lithostratigraphy and of potential source rock and reservoir intervals in the region

4. Potential field modelling of sub-Zechstein basin architecture

Interpretation of the grids of long-offset seismic data has provided a much improved first-pass image of sub-Permian basin architecture beneath the Central North Sea. Nevertheless, there remain areas where the basin architecture is poorly resolved beneath complex structure in the Mesozoic strata, or where the long-offset data coverage is currently sparse. A programme of potential field modelling was therefore initiated to improve resolution of the sub-Permian structure in these areas, and to provide QC in other areas of ambiguous seismic interpretation.

A 3D-forward and inversion modelling technique has been used to separate the gravity response of the crystalline (sub-Lower Palaeozoic) basement from the gravity responses of its overlying Lower Palaeozoic, Devono-Carboniferous, Permian and post-Permian sedimentary basins. The principal aim for the 3D modelling has been to resolve a depth surface to high-density or crystalline basement - this surface then defines the base of the accommodation space to be filled by the Lower Palaeozoic and overlying sedimentary basins.

Construction of the potential field model has been an iterative process, with successive iterations being designed to improve fit with the geological interpretation in areas of good well control and seismic data quality. Initial modelling assumed a uniform lower crustal density beneath the Central North Sea, but later models included low density granitic bodies within the basement.

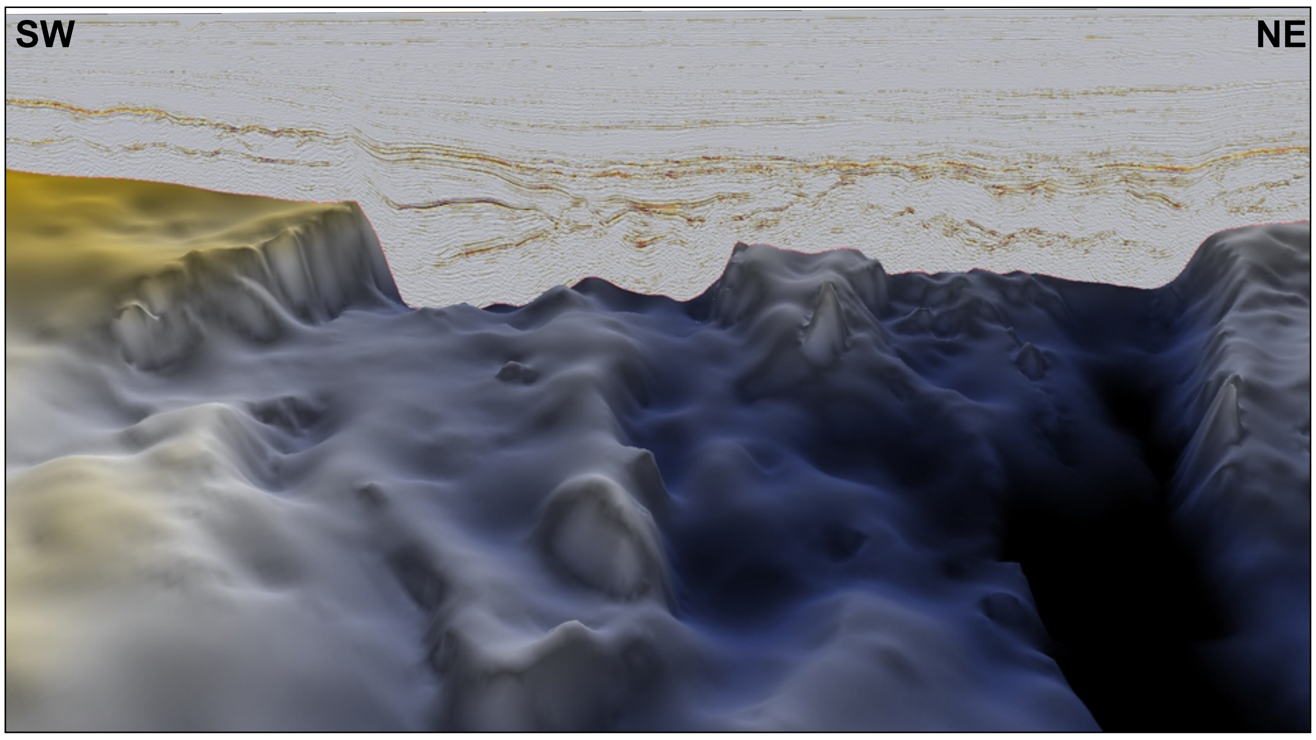
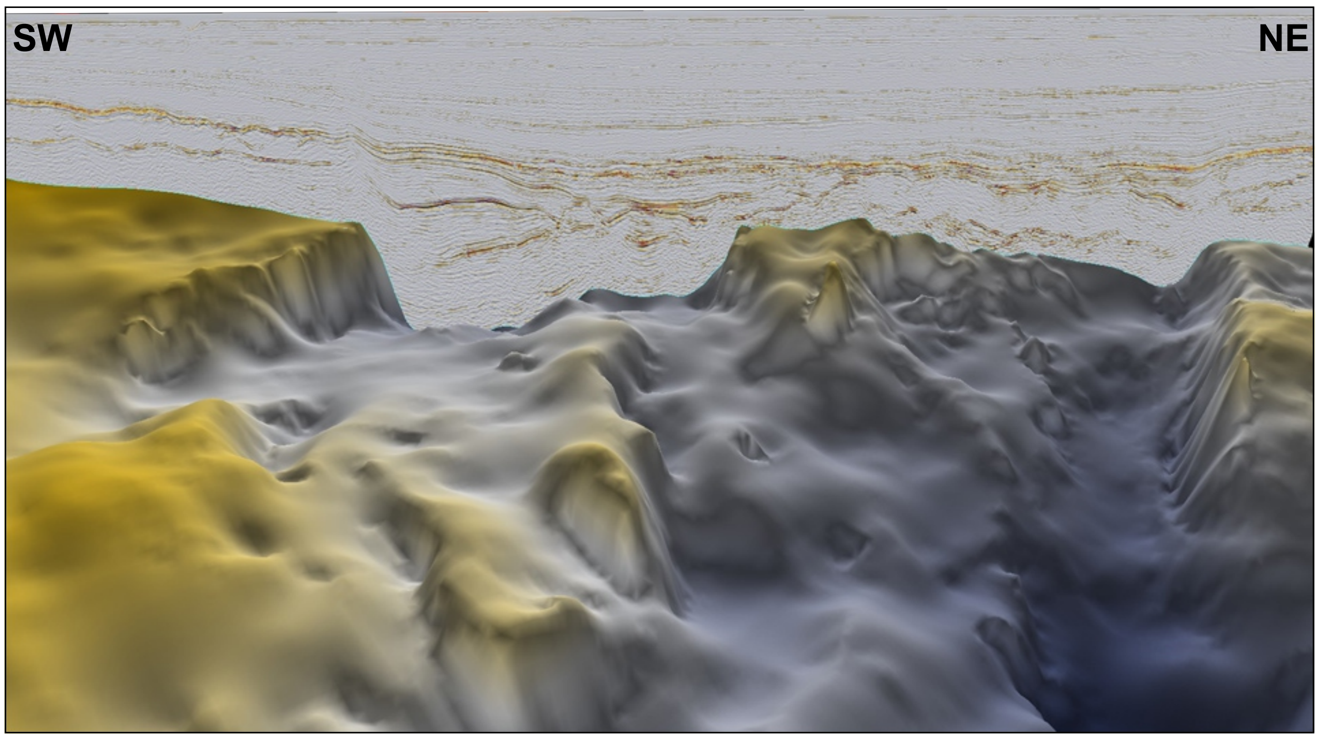


Fig. 6 Long-offset 2D seismic profile superimposed on a 3D view of the homogeneous crystalline basement model (with only 3 granite bodies added). The seismic profile traverses the West Central Shelf, the West Central Graben, the Forties-Montrose High, the East Central Graben, and ends on the Jaeren High with its Devono-Carboniferous core. 2D seismic data courtesy of TGS NOPEC Geophysical Co. (UK) Ltd.

The next phase of modelling will introduce even more lateral density variations into the basement body and these will be based on known geology and refraction seismic studies which have helped to define the different basement terrains within the project area. Figures 6 and 7 show two end-member results from the current modelling. Figures 6 shows a long offset seismic line superimposed on the homogenous basement model (with only three granite bodies added) and figure 7 shows the same seismic line, but this time superimposed on a basement surface which includes significant lateral density variation based on a regional seismic refraction interpretation (Lyngsie, 2007). The variable density basement has helped to modify the 3D modelled basement surface, for example, the basement beneath the West Central Graben on Figure 7 is a few hundred metres lower than that seen on Figure 6 which may indicate that Palaeozoic sediments are preserved even in the deepest parts of the graben. Further iterations of lower crustal density variation are under way to provide a basis for modelling the Devono-Carboniferous basin architecture in areas of the North Sea that contain sparse or no long-offset seismic data coverage. The impact of each iteration can be assessed visually, as on Figure 7, by comparing the geological interpretation with the resultant top crystalline basement surface on key seismic profiles across the study area.

Fig. 7 Long-offset 2D seismic profile superimposed on a 3D view of the crystalline basement model which includes significant lateral density variation based on a regional seismic refraction interpretation. The seismic profile traverses the West Central Shelf, the West Central Graben, the Forties-Montrose High, the East Central Graben, and ends on the Jaeren High with its Devono-Carboniferous core. 2D seismic data courtesy of TGS NOPEC Geophysical Co. (UK) Ltd.



5. Seismic data and interpretation

Long-offset seismic data offers improved imaging of the deep structure of the Central North Sea. Imaging of the pre-Zechstein section is strongly influenced by structural complexity of the Zechstein to Cenozoic overburden; thus seismic imaging is worst beneath the Central Graben. Elsewhere, seismic interpretation of Lower Carboniferous units relies heavily on comparison with equivalent drilled strata on the southern flank of the Mid North Sea High.

5.1 Sub-Zechstein isopachs

The Middle Devonian Kyle Limestone forms a conspicuous, high-amplitude and continuous reflector in the Auk-Argyll area. Beyond the limit of the Kyle Limestone event, the deepest reliable event is taken as representing the transition from late Devonian continental red-bed deposits to early Dinantian Cementstone Group-equivalent strata and has been labelled as near base Dinantian. The areas in which Kyle Limestone and intra-Dinantian reflectors have been picked are not mutually exclusive.

The isopachs from the base of the Zechstein to the Kyle Limestone reflector (or near base Dinantian reflector where the former cannot be picked) provide a first impression of the potential thickness of Middle Devonian to Lower Permian strata in the region, as derived from the seismic interpretation (Fig. 8).

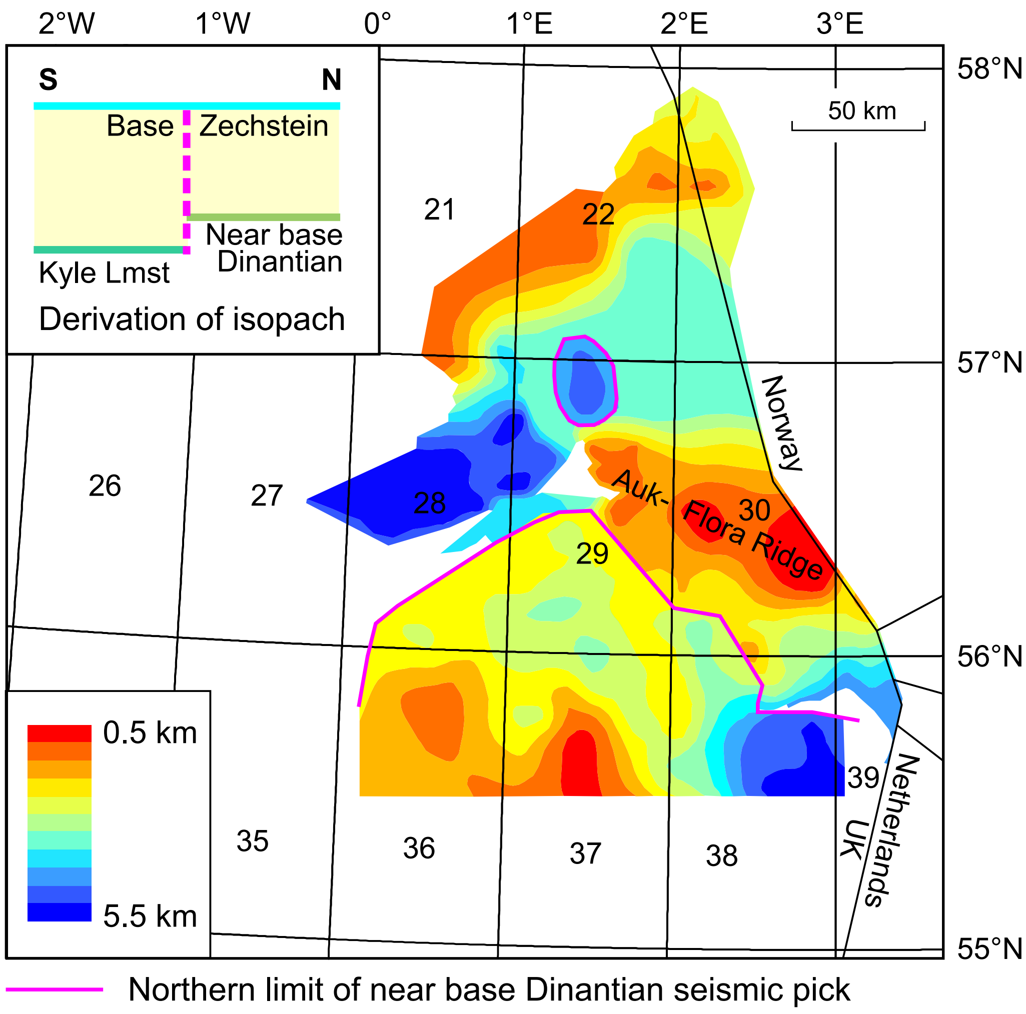
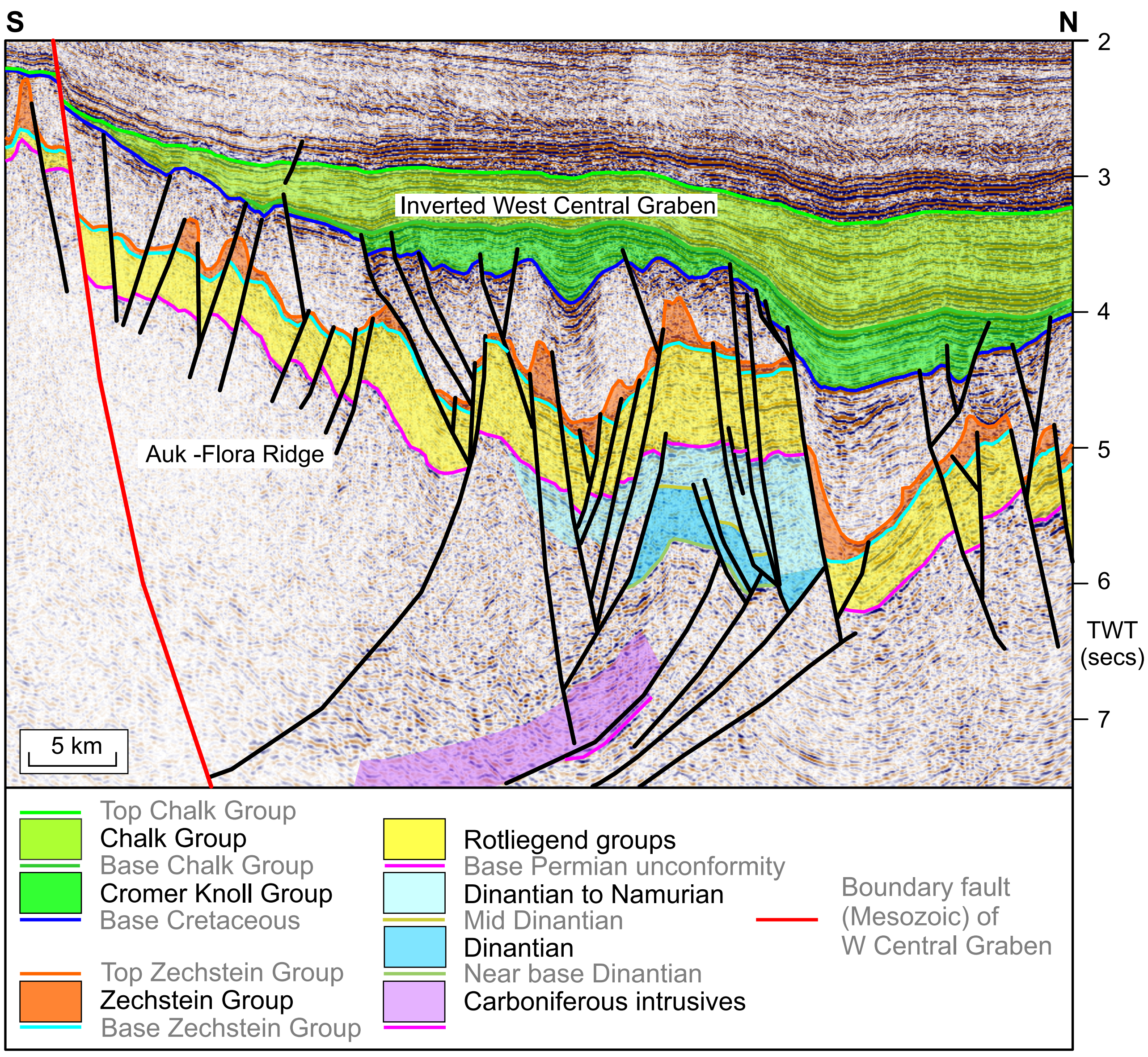


Fig. 8 Approximate thickness of pre-Zechstein Upper Palaeozoic (base Zechstein Gp to near base Dinantian, or where not interpretable base Zechstein Gp to Middle Devonian Kyle Limestone); isochrons converted to

5.2 Auk-Flora Ridge area



All of the onshore examples of Lower Palaeozoic basement blocks are bounded by prominent oblique-slip, reverse or normal fault systems. The northern flank of the Auk-Flora Ridge is interpreted to be a major reverse fault system. The Dinantian and older beds at the centre of the profile appear to be folded, and are underlain by high-amplitude dipping events that are tentatively interpreted as igneous intrusives.

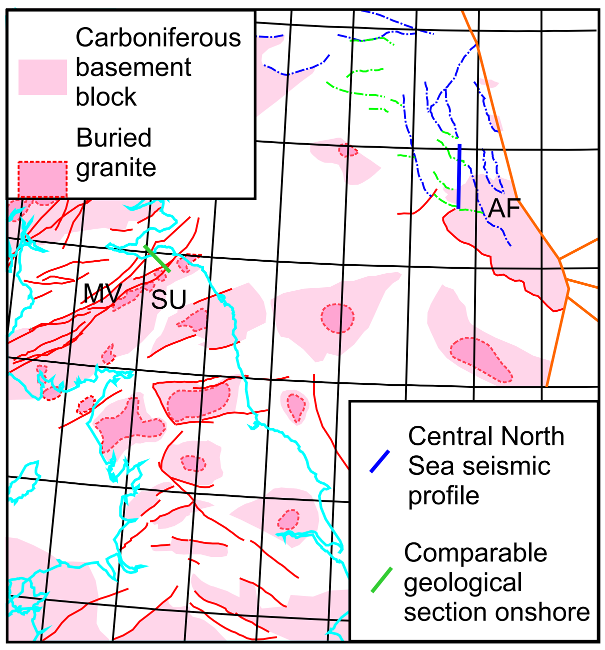
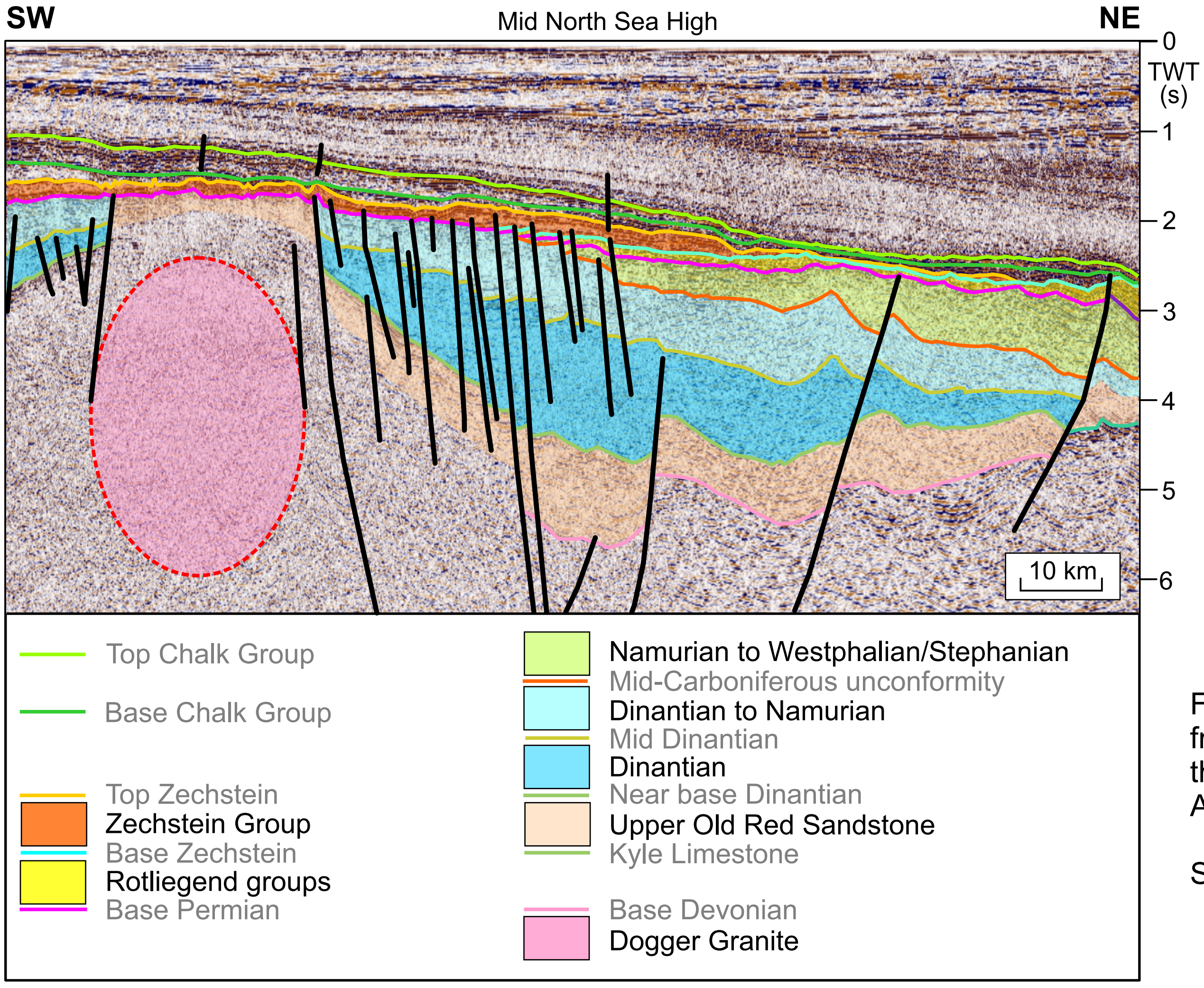


Fig. 9 Interpretation of example seismic profile crossing the northern flank of the Auk-Flora Ridge (AF) (on inset map MV Midland Valley of Scotland; SU Southern Uplands). Seismic data courtesy of CGGVeritas

5.3 Mid North Sea High area



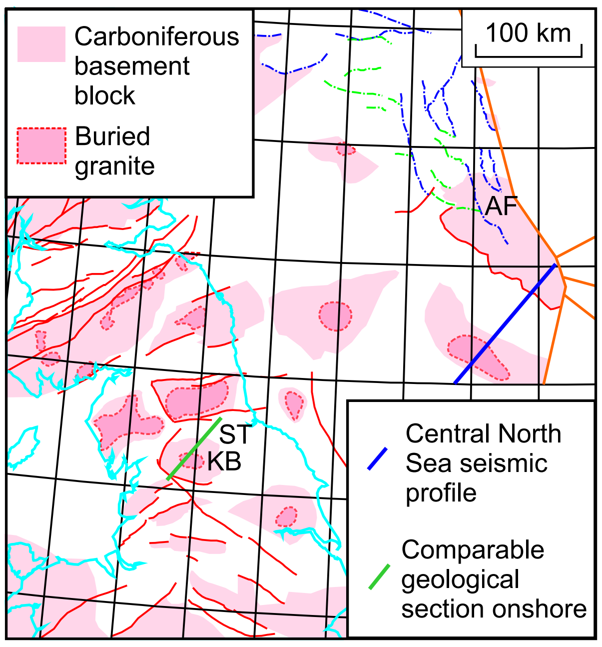
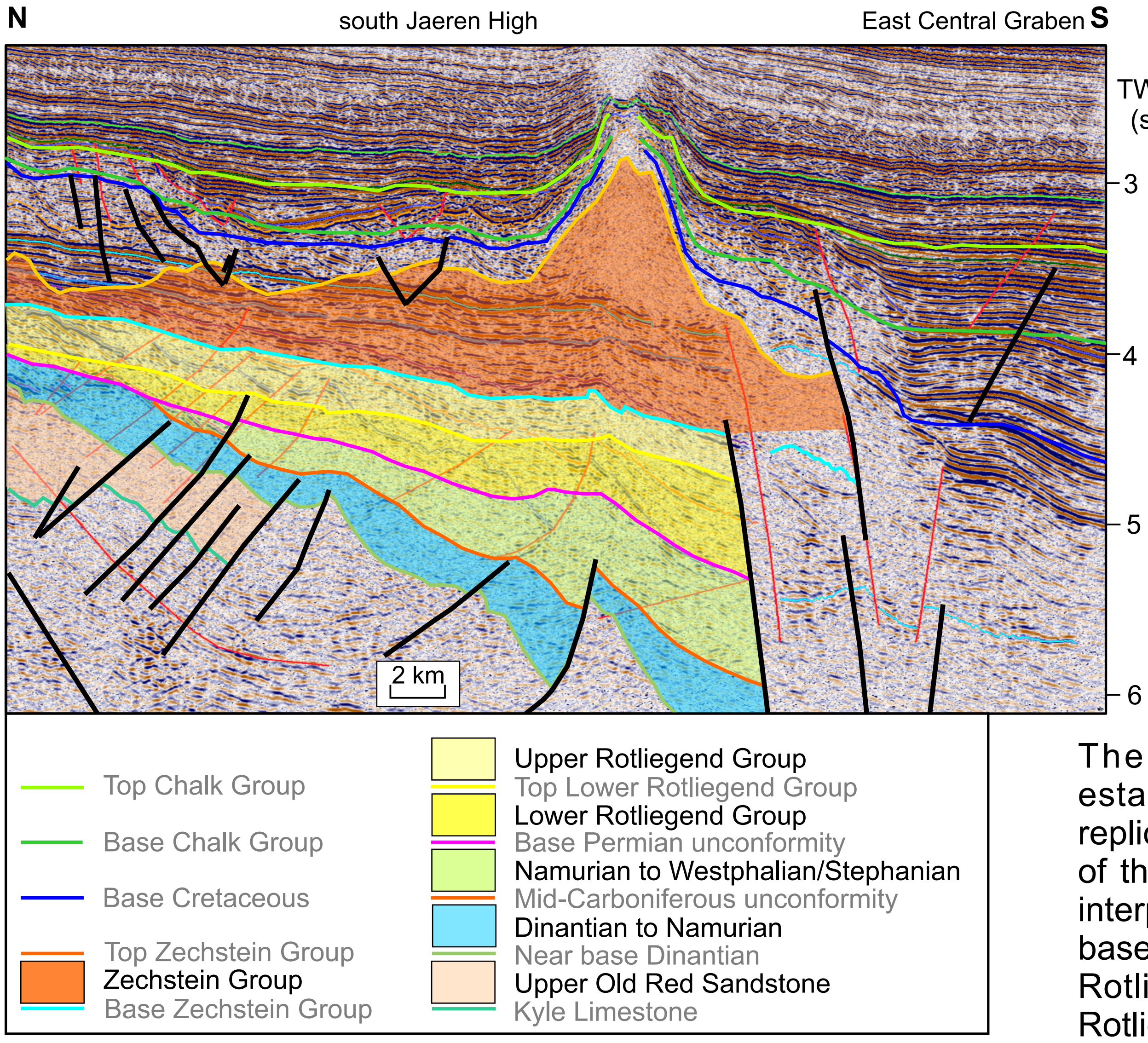


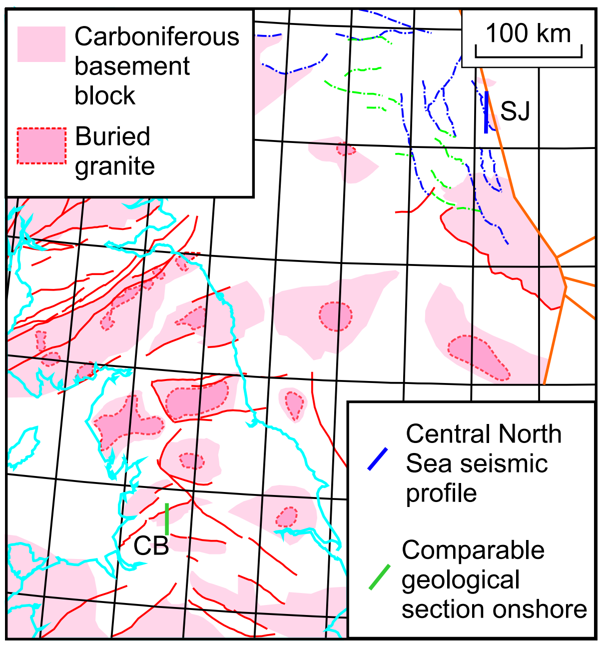
Fig. 10 Interpretation of example seismic profile from the Dogger Granite to the southern flank of the Auk-Flora Ridge (AF Auk-Flora Ridge; KB Askrigg Block; ST Stainmore Trough)

Seismic data courtesy of TGS

South of the Auk-Flora Ridge, there is compelling evidence for the preservation of up to 5.5 km of Upper Devonian to Dinantian strata in a half-graben feature within what is conventionally regarded as the Mid North Sea High (Fig. 10). Notably, this basin's fill could potentially include Scremerston Coal Group-equivalent gas-prone source rocks, although thermal modelling (Hay *et al*. 2005) suggests that such may be only marginally mature here. The southern flank of this Upper Devonian to Dinantian basin is constrained by a prominent Lower Palaeozoic basement block that was persistently buoyant through Carboniferous times. Potential field modelling predicts that this Lower Palaeozoic basement block contains a Caledonoid granite core (Dogger Granite). Comparable granite-cored Lower Palaeozoic basement blocks in England include the Askrigg Block, and the half-graben on the profile is thus analogous to the early Carboniferous Stainmore Trough of northern England.

5.4 South Jaeren High area



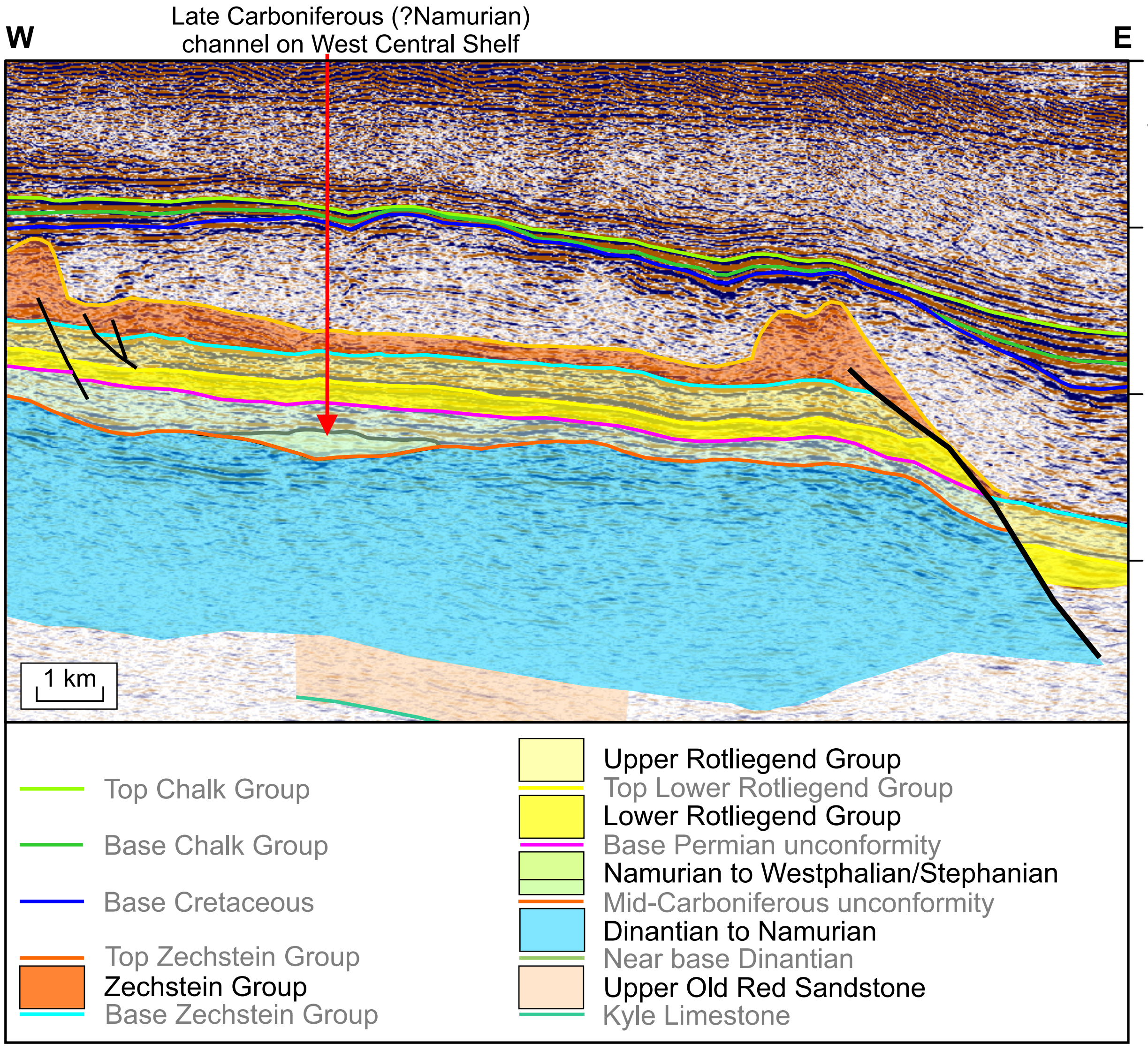


CB Craven Basin SJ south Jaeren High

Fig. 11 Interpretation of example seismic profile from the south Jaeren High. Seismic data courtesy of CGGVeritas

The seismostratigraphic relationships established in the Auk-Flora Ridge are replicated on the Jaeren High. The southern part of the Jaeren High Mesozoic footwall block is interpreted to overlie another pre-Carboniferous basement block. Both a uniformly thick Upper Rotliegend and northward-thinning Lower Rotliegend unit are also clearly developed above a base Permian truncation surface.

5.5 West Central Shelf area



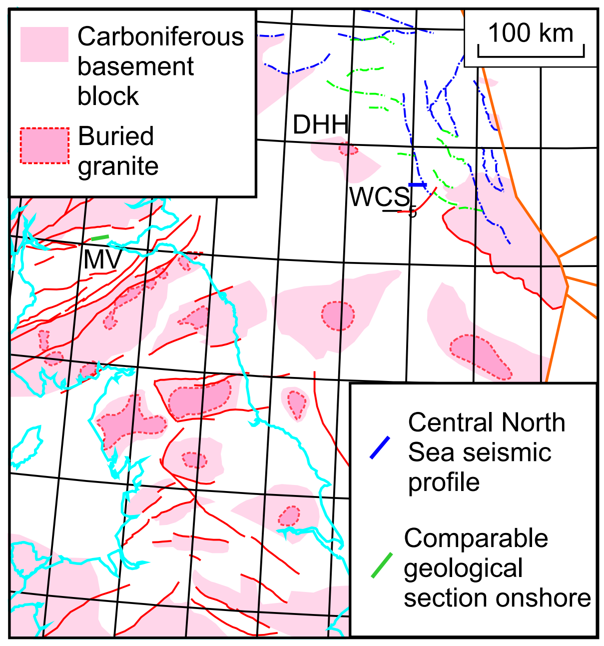
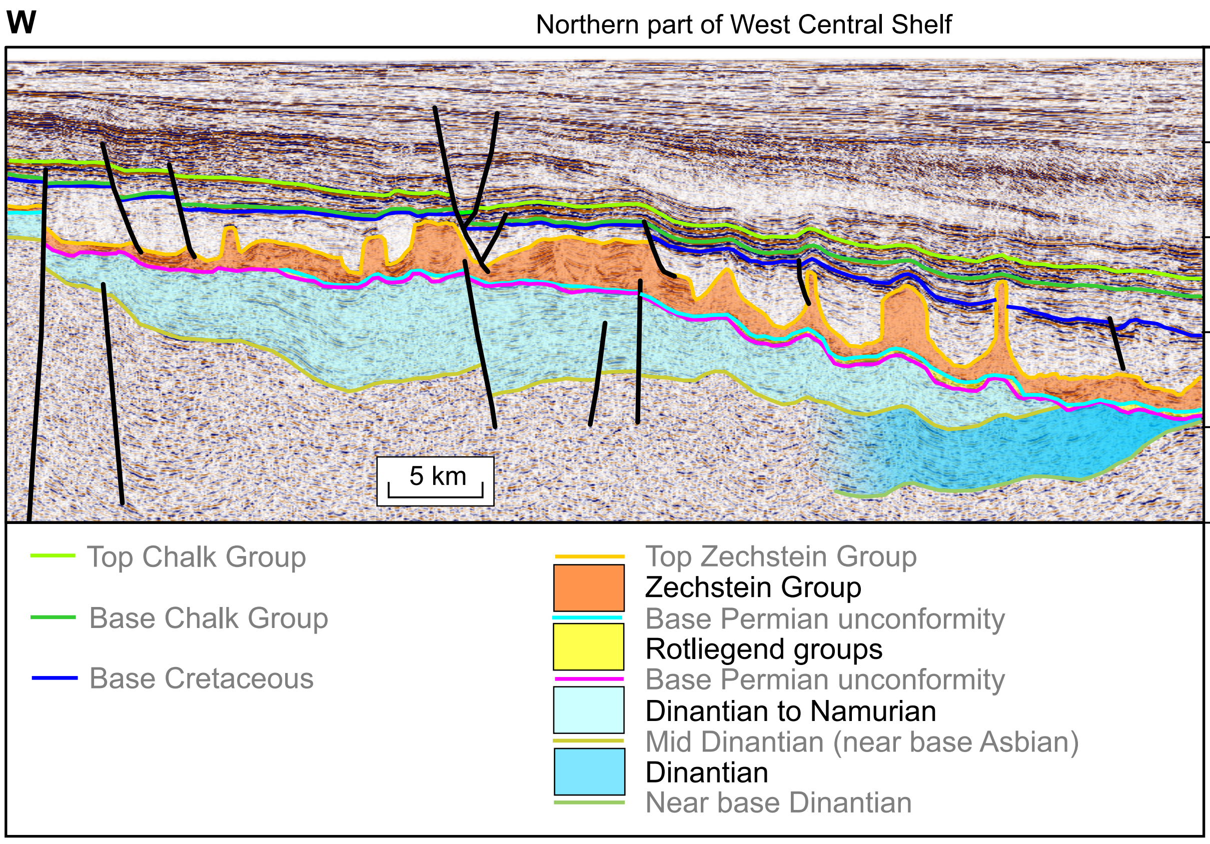


Fig. 12 Interpretation of example seismic profile from the West Central Shelf (WCS); (DHH Devil's Hole Horst; MV Midland Valley of Scotland)

Seismic data courtesy of CGGVeritas

The Lower Permian, Rotliegend Group strata are divisible into two discrete seismostratigraphic units acrioss part of the West Central Shelf (Fig 12). Locally, a strongly erosional intra-Carboniferous unconformity dissects into a seismic facies of discontinuous high-amplitude reflectors that may be indicative of coal measures. A lenticular sediment body imaged directly overlying the deepest notch in the unconformity surface is interpreted to represent the fill of an erosional channel. In three dimensions, both the channel and its infill body trend roughly W-E and are up to 2 km wide. Their scale and trend are comparable with mapped mid-Namurian channel features associated with an influx of coarse detritus in the Midland Valley of Scotland



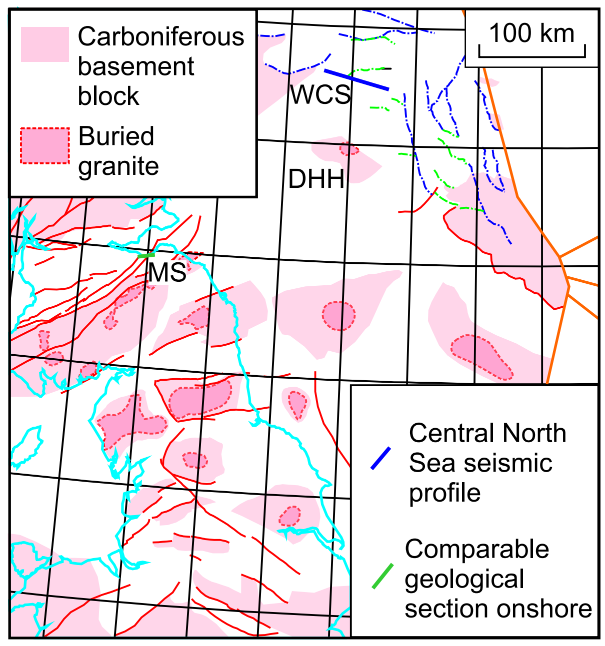


Fig. 13 Interpretation of example seismic profile from the West Central Shelf (WCS); (DHH Devil's Hole Horst; MS Midlothian Syncline, Midland Valley of Scotland).

Seismic data courtesy of TGS

Across the northern part of the West Central Shelf lies a simple pre-Permian syncline, bounded to the west by a westerly-dipping reverse fault (Fig. 13), and comparable in style and orientation if not in scale to the Midlothian Syncline in the Midland Valley of Scotland. The latter developed in the late Carboniferous as syn-sedimentary folding superseded extension in front of a basement block. The two profiles in Figs 12 and 13 suggest that large parts of the Carboniferous tectonic style beneath the West Central Shelf has more in common with the Midland Valley of Scotland than with the tectonic style of the Auk-Flora area and the eastern part of the Mid North Sea High.

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6 Implications for Central North Sea Carboniferous petroleum system

Source rocks

- Mid-Dinantian coal measures (cf. Scremerston Coal Group of northern England) offer significant volumes of source rocks in most of the Central North Sea's Lower Carboniferous basins.
- Non-marine oil shales (cf. Midland Valley of Scotland) may be present locally.
- Dinantian to early Namurian organic-rich marine oil shales, the principal source rocks for the oil and gas fields of the East Irish Sea Basin and the East Midlands of England, are almost certainly absent from the Central North Sea. Westphalian coal measures, the principal source rocks in the Southern North Sea, have been completely eroded across much (but not all) of the Central North Sea.

Source rock maturity

- Much of the Midland Valley Carboniferous source rock interval was raised out of the oil window by Paleogene uplift, but petroleum generation may be continuing in the deepest-buried strata there and beneath the Central North Sea today (Underhill *et al*. 2008).
- Mid-Dinantian coal-measure source rocks beneath south-central Quadrant 29 have been modelled as mature for oil generation, and may even have entered the gas window locally (Hay *et al*. 2005). Up to 28 billion barrels of oil and 156 tcf of gas could have been expelled from this area alone since the Paleocene.
- Conversely, Hay *et al.* (2005) predicted that any Dinantian strata preserved in Mid North Sea High Carboniferous basins are only marginally mature for oil generation.

Plays and traps

- Plays are largely dependent on the efficiency of their regional Zechstein Group evaporite topseal.
- Where this seal is intact, hydrocarbon charge will be limited to sub-Zechstein reservoirs and traps.
- Seal breach (areas of Zechstein Group salt withdrawal) provides opportunities for charging Triassic to Tertiary reservoirs.
- Rotliegend aeolian sandstone targets above thermally mature Carboniferous source-rock basins: structural traps, or basin-margin pinch-out traps.
- Potential sub-Rotliegend targets fall into three categories: i) Zechstein subcrop traps beyond the limit of the Rotliegend fairway, ii) Lower Rotliegend subcrop traps, and iii) intra-Carboniferous traps.

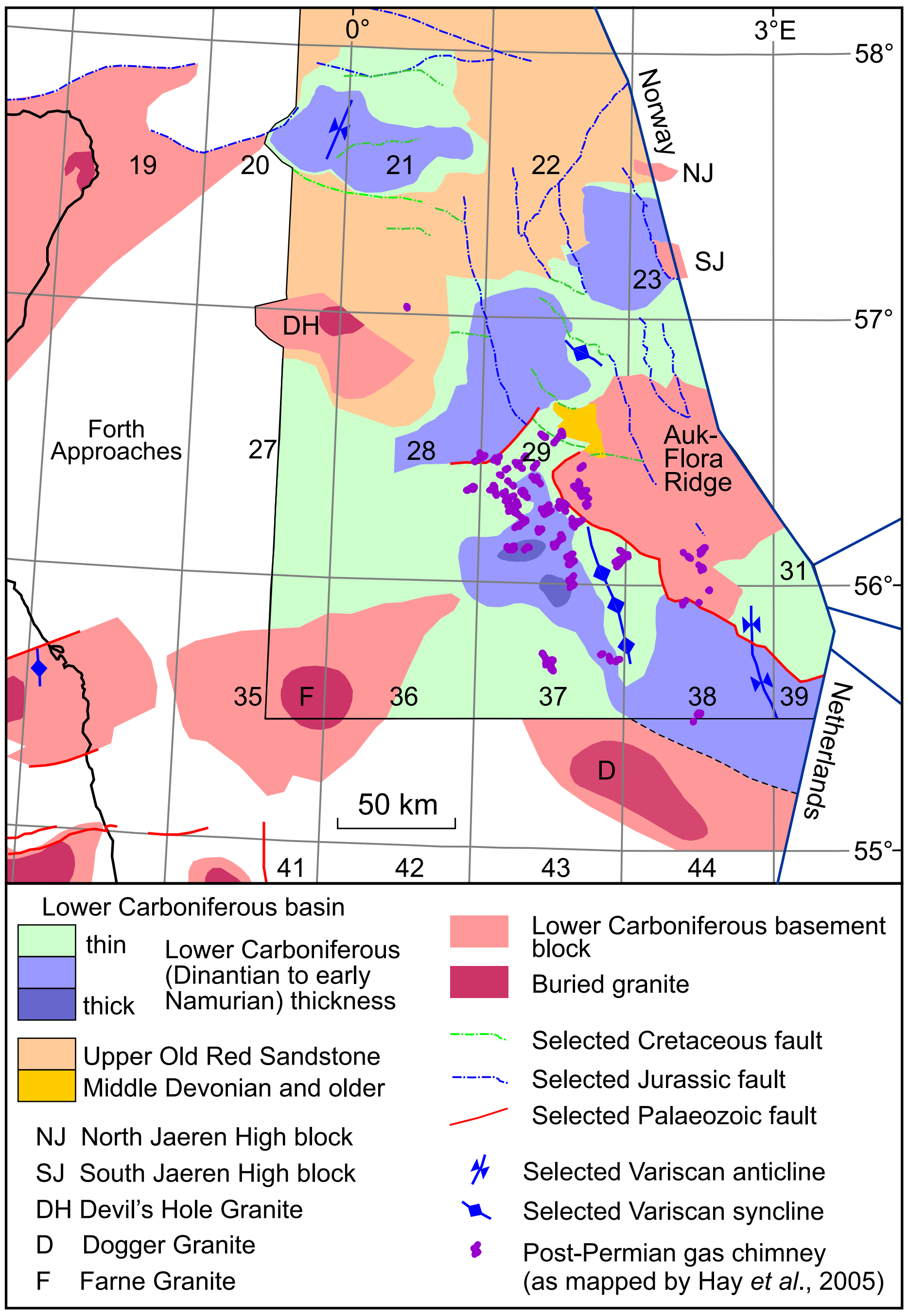

Fig. 14 Lower Carboniferous basin configuration, Central North Sea

7. Conclusion

Seismic interpretation augmented by potential field modelling has revealed a Devono-Carboniferous basin architecture for the Central North Sea that exhibits many features in common with the contemporary basins of northern England and southern Scotland. By analogy with these basins, their Central North Sea equivalents are likely to contain significant volumes of coal-measure and perhaps also oil-shale source rocks. Where thermally mature, these source-rock intervals are key elements of an underexplored Carboniferous petroleum system, potentially extending far to the west of the Jurassic source kitchen that has been the focus of almost all Central North Sea exploration to date. Exploration opportunities associated with this petroleum system occur both in Devonian to Lower Permian plays beneath the regional Zechstein evaporite seal and, where halokinetic thinning has enabled seal breach, in the underexplored Mesozoic and Tertiary plays above.

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Lyngsie, S.B. 2007. Continental sutures and their influence on rifting in the North Sea. PhD. Thesis, University of Copenhagen.

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