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Structural and Stratigraphic Evolution of the Mid North Sea High Region of the UK Continental Shelf

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Abstract
Interpretation of newly-acquired seismic and legacy well data has led to a greater understanding of the Upper Palaeozoic-Recent geological evolution of the Mid North Sea High (MNSH), an underexplored region of the Central North Sea. The position of granite-cored blocks controlled the distribution of Devono-Carboniferous highs and basins before Variscan uplift led to peneplanation and the creation of the Base Permian Unconformity. The MNSH became the dominant feature during the Permian when it formed a W-E striking ridge between the Southern and Northern Permian Basins. Following a period of non-deposition, sedimentation was renewed in the Late Permian to Triassic before Middle Jurassic doming caused uplift to the north-east. Subsequent Late Jurassic North Sea rifting transected the MNSH to create the Western Platform between the Central Graben and Moray Firth rift arms. Following Cretaceous post-rift deposition, the area experienced a significant easterly tilt in the Cenozoic that led to the demise of the MNSH as a prominent topographic feature. The tectonic and stratigraphic evolution exerts a strong control over reservoir facies distribution, source rock deposition and maturation. However, the area is not barren of petroleum potential. Despite the lack of Upper Carboniferous source rocks over large areas, hydrocarbon potential is evident through shows in legacy wells, indicating the Lower Carboniferous as a potential source rock. Cenozoic uplift to the west imparted a regional tilt, the effects of which remains key to unlocking the area's prospectivity since it reconfigured structures and formed remigration pathways from Lower Carboniferous and Jurassic source rocks.

Introduction
After almost six decades of exploration, the North Sea is generally considered to be a mature petroleum province. Whilst vast areas of the basin have seen intense exploration activity, other parts remain relatively underexplored. One such area is the region spanning between the east coast of the UK and the North Sea rift system (Fig. 1). Loosely defined as the Mid North Sea High (MNSH), licenses were taken and wells drilled in the early years of UKCS exploration. However, drilling activity rapidly tailed off as attention focused on the highly prospective adjacent basins: the Southern Permian, Central Graben and Moray Firth Basins. The region was largely neglected in subsequent licensing rounds.

In an attempt to rejuvenate interest in the area, the UK Government supported the acquisition of new seismic data as part of a larger programme promoting Frontier Basins of the UK Continental Shelf (UKCS). This paper documents the interpretation of the seismic data that enables new insights to be gained about the tectono-stratigraphic evolution and petroleum prospectivity of the area. The results of the work help resolve long-standing issues regarding the true nature and genesis of the Mid North Sea High, demonstrate the controls it had on the distribution of Upper Permian (Rotliegend and Zechstein Group) clastic and carbonate deposystems, and highlight the overprinting role that Cenozoic tilting has had in controlling the geographical extent of petroleum maturation and (re)migration in the region. As such, the seismic acquisition and our subsequent study help to provide a new understanding of the factors governing prospectivity in the area, an awareness of which has seen new block awards in recent offshore licensing rounds.

Current Understanding and Tectonic Setting

Exploration History

The very first wells to be drilled in UK waters were located on the Mid North Sea High (MNSH) (Brennand et al. 1998). Well 38/29-1 (Fig. 2) was spudded in December 1964 and aimed to test the stratigraphy of the UKCS down through the Carboniferous. The well unexpectedly encountered numerous missing sections through the Jurassic to Upper Triassic, and Lower Permian to Carboniferous. No hydrocarbons or potential source rocks were identified. A second well was drilled the following year 40 km to the southwest, along the southern margin of the MNSH (Fig. 2). Well 44/02-1 was also dry, however, Carboniferous coals of Namurian age were penetrated. The first gas was discovered in September 1965 at the West Sole Field in the Southern North Sea, followed by a number of nearby Permian Rotliegend accumulations. This, along with the discovery of oil in the Central North Sea at the Norwegian Ekofisk Field in December 1969, resulted in exploration efforts becoming increasingly focused on the Southern North Sea Gas Basin and the Upper Jurassic trilete rift system of the Central and Northern North Sea (Fig. 2). The MNSH region has, therefore, remained largely underexplored in the last decades and has not replicated the success of its adjacent prolific oil and gas basins.

Despite this downgrading of prospectivity, there have been a number of important discoveries made on the margins of the study area. The discovery of gas in the Gordon Field in 1969 opened up the Triassic Bunter Sandstone Play along the Southern margin of the MNSH, and ultimately led to the discovery of the nearby Forbes and Esmond Fields. It was not until the 1990s that deeper play levels were identified along this southern margin, with a small uneconomic accumulation being identified at Crosgan (Fig. 2). Gas was reservoired within Carboniferous Namurian sands and Permian Zechstein dolomites, importantly opening up the possibility of a Lower Carboniferous play fairway to the north of the existing Carboniferous Westphalian discoveries of the Southern North Sea Gas Basin (Besly 2018). This led to the discovery of Breagh in 1997, reservoired within Lower Carboniferous Namurinan Yoredale and Visean Scremerston sandstones (Booth et al. 2018). The most significant discovery along this southern margin was made in 2012 at Cygnus (Fig. 2). At over 600 bcf recoverable, Cygnus is the largest gas development in Southern North Sea in over 30 years. This Base Permian inversion structure was first drilled in 1988, however the reservoir was deemed to be of poor quality and non-commercial. Re-evaluation and advances in technology have allowed for the re-discovery and development of this Permian Rotliegend and Carboniferous Westphalian field (Catto et al. 2018).

To the north of the MNSH, fields are charged from the oil prone Upper Jurassic Kimmeridge Clay Formation of the Central Graben. A number of noteworthy discoveries have been made within the study area, on the southwest flank of the graben, the earliest of which is the Auk Field (Fig. 2). Discovered in 1970, the Auk Field consists of stacked reservoirs within the Permian Zechstein and underlying Rotliegend within a large tilted fault block (Trewin and Bramwell 1991). This was followed by a number of discoveries to the southeast along the margin of the Central Graben within upthrown Upper Jurassic (Fife, Fergus, Fulmar), Rotliegend (Innes Field), and Carboniferous Westphalian (Flora Field) reservoirs. The most significant oil discovery in the study area is located in the very north, at the edge of the Outer Moray Firth. Discovered in 2001, the Buzzard Field is estimated to contain over 1,500 MMStb OOIP within an Upper Jurassic turbidite stratigraphic trap (Ray et al. 2011). Most recently, the Catcher Field was sanctioned in 2010, and developed as a cluster with the nearby Varadero and Burgman Fields (Fig. 2). They produce from Late Paleocene to Early Eocene turbidite sands. A number of unsanctioned heavy oil accumulations are identified nearby at the Pilot Cluster. Both the northern and southern margins of the MNSH, therefore, have shown continued high-volume exploration success from the initial stages of North Sea exploration through to present day, and currently provide *ca*. 9% of domestic gas and approximately a quarter of domestic oil supply to the UK.

Tectonostratigraphic Setting

Initial regional gravity-based surveys, in the 1950s resulted in the first interpretations of the subsurface structure of the North Sea (Collette 1958). However, it was not until the acquisition of seismic data (Cook 1965) that the Mid North Sea High was first identified and mapped (Heybroek et al. 1967). Although early seismic failed to allow interpretation of the Pre-Zechstein, the Base Permian was mapped regionally and the MNSH was described as a Western extension of the Ringköbing-Fyn High that saw thin Zechstein deposition compared to adjacent salt basins. Glennie (1998) now defines the MNSH as an E-W orientated High separating the North and South Permian Basins and notes the orientation as being sub-parallel to the Variscan front, and therefore likely formed as a result. Much emphasis has been put on the evolution of the surrounding basins, and the tectonic evolution of the wider North Sea is now well constrained.

Basement mapping by Frogtech Geoscience (2016) identifies six North Sea Basement Terranes associated with the collision of palaeo-continents Avalonia, Baltica and Laurentia (Fig. 1): 1) The *Grampian Highland Terrane*, derived from Laurentia, was highly deformed during its collision with Avalonia and the resulting Caledonian Orogeny; 2) The *Midland Valley Terrane* comprises of Cambrian to Ordovician Iapetus Ocean ophiolite and forearc complexes (Frogtech Geoscience 2016) that have been deformed by dextral strike-slip movement along the bounding Highland Boundary and Southern Uplands Faults (Underhill et al. 2008); 3) The *Southern Uplands Terrane* is formed from an accretionary wedge of deformed and metamorphosed Ordovician and Silurian deep water sediments deposited in the Iapetus Ocean that once separated Laurentia and Avalonia (Frogtech Geoscience 2016); 4) The *North Sea South Terrane* represents the continent of Baltica once separated by the Tornquist Sea; 5) *Devil's Hole Terrane* is comprised of basement of unknown age and origin. This long-standing high is located at the triple junction between the three palaeo-continents (Fig. 1) and is likely formed of fragments of each (Frogtech Geoscience 2016); and 6) The *Leinster-Lakesman Terrane* represents the palaeocontinent of Avalonia. Closure of the Iapetus led to volcanic activity within the basement across the south of the study area (Frogtech Geoscience 2016) and the emplacement of numerous granite intrusions. Granites have been rarely penetrated by offshore wells, but onshore dating suggests an emplacement date of Late Silurian – Carboniferous (Ziegler 1990; Kimbell et al. 2010).

Following the Caledonian Orogeny, large volumes of sediment were eroded from the Mountain range in the north. At this time, much of the North Sea formed a depocentre where Devonian fluvial, lacustrine and aeolian Old Red Sandstones are now identified in the subsurface (Cameron 1993). A change in stress regime during the Carboniferous led to transtensional and extensional basins forming along lineaments created in the Caledonian Iapetus and Tornquist orientations (Glennie and Underhill 1998). In the Late Carboniferous (Westphalian), extension ceased, and compressional movements associated with the closure of the Rheic Ocean and the Variscan orogeny initiated (Glennie and Underhill 1998). Post-orogenic collapse and volcanism during the Early Permian saw uplift and erosion, followed by thermal subsidence and the deposition of the Rotliegend Group of sands, silts and mudstones (Glennie et al. 2003). The Northern and Southern Permian Basins were formed by a series of depressions or half grabens that were separated by the MNSH (Fig. 1) (Doornenbal and Stevenson 2010). Continued subsidence through the Late Permian led to the deposition of the Zechstein Group (Doornenbal and Stevenson 2010) consisting of a succession of evaporites and carbonates (Tucker 1991). Renewed extension in the Triassic formed the Dowsing and South Hewett fault zones which show evidence for syndepositional movement and the deepening of the Sole Pit Basin (Fig. 1) (Pharaoh et al. 2010).

Triassic subsidence was interrupted in the Middle Jurassic by a mantle-driven thermal doming in the Central North Sea (Underhill and Partington 1993) and associated formation of the Rattray Volcanic Province at the now triple junction the of the Jurassic rift system (Quirie et al. 2019). During the Late Jurassic to Early Cretaceous, a major episode of rifting occurred in the Central and Northern North Sea to form the Viking Graben, Moray Firth Basin and the Central North Sea Trough (Fig. 1) (Erratt et al. 1999). Importantly, the initiation of the Central Graben resulted in the separation of the MNSH from its Eastern continuation: the Rinkøbing-Fyn High (Fig. 1). By the Early Cretaceous, the focus of rifting had switched to the Proto-Atlantic, and thermal subsidence began in the North Sea (Erratt et al. 1999). Late Cretaceous to Mid Tertiary compressional reactivation of faults is thought to be associated with the Alpine Orogeny to the southeast (Cartwright 1989) and resulted in uplift and inversion anticlines across Southern England (Underhill and Stoneley 1998), the Southern North Sea (Glennie and Boegner 1981; Van Hoorn 1987) and Central Graben (Cartwright 1989). Today, continued thermal subsidence leads to differential sediment loading and associated salt movements (Glennie and Underhill 1998), but in general this is a tectonically quiet time for the Central North Sea.

Data and Methodology

Seismic data

In an effort to encourage renewed exploration interest in under-explored regions of the UKCS, the UK's Oil and Gas Authority (OGA) launched their 'Frontier Basins Research Programme' in 2015. As part of this initiative, the OGA provided sponsorship for the acquisition and release of long offset 2D seismic data by WesternGeco over the MNSH, Rockall and Western Approaches. A two-year postdoctoral project award was made to Heriot Watt University in 2016 to provide an independent academic view on the newly-released MNSH data-set and aimed to review the petroleum systems and their remaining exploration potential.

The newly acquired 2D long offset seismic comprises over 10,000 km of line data (Fig. 3). In addition, a number of reprocessed and legacy lines were released to complement the WesternGeco survey (Fig. 3). The MNSH_2015 data is zero phase, normal polarity (Fig. 4). Data quality is moderate to excellent from the seabed down to the Base Zechstein, deteriorating from approximately 500 ms TWT in the west to 2500 ms TWT in the east (Fig. 4).

Following quality control of the data, tectonostratigraphically significant horizons were picked across the survey area to identify dominant structural trends and depocentres. Thirteen regionally significant horizons were chosen for interpretation which formed either onlap / truncation surfaces, or showed significant acoustic impedance contrast (Fig. 5; Table 1). Seismic to well (S2W) ties were completed for wells with check-shot data to tie the seismic observations to the lithostratigraphy. Surfaces were generated using the following workflow: 1) Initial interpretation tied to wells and seismic response; 2) Infill interpretation in areas without S2W tie, including the interpretation of legacy seismic where required; 3) Gridding completed using trend surfaces where appropriate; 4) Smoothing where required; 5) Surfaces combined or eliminated where erosion has removed stratigraphy; 6) Isochron maps generated from surfaces; and 7) Surface maps and isochrons were combined with well information to make conclusions on facies distributions and main depocentres through time. Where required, a very simple 'backstripping' was completed by removing overburden thickness from surfaces.

No time-to-depth conversion has been completed as part of this study. After review of the available check-shot data, it was concluded that the data requires specialist input from a geophysicist on account of the multiple uplift events and how they affect the velocities across the region. In particular, the fastest velocity functions are seen in the deepest part of the basin and are likely controlled by localised uplift, changing thicknesses of Cretaceous chalk and/or Zechstein salts, and changing Zechstein facies. Lateral velocity changes across the study area will be of key importance when time-to-depth conversion is carried out.

Well data

In addition to the open access release of new and legacy seismic data, the OGA also released a complementary set of legacy wells. 98 wells were supplied (Fig. 3) with various quantities of supporting data: well heads and trajectories with assorted well logs; well tops across a selection of the wells; check shots for 32 wells; core analysis for 6 wells, including poroperm and saturation readings; and various supporting documents including completion logs, final well reports, palynology reports etc. An additional set of 37 wells were downloaded from the Common Data Access web portal (now replaced by the OGA's National Data Repository, NDR) (Fig. 3). These were added in order to better constrain the structural evolution of the Southern Margin of the MNSH.

All well data was standardised with respect to well top nomenclature and depth units. This was used to produce a series of well penetration, thickness, and facies maps which could be fed into play mapping. In addition, a single page well summary sheet and well failure analysis was completed for each well in the study (Brackenridge et al. 2018). Digitised composite logs and final well tops were compiled so that a series of well correlation panels could be generated. Finally, a number of burial history curves were created for wells selected to complement key seismic lines.

Three wells were identified for burial history reconstruction along a N-S transect across the MNSH: 39/02- 4, 38/16- 1 and 43/06- 1 (Fig. 3). The inputs for the creation of the burial graphs were the stratigraphic tops and ages from the wells, the main lithologies in each section, estimates of the amount of missing section at unconformities, the duration of these erosion events and the palaeo-bathymetric history. These inputs were then supplied to Shell's proprietary basin modelling tool, BPA-CAULDRON. The decompaction behaviour of the sediments in BPA-CAULDRON is dependent on the input lithologies or lithology mixes, the vertical effective stress and the estimated pore pressure.

Additional data & previous studies

The OGA_2015 seismic and well data was released open access via the OGA data centre website as part of a larger data pack containing limited seismic horizon interpretations, gravity and magnetic data. Prior to this data release, a number of bespoke studies on legacy data over the MNSH were commissioned, for which a number of companies completed studies including the Frogtech's depth to basement study (Frogtech Geoscience 2016), the British Geological Survey's Paleozoic Plays study (Monaghan et al. 2015) and Lloyd's Register's regional mapping project (Lloyd's Register 2019) amongst others. These studies have helped inform aspects of the interpretation of the newly release OGA_2015 data where required.

Results and Interpretation

Seismic mapping and well results

The seismic and well data was used to interpret thirteen regionally significant horizons (Table 1; Fig. 4; 5). Of these, four horizons are onlap / truncation surfaces, and are classed as unconformities. These are: 1) The Base Permian Unconformity, an angular unconformity separating Carboniferous and Devonian tilted fault blocks from overlying Upper Permian facies; 2) The Mid Cimmerian Unconformity, observed only in the north of the region where Upper Jurassic strata onlaps onto the Lower Triassic; 3) The Base Cretaceous Unconformity, a significant erosional truncation surface with a complex subcrop of Jurassic, Triassic and Permian strata; and 4) The Mid Tertiary Unconformity, a diachronous onlap surface in the upper part of the seismic onto which sediments prograde from the northeast (Fig. 4; 5).

In addition, a number of significant high amplitude horizons represent regional facies changes (Fig. 5). These define the remaining seven horizons interpreted: 1) The Top Permian Rotliegend, or Base Zechstein, represented by a strong soft event that signifies a move from halites and evaporites of the Zechstein to the underlying clastics of the Rotliegend; 2) The Top Permian Zechstein, or top salt; 3) The Top Lower Triassic is picked close to the well top where the overlying Upper Triassic Rot Halite forms a regional acoustic impedance (AI) peak. 4) The Top Upper Triassic is observed only in the south of the study area; 5) The Top Lower Cretaceous, or Base Chalk forms a regionally-interpretable AI soft peak in the seismic as chalks give way to the marly muds of the Lower Cretaceous; 6) The Top Upper Cretaceous

Chalk with a strong AI peak in the seismic. To the northeast of the study, Lower Paleocene chalks are also recorded in the well data, but a chronostratigraphic Upper Cretaceous seismic pick has been maintained; and 7) The Top Balder (or equivalent), dated as Early Eocene, represents the opening of the Atlantic Ocean to the northwest. In addition, the seabed was picked, and a near top basement was interpreted. Locally, the top basement is clearly imaged where the highly reflective Devonian Kyle Limestone is present, however, elsewhere the basement was interpreted with the aid of gravity data and the Frogtech 'Depth to Basement' study (Frogtech Geoscience 2016).

Structural evolution & facies distribution

Mapping of unconformity (UC) surfaces has allowed for the MNSH to be placed within the North Sea tectonostratighaphic framework. Four mega-sequences are identified (Fig. 5; 6) on the basis of seismic reflection terminations at key unconformities (Base Permian UC, Base Cretaceous UC and Mid Tertiary UC). In addition, the Mid Cimmerian UC is identified locally and forms part of major Tectonostratigraphic Sequence B. Each seismic sequence boundary, and the facies within each unit are instrumental to understanding the structural evolution of this region.

Top Basement – Base Permian UC <Heading 3>

Tectonostratigraphic Unit A is bounded by the basement and topped by the Base Permian Unconformity (BPU). The isochron thickness map (Fig. 7) reveals highly variable thickness changes across the region: reaching over 3000 ms TWT within isolated depocentres, and thinning to approximately 600 ms over basement highs in the centre of the study area. Here, we propose that the Basement exerts a strong control on the distribution of Devonian-Carboniferous sediments. In the North, the Forth Approaches Basin forms a depocentre on the Midland Valley Terrane (Fig. 1; 7). This basin is bounded by the Highland Boundary and the Southern Uplands Fault complexes, which greatly reduce the seismic imaging and therefore the confidence in basement interpretation in this region. The Devono-Carboniferous succession overlying the *Southern Uplands Terrane* consists of multiple small-scale depocentes separated by localized highs (Fig. 7). This is interpreted as being in response to the underlying accretionary wedge of deformed and metamorphosed Iapetus Ocean deposits (Frogtech Geoscience 2016). The *Devil's Hole Terrane* is represented by a Devono-Carboniferous thin across the Devil's Hole Horst (Fig. 7). Closure of the Iapetus led to deformation, volcanic activity and the emplacement of numerous granite intrusions across the Lenister-Lakesman Terrane in the south (Frogtech Geoscience 2016). The presence of granites across the MNSH has long been documented in gravity studies (Donato et al. 1983; Kimbell and Williamson 2016). Well 37/25-1 penetrated the basement on the mapped Dogger granite (Fig. 7). It recorded an increasing volume of quartzite cuttings and a significant decrease in ROP as the drill string reached the basement. Cuttings showed "*transparent, white, locally pink, very hard, blocky, massive quartz with randomly orientated euhedral biotite inclusions up to 1mm*" (Esso 2009). The Completion Log describes the basement lithology as '*Metamorphics 2346-2359 m*' (Esso 2009). This suggests that the granites have intruded into basement blocks (rather than forming basement themselves) and act as a buoyant core to strengthened crustal blocks.

Although imaging of the top basement is generally very poor, locally, blocks are topped with high amplitude, laterally continuous seismic reflections (Fig. 8). Two wells have penetrated this high amplitude package: well 37/12-1 and well 38/03-1 (Fig. 9). They show that the marked acoustic impedance increase is due to the presence of the Devonian Kyle Limestone. Nearby well 37/25-1 targeted this stratigraphic level at the Devonian Corbenic prospect, but did not encounter the Kyle reservoir (Fig. 9). This high amplitude seismic package is absent at the core site (Fig. 8). Detailed seismofacies mapping of the unit shows its distribution is restricted to the Dogger and Auk Highs in the east of the study area (Fig. 9). The high amplitude Kyle limestone package is absent from the west of the study area, and although very few wells penetrate this stratigraphic level, three wells in the west confirm that the Kyle is not present here (Fig. 9). These observations suggest that granite placement had occurred as early as the Devonian to form the relative highs for limestone deposition to occur. This is in agreement with radiometric dating of granites onshore (Ziegler 1990).

Erosion of the Caledonian Mountain Range to the north generated huge volumes of sediment, deposited across the Central North Sea as fluvial, lacustrine and Aeolian Old Red Sandstones (Cameron 1993). However, where granites were present, they locally acted to increase the buoyancy of basement blocks and generated long-standing isolated highs, over which more limited Devonian deposition occurred. This is comparable to the traditional block and trough morphology seen at this time along the east coast of the UK. A number of wells in the north of the study area penetrate Devonian sandstones (Fig. 7), however core and field descriptions in the Midland Valley (wells 26/12-1 and 26/14-1) report that the Devonian is highly altered. This is confirmed in the northeast where wells 38/03-1 and 38/10-1 report low porosity (<16%) and NTG (<0.26) values.

The Carboniferous forms the upper part of Tectonostratigraphic Unit A. Three significant Carboniferous subdivisions are identified in legacy wells; 1) The Lower Carboniferous Visean, consisting of the Scremerston, Fell Sandstone and Millstone Grit Packages; 2) The Upper Carboniferous Namurian Yoredale Package; and 3) the Upper Carboniferous Westphalian Coal Group. Despite seismic imaging challenges, there is evidence of expanding sections throughout the survey (Fig. 10). Inversion is clearly seen in various locations (Fig. 10), likely associated with the Variscan Orogeny (Glennie and Underhill 1998). To the southeast of the study area, the Base Permian Unconformity (BPU) is clearly imaged where erosional truncation of the Carboniferous within tilted fault blocks has occurred (Fig. 10). This uplift and erosion has resulted in a complex subcrop of the Devonian and Carboniferous below the Base Permian Unconformity with a general trend towards older stratigraphy subcropping in the north and over the buoyant granite highs, for example the Dogger Granite High (Fig. 7).

The Carboniferous contains a number of plays of interest, and important source rock intervals. The Uppermost Carboniferous Westphalian play fairway is defined by the overlying Permian Silverpit Mudstone which acts as the principal top seal. Although present at the southernmost MNSH at Cygnus and in the north east at the Flora Field, the Westphalian is not described in detail herein as well penetrations show that it does not extend across the MNSH (Fig. 7; 11). It does feed into play mapping as an important source rock across the southern margin of the study area. The underlying Yoredale Formation is seen in well penetrations across the south and northeast of the study area (Fig. 7; 11). It represents a highly cyclic deltaic succession consisting of interbedded muds, sands and limestones (Fig. 11) (Doornenbal and Stevenson 2010). Delta-top fluvial sands form good reservoir targets. Deposition is thought to have occurred over much of the Southern MNSH region, with the exception of local granite-cored highs such as the Dogger High. In the Southern North Sea, the Millstone Grit represents a basinal Yoredale equivalent. The Upper Carboniferous Namurian Play is proven to work at Breagh, located on the southern margin of the MNSH (Fig. 2). An additional non-commercial accumulation is identified to the northeast of the Breagh discovery at Crosgan (Fig. 2). The underlying Visean is formed of three distinct Formations (Fig. 11): 1) The basal Cementstone Formation, consisting of interbedded mudstones, thin sands and limestone. Deposited in an arid coastal plain and lake setting (Cameron 1993), the Cementstone shows little reservoir potential, and low seal integrity due to the overlying Fell Sandstone Formation. 2) The Fell Sandstone is a thick succession of coarse-grained fluvial-alluvial deposits. This laterally extensive, high NTG sand unit (Fig. 11) shows good reservoir potential. However, it relies on charge from the overlying Scremertson and Westphalian, or its lateral equivalent basinal Cleveland Group. 3) The overlying Scremerston Formation is a succession of interbedded sands, silts, muds and coals (Fig. 11) deposited in a delta plain environment (Cameron 1993). Fluvial distributary channels provide reservoir section, and interbedded coals provide source rock potential. The Visean extends well onto the MNSH Platform, and is seen within the Forth Approaches Basin. It is locally absent across the Dogger High and to the northeast of the study area (Fig. 7).

Base Permian UC - Base Cretaceous UC <Heading 3>

Tectonostratigraphic Unit B, between the Base Permian Unconformity (BPU) and the Base Cretaceous Unconformity (BCU), shows continued thinning across the central part of the study area and thickening into the South Permian, North Permian and Forth Approaches Basins to almost 2000 ms TWT (Fig. 6).

The Rotliegend sits directly above the BPU. Well penetrations confirm its distribution is limited to the North and South Permian Basins and the Forth Approaches Basin (Fig. 12). The isochron shows a thickening to over 400 ms TWT in the North and South Permian Basins (Fig. 12 A). There is an additional accumulation in the Forth Approaches Basin, although there is no evidence from well or seismic data that this is in communication with the North Permian Basin. Over the central part of the study area, the Rotliegend is absent and the Permian Zechstein sits directly above the Carboniferous, indicating that this area remained a regional high throughout the Lower to early Upper Permian. Well data shows that at the time of deposition, the region was exposed to semi-arid tropical desert conditions and consists of playa-lake and aeolian deposits. A number of distinct facies are seen across the region (Fig. 12 B). The youngest Permian deposits are seen in the very north east of the study area, where Lower Permian basalts and tuffs are seen (Fig. 12 B). These are the Inge Volcanics, which extend eastwards into Denmark, Germany and Poland. They are thought to represent post-Carboniferous transtensional faulting in the region (Glennie and Underhill 1998). Above and adjacent to the Inge Volcanics in the north of the region, the Auk Formation is dominantly dune-bedded sandstones (Cameron 1993), resulting in an attractive thick aeolian sandstone reservoir target (Fig. 12 B). Locally the Auk formation is interbedded or replaced by the Fraserburgh Formation (Fig. 12 B) (Doornenbal and

Stevenson 2010). Although no wells in this study penetrated this formation, studies show this muddy siltstone represents a dune-bordered sabkha deposit with limited reservoir potential (Cameron 1993). To the south of the MNSH, the Silverpit Mudstones represent a large playa lake (Johnston et al. 1994) (Fig. 12 B). The southern margin of this lake has previously defined the play fairway for the Leman Sandstone play of the Southern North Sea – which is formed of lake margin and aeolian sandstones. The recent discovery at the Cygnus Gas Field is the first to target the thin northern margin of the Silverpit Lake, and shows red silt-rich sandstones of fine to medium grainsize pinching out onto the MNSH (Fig. 11). These are interpreted to have been deposited on a playa shoreline environment that shows evidence for repeated flooding and drying events (Catto et al. 2017). The Permian Rotliegend is a *proven* play within the study area, both on the north eastern margin at the Auk Field, and the southernmost margin at Cygnus (Fig. 2).

Directly overlying the Rotliegend, the Zechstein Group consists of repeated sequences of carbonates and evaporites with minor mudstones deposited during the Late Permian (Taylor 1998; Johnston et al. 1994). Mapping the Top Zechstein is challenging for a number of reasons: 1) The lithostratigraphic top identified in well penetrations is not always represented by a significant AI contrast; 2) There are numerous lateral changes in depositional facies leading to changing acoustic characteristics; 3) Salt halokinesis and overburden faulting has resulted in complex salt pillows, diapirs and wings being formed within depocentres. Despite these challenges, a Near Top Zechstein surface has been mapped regionally and shows a broad deepening to the east down to approx. 3200 ms TWT. An isochron of the Zechstein Group (Fig. 13 A) shows its presence over much of the study area with the exception of the very west where Tertiary erosion has occurred. The isochron clearly highlights zones of halokinesis in the North and South Permian and Forth Approaches Basins. Salt diapirs reach a maximum thickness of 800 ms TWT. Figure 14 demonstrates the changing Zechstein seismofacies across the study. Internal reflections within the Zechstein relate broadly to the Z1-5 cycles which were formed due to multiple desiccation events. High amplitude hard reflections represent anhydrite layers directly below carbonate build-ups (Taylor 1998). Two distinct seismofacies are identified. Firstly *carbonate dominated facies* are characterised by high amplitude laterally continuous reflections with common ramp or platform morphologies (Fig. 14). They correlate to regions where the isochron thins to less than 120 ms (Fig. 13 A). Wells penetrating these thins generally show dolomite layers of up to 16% porosity and are named the Mid North Sea, Dogger, and Auk- Flora Carbonate Platforms (Fig. 13 B). Although lacking in well control, seismic observations suggest that the Devil's Hole platform also comprises carbonate platform facies (Fig. 13 B). Salt-dominated facies form the thickest accumulations of the Zechstein Group, and are found in the North and South Permian, and Forth Approaches Basins (Fig. 13). Facies mapping suggests a salt 'sea-way' protruding through Quad 37 that separates two carbonate margins (Fig. 13) (Jenyon et al. 1984). Where the salt basin reaches thicknesses of over 500 ms TWT, salt pillows and diapirs dominate. Mapping of the salt structures is biased due to spacing and orientation of 2D seismic lines, however it is clear that salt structures are orientated NW-SE to NNE-SSW, likely due to gravitational compression of the salt away from basin margins. These facies have been compared to well results and mapped across the AOI to produce a facies map (Fig. 13 B). The Permian Zechstein Dolomites are a proven play on the northern edge of the study area at the Auk Field (Fig. 2). These dolomites were developed on the long-standing Auk High, and the reservoir shows excellent vuggy porosity, charged with Jurassic oils sourced from the Central Graben (Trewin et al. 1991). Elsewhere, the Zechstein dolomites record a number of shows across the region, and one uncommercial discovery is identified at Crosgan, located on the southern margin of the MNSH (Fig. 2). Despite these positive indications of a widespread working play, the Zechstein Dolomites of the MNSH have yet to replicate the success of its counterpart onshore Poland in the easternmost South Permian Basin. The Bronsko and Koscian discoveries (Doornenbal and Stevenson 2010) make good analogues for the dolomite play of the Mid North Sea High.

Tectonostratigraphic Unit B is topped by Triassic and Jurassic strata. Over the MNSH, much of the upper Mesozoic section is absent due to erosion. The resulting Mid Cimmerian and Base Cretaceous Unconformities show a complex interaction over the region. Lower Triassic deposition is largely limited to the salt mini-basins generated by salt halokinesis in the underlying Zechstein (Fig. 15 A). Over much of the north east of the region however, the Triassic is absent due to Jurassic uplift and erosion. The Mid Cimmerian Unconformity has been identified in the Moray Firth and Viking Graben and represents Early to Mid Jurassic mantle-driven thermal doming under the triple rift junction of the Central North Sea (Underhill and Partington 1993). As a result of this uplift, localised Lower Triassic erosion has occurred in the north east of the region, and there is a significant break in deposition, with no Upper Triassic or Lower - Mid Jurassic sedimentation preserved. The Upper Jurassic is clearly seen to onlap the Mid Cimmerian Unconformity and indicates renewed subsidence prior to the onset of rifting in the Central Graben (Fig. 4; 15 B). It should be noted that in the south of the region, within the Solepit Basin, there is no evidence for a break in sedimentation with a full Triassic and Jurassic sequence being identified. The interaction of these major unconformities can be illustrated with the Mid Cimmerian and Base Cretaceous Unconformity Subcrop Maps (Fig. 15 C; D). The maps show that these two unconformities become conformable to the south. This area shows a complex structural evolution, with the Dowsing and North Dogger Fault Zones clearly mappable in the isochron (Fig. 15). These fault zones are made up of large, listric, extensional faults that detach in the Triassic and Permian evaporate sequences. Well data confirms that the most widespread Lower Triassic facies is the Smith Bank Formation, which was deposited across a hot, arid continental plain that consisted of playa mud flats. Locally, ephemeral desert lakes formed within the basin depocentres where salt-withdrawal strongly controls deposition. Clastic input was limited, or certainly sourced distally and deposited in a low- energy environment. Any sand beds encountered are thin (<1 m), and as a result, the Smith Bank Fm. shows little to no reservoir potential. To the south, the Bacton Group represents a succession of distal floodplain and playa lake muds topped by the Bunter Sandstone fluvial and alluvial sands. Sand deposition appears to be restricted to depocentres adjacent to structural highs that can provide clastic input. Within the study area, the Bunter sands are interpreted as being deposited by braided rivers on a series of alluvial fans (Bifani 1986), eroded proximally from the footwall of the Dowsing and North Dogger Fault zones (Fig. 15). Due to Jurassic erosion of the MNSH, there are a number of regions where the Triassic is completely absent, including the east of the study area, the Mid North Sea Platform and Devil's Hole High (Fig. 15). Later Tertiary uplift has removed the Triassic in the west of the region (Fig. 5). The Lower Triassic Bunter Sandstone is a proven play over the southern margin of the MNSH at the Esmond Cluster

(Fig. 2). To the west, the non-commercial Furasta Field remains an unsanctioned discovery. All these fields show under filled gas accumulations within salt-cored anticlines at Triassic Bunter Sandstone level. The fields are sealed by the Upper Triassic Rot Halite and a thick succession of upper Triassic mudstones.

Mapping of facies distributions and isochron thins therefore suggests that the Mid North Sea High Platform and Dogger Granite High remained elevated throughout the deposition of Tectonostratigraphic Unit B, with additional Jurassic uplift of the north east of the study area, related to the central North Sea rift system, forming a Western Platform on the flank of the graben. The South Permian and Sole Pit Basin in the south, and the Forth Approaches and North Permian Basins in the north are the main depocentres for sediment at this time.

Base Cretaceous UC - Mid Tertiary UC <Heading 3>

Directly overlying the Base Cretaceous Unconformity are the Lower Cretaceous Cromer Knoll and Upper Cretaceous Chalk succession. These units signify a move to more stable tectonic conditions. This package is locally modified by Zechstein salt movement which forms NW-SE striking mini-basins (Fig. 6). In the central study area, where salt is thin or absent, Tectonostratigraphic Unit C is fairly consistent in thickness at around 750 - 1000 ms TWT. Of note is the thinning in the north east along the flank of the Central Graben (Fig. 6). It is in this region that additional thinning occurred during Mid Cimmerian uplift and erosion. In the west of the study area there is a dramatic thinning to zero thickness where the unit is subcropping the seabed due to Tertiary tilting and erosion (Fig. 4; 6).

Tectonostratigraphic Unit C can be subdivided into two units: 1) The Cretaceous, predominantly Upper Cretaceous chalk succession, with the Lower Cretaceous section being very thin across the MNSH (<200 ms); and 2) The Lower Paleogene clastics which is topped by the Mid Tertiary Unconformity (MTU). By the early Cretaceous, the focus of rifting had switched to the Proto-Atlantic, and thermal subsidence began in the North Sea (Erratt et al. 1999). This was a relatively quiet time in the tectonic evolution of the area with ongoing thermal and compaction-related subsidence with minor fault reactivation. The Lower Paleogene (Palaeocene, Eocene, and earliest Oligocene) section shows significant thinning over the Cygnus Field in the southeast of the study area. No related faulting is observed in the post-salt, but the inversion is represented by a broad anticline. This suggests that inversion of the Base Zechstein Cygnus structure, and therefore trap formation, occurred at this time. Given this timing of the inversion and the orientation of compression, it is tentatively assigned to far-field stresses related to the Pyrenean Orogeny (Parrish et al. 2018), and/or Alpine Orogeny (Ziegler 1983).

Mid Tertiary UC – Seabed <Heading 3>

The Mid Tertiary Unconformity (MTU) is gently dipping to the north east with only some minor modification by halokinesis. Overlying Tectonostratigraphic Unit D is absent over the west of the study area, thickening in the north east to approximately 2000 ms TWT and forming a thickening wedge of prograding sediment sourced from the east. (Fig. 4; 6). The MTU represents the regional tilting of the United Kingdom in response to the opening of the Atlantic Ocean (Guariguata-Rojas and Underhill 2017). Only a handful of wells in the study name formation tops in the Tertiary, and date the unconformity surface to 'Top Hordaland' or Early Eocene to earliest Oligocene. Therefore, the MTU is dated at approximately 30 Ma at this location. Further east in the Dutch sector, the downlap surface is dated to the Miocene Unconformity (Verweij et al. 2018). It is therefore likely that this surface is highly diachronous.

Discussion

Defining the Mid North Sea High

The newly acquired OGA_2015 regional seismic data allows for a revised evaluation of the structural evolution and facies distribution over the Greater Mid North Sea High region of the Central North Sea (Fig. 16). This study identifies four tectonostratigrahic megasequences that each represent a significant tectonic reorganisation of the Central North Sea.

Tectonostratgraphic Unit A comprises the Devonian and Carboniferous. This study clearly demonstrates that basement terrane exerts a strong control over the Devonian and Carboniferous depocentres. Detailed seismofacies mapping of the Devonian Kyle Limestone (Fig. 9) demonstrates that early emplacement of granite bodies in the east of the study area has created isolated buoyant basement blocks at the Dogger and Auk Highs, much like the block and trough morphology observed onshore at the time. Therefore, during the Devonian and Carboniferous, the MNSH was a region of isolated highs separating a number of heavily faulted depocentres (Fig 7; 16).

The Variscan Orogeny marked a time of uplift and erosion over the Central North Sea. The Base Permian Unconformity shows erosional truncation of underlying Tectonostratigraphic Unit A (Fig. 10), and a complex subcrop of Carboniferous and Devonian strata over isolated highs such as the Dogger High and Mid North Sea Platform (Arsenikos et al. 2015). The limited distribution of Permian Rotliegend over the Base Permian Unconformity (Fig. 12) shows that following the Variscan Orogeny, the MNSH was a much more regionally-extensive feature. Facies mapping of the overlying Zechstein has shown carbonate-dominated deposition across the Mid North Sea High, Dogger, Auk, Flora and Devil's Hole Platforms and indicates that these areas were a relative high compared to the adjacent salt basins of the North and South Permian and Forth Approaches Basins (Fig 13; 16).

The Triassic saw renewed extension and the development of the Dogger and North Dowsing Fault zones in the south (Fig. 15). In the north, there is a complex interplay of Mesozoic unconformities developed in association with the Jurassic rifting of the Central North Sea. The Mid Cimmerian Unconformity is tied to the thermal doming of the Central North Sea prior to the development of the trilete rift system (Underhill and Partington 1993). Continued rift development led to rift flank uplift in the NE along the edge of the Central Graben, which is identified as a NW-SE oriented region where Jurassic strata is absent (Fig. 15 B). Moving southwards, the Mid Cimmerian UC becomes conformable with the Base Cretaceous UC. Therefore, there is a significant reconfiguration of the MNSH during the Mesozoic, with uplift focussed in the northeast, along the western flank of the Central Graben. We propose that the region should be named the *Western Platform*. Erosion has led to a complex subcrop of Triassic and Jurassic strata across the region (Fig. 15), however burial curves suggest reduced rates of sediment accumulation throughout the Triassic and Jurassic (Fig. 16), and therefore the region remained a High throughout the development of Tectonostratigraphic Unit B.

Lower Cretaceous deposits are extremely thin over the study area. Upper Cretaceous Chalk deposition blankets the region, with the exception of the Western Platform of the Central Graben which shows a depositional thin (Fig. 4; 6). This indicates a switch to widespread post-rift thermal subsidence and basin fill. The Paleocene documents the beginning of a regional tilting of the UK with progradation from the west (Fig. 4). In the northwest of the region, the highly reflective Balder Package signifies the opening of the Atlantic Ocean, and the beginning of the demise of the MNSH. In the south, far field stresses generate localised tectonic activity, and it is during this time that inversion is seen across the Cygnus structure to the South of the Dogger High.

Tectonostratigraphic Unit D is formed of a thickening wedge of prograding sediment sourced from the east. It is separated from Tectonostratigraphic Unit C by the Mid Tertiary UC, a complex diachronous surface which was formed during the tilting of the study area down to the east. Uplift in the west has caused extensive erosion at the seabed, and a progressive subcropping of Mesozoic Strata westwards (Fig. 4). This tilting led to a significant tectonic overprinting, and the disappearance of the MNSH and Western Platform as prominent features. Jones et al. (2002) propose that the uplift is a result of magmatic underplating of the crust related to the interaction of Atlantic Sea Floor Spreading and the Iceland Plume. Others suggest asthenosphere diapirism generating domal uplift related to the eastward advance of the plume towards Europe (Rohrman et al. 1996). Finally, other authors attributed the uplift to crustal compression associated with plate boundary forces (Hillis et al. 2008). We note that the uplift is coincident with Sea Floor Spreading switching off in the Labrador Sea and the onset of Pyrenean orogenic compression (Doré et al. 1999, Parrish et al. 2018).

Implications for petroleum prospectivity

The tectonic evolution of the MNSH and Western Platform region has important consequences for the hydrocarbon prospectivity of the region. Despite some promising indications of remaining hydrocarbon potential along the margins of the region (Fig. 2), the prospectivity has historically been downgraded compared to the adjacent Central Graben and Southern Gas Basin. Here, we discuss how the structural evolution of the region controls aspects of the petroleum play.

Reservoir <Heading 3>

Reservoir facies are identified at multiple levels within the succession, principally: 1) Devonian Kyle Limestone; 2) Lower Carboniferous Visean sandstones; 3) Carboniferous Namurian sandstones; 4) Permian Rotliegend sandstones; 5) Permian Zechstein carbonates; and 6) Triassic Bunter sandstone. The distribution of each of these reservoir facies is strongly controlled by the nature of the MNSH at the time of deposition.

The Devonian Kyle Limestone is the stratigraphically oldest potential reservoir in the region. Mapping of seismiofacies tied to well data shows that the Kyle is restricted to the east of the study area over the Dogger and Auk granite-cored highs (Fig. 9). This suggests that the emplacement of buoyant granite bodies exerted a strong control over reservoir distribution as early as the Devonian. Overlying the Kyle Limestone, the Devonian Old Red Sandstones show poor reservoir potential due to diagenesis that has occurred during numerous phases of deformation.

The Carboniferous is absent from most wells in the north of the study area (Fig. 7). At this time, the gross depositional environment is interpreted to be a large southward prograding delta system, fed by sediment eroded from the Caledonian Mountains in the north (Doornenbal and Stevenson 2010; Monaghan et al. 2017). Within the Namurian, fluvio-deltaic sandstones form an attractive, and proven target. Within the underlying Visean section, the Scremerston fluvial sands are proven at Breagh, and the fluvial Fell Sandstone is a high net to gross potential target (Booth et al. *this volume*). Mapping the extent of these reservoirs is extremely challenging given the faulted nature of the Carboniferous section, the poor pre-Zechstein seismic imaging, and the highly cyclic nature of the Carboniferous deltas. Locally, distribution of the Carboniferous is altered where isolated granite-cored structural blocks form topographic highs (Fig. 7). These regions form attractive traps, however sands deposited are likely to be poorer quality where they are locally sourced from isolated highs (due to lower sediment maturation and sorting) when compared to open delta plain fluvial or shoreface deposits.

Throughout the Permian, the MNSH exerts a strong control on reservoir distribution. The High becomes an E-W trending regional feature separating the North and South Permian Basins. Variscan uplift caused erosion and non-deposition over the High, and deposition of the Rotliegend was restricted to the North and South Permian and Forth Approaches Basins where aeolian and lacustrine shoreface sands have accumulated (Fig. 12). Regional subsidence led to marine flooding across the entire region and the deposition of the Zechstein group. Carbonates define the relative highs at the time, which can be accurately mapped using well penetrations and seismofacies (Fig. 13). The reservoir is proven at the Auk Field in the northeast, and at Crosgan in the southwest, with much reservoir potential remaining across the region, particularly across the west of the MNSH, where a large carbonate platform can be mapped (Patruno et al. 2017) and in the North where the Devil's Hole Carbonate Platform remains untested.

The Triassic overlies the Permian Zechstein. There is limited reservoir potential with the exception of the southern margin where the Dogger and North Dowsing fault zones provide local sediment input for the Bunter sandstones (Fig. 15). The modern distribution of the Lower Triassic is further controlled by Jurassic erosion of the MNSH, resulting in the Mid Cimmerian and Base Cretaceous Unconformities and leading to a number of regions where the Triassic is completely absent over the Western Platform in the east of the study area, the Mid North Sea Platform and Devil's Hole High (Fig. 15). Later Tertiary uplift has removed the Triassic in the west of the region (Fig. 15).

No significant additional potential reservoir sections are identified over the MNSH with the exception of the Tertiary. Early Tertiary deep water sands form the reservoir at the Catcher Cluster in the north on the margin of the Central Graben (Fig. 2). However, these deep water sands are not likely to extend outside the graben system and onto the Western Platform and so have been excluded from the discussion. Additional potential reservoirs have been noted in the east of the region in the upper Tertiary prograding wedge of Tectonostratigraphic Unit D. These glacial and fluvial delta top sands show excellent reservoir potential, however shallow burial depths make them a challenging play to exploit. There have been a number of small discoveries at this stratigraphic level made in the Dutch North Sea which have been producing since 2007 (Verweij et al. 2018).

Trap & Seal <Heading 3>

The nature of trapping mechanisms across the MNSH varies per play, and is strongly controlled by structural evolution and facies distributions. Carbonate reservoirs (Devonian Kyle, Permian Zechstein) rely on some stratigraphic component to trapping. Clastic plays are more variable, with pre-Zechstein plays (Carboniferous Namurian and Visean) generally exhibiting 3-way structural traps within faulted blocks. The plays rely on Base Zechstein caprocks, however past drilling activity is skewed to identifying these closures, and intraformational seals remain poorly understood (Belsy et al. 2018). Post-Zechstein plays have variable trapping mechanisms. Triassic Bunter fields are generally simple 4-way salt-cored anticlinal structures. Although not discussed in detail herein, Upper Jurassic and Tertiary fields along the north of the study area are stratigraphically trapped within deep-water turbidite deposits.

The regional tilting of the area has important implications for hydrocarbon remigration and trap formation. Simple backstripping of the late Tertiary to reconstruct the margin pre-tilt has been completed (by removing Tectonostratigraphic Unit D overburden) (Fig. 17). Using a key regional seal, the Base Zechstein surface, the effects of the tilt are clearly demonstrated. With the removal of the thickening sediment wedge in the east of the study area, the Base Zechstein surface shows a distinct high in the NE. This tectonic tilting has important implications for the maturation of source rocks in the region. It has also likely promoted re-migration of hydrocarbons from deep traps in the east of the study area up dip towards the west. Uplift and erosion in the west has resulted in strata subcropping the seabed (Fig. 4), and has likely meant the loss of hydrocarbons in this region. Further work is required to accurately conduct a regional backstripping that incorporated compaction trends.

Source Rocks and Charge <Heading 3>

Source distribution, generation and migration are key risks when exploring the MNSH. There are two proven petroleum systems that charge fields along the margins of the High. Firstly, in the north and north east, fields are oil charged by Kimmeridge-sourced marine mudstones. Deposition was focused within the axis of the Central Graben where maximum Kimmeridge Clay thicknesses reach approximately 1000 ft (Fraser et al. 2003). In the footwall to the main bounding faults of the rift, the Upper Jurassic rapidly decreases in thickness. A number of wells in this study record Upper Jurassic sediments (including Kimmeridge Clay source rock), but thicknesses rarely exceed 350 ft for the entire Upper Jurassic section thus restricting its source potential over the MNSH. In addition, the construction of burial curves has been used to examine the magnitude of uplift events using predicted sedimentation rates (Fig. 16). The burial curve for well 38/16-1 illustrates that the MNSH remained a region of limited subsidence throughout the Mesozoic and Cenozoic compared to adjacent basins (wells 43/06-1 and 39/02-4). The Kimmeridge Clay source rock reaches depths of over 5000 m within the axis of the Central Graben (Day et al. 1981). Therefore, source rocks on the High will not have reached the oil maturation window historically. Charge from the Kimmeridge Clay, therefore, requires long-distance migration from the source kitchen within the Central Graben where this prolific source rock is actively generating and burial depths switched on early oil expulsion in the Tertiary (Cornford 1998). Bounding faults do allow for the uplift of older strata above the source rock, and establish a potential migration route. In reality, however, the complex nature of these bounding fault complexes leads to arduous migration routes and possible migration shadows. This is further complicated by the re-migration of oil during the Mid Tertiary tilting event (Fig. 17), which provides opportunity for Jurassic oils to move westwards. This re-migration into highs across the Western Platform (for example at Devils Hole) is quite possible, but is extremely challenging to de-risk. Further work is therefore required to assess the charge story along the Western Platform.

The second MNSH petroleum system of interest is the Carboniferous-sourced gas system of the Southern North Sea Gas Basin. Historically, the Upper Carboniferous Westphalian coal measures have been deemed the main source rock to the plays of the Southern North Sea. Over the MNSH however, the Westphalian is largely absent (Fig. 7). Recent publications have demonstrated the potential for a second source rock within the Carboniferous at the Scremerston coal level along the southern margin of the study area (Belsy et al. 2018; Grant et al. 2018). The Breagh Field (and Crosgan unsanctioned discovery) are outliers to the main Carboniferous play fairway. Basin modelling over the Breagh discovery shows that the Scremerston coal measures could be a viable source for the accumulation, and therefore opens up a much wider zone of prospectivity over the Southern Margin of the MNSH (Monaghan et al. 2017; Grant et al. *This volume*).

An additional source rock, and important indicator for burial, is the Permian Zechstein Kupferschiefer. Shows are noted in the Zechstein dolomites in the west, in the Forth Approaches Basin, in Quad 41 and Quad 42. The Permian Zechstein, therefore contains all the components of a petroleum play: source, reservoir (dolomites) and seal (halites and anhydrites) (Patruno et al. 2017). However, the Kupferschiefer rarely exceeds 2 metres in thickness, therefore limiting the source rocks potential to generate economic volumes. Finally, the potential for biogenic shallow gas accumulations in the region should be noted. The play fairway lies mainly to the east this study, in the Dutch North Sea. Here, a number of fields are under development with play GIIP estimates ranging from 1.2 – 4.1 tcf (Verweij et al. 2018). Well 39/16-1 encountered one such biogenic gas accumulation on the eastern flank of the Dogger High. The well targeted N-S orientated shoreface sands in front of the westward-prograding delta. Although the End of Well Report records that Pliocene sands were thinner than expected, bright spots observed in the seismic were confirmed to be gas-bearing intervals. Elsewhere, there are additional bright spots and evidence for shallow gas, however these are not likely to show the volumes seen in accumulations across the Dutch Play Fairway given their distal location from the sediment source in the east.

Conclusions

This study examines the newly acquired regional 2D seismic data-set over the Mid North Sea High funded by the UK's Oil and Gas Authority as part of their Frontier Basin's Programme. It is the first study to examine the Mid North Sea High stratigraphy from Devonian up to present day.

Seismic mapping identifies four key Tectonostratigraphic Units that correlate to plate-scale tectonics. Each plate cycle exerts a strong control over the Mid North Sea High Region which shows an evolving nature and spatial extent. We demonstrate that during Tectonostratigraphic Unit A – the Devonian and Carboniferous – the study area was largely a depocentre for sediments being shed from the Caledonian Mountains in the north. Seismic facies mapping shows that granite-cored blocks formed localized highs across the region. Following the Variscan Orogeny, the Mid North Sea High was a regionally-extensive feature, orientated W-E and separating the North and South Permian Basins. A connecting seaway is mapped during the Zechstein that separates the Mid North Sea High Platform from the Dogger-Auk Platform. The region remained a relative high throughout the early Mesozoic, however the focus of uplift moved to the flank of the Central North Sea trilete rift in the north east, forming the Western Platform. The Mid Tertiary saw a complete tectonic reorganization of the region and the demise of the Mid North Sea High. Regional tilting of the UK relating to the opening of the Atlantic Ocean led to uplift in the west of the study area and the progradation of sediments from the east.

This evolution of the region has important implications for hydrocarbon prospectivity. For example, during the Permian, the clastic-dominated Rotliegend system saw erosion and non-deposition over much of the Mid North Sea High, and the play is restricted to the adjacent North and South Permian Basins. This is in contrast to the Upper Permian Zechstein play which sees carbonate reservoir facies deposited across the Mid North Sea High, with non-reservoir facies within the adjacent basins. It can therefore be concluded that the evolution of the Mid North Sea High exerts a strong control on the distribution of play elements. Carbonate reservoir distribution is restricted to the high, although is susceptible to erosion. Clastic reservoir deposition is strongly controlled by uplift and erosion of the Mid North Sea High providing sediment influx to adjacent depocentres. Multiple uplift events have controlled the distribution of source rocks and their maturation history. Finally, the major tectonic reorganisation in the mid Tertiary has led to the re-migration of hydrocarbons to the west, into newly-formed traps or to the seabed. Basin modelling is required to fully understand the consequences of this uplift event for the petroleum systems.

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Tables

OGA Data Pack	THIS STUDY			
	Seismostratigraphy	Chronostratigraphy	Lithostratigraphy	**FINAL NOMENCLATURE**
Waterbottom	Seabed	various	various	**Seabed**
-	Mid Tertiary UC	various	various	**Mid Tertiary Unconformity (MTU)**
-	-	Top Palaeocene	Top Balder	**Top Palaeocene**
Top Chalk	-	Top Upper Cretaceous	Top Chalk*	**Top Upper Cretaceous**
Base Chalk	-	Top Lower Cretaceous	Top Cromer Knoll	**Top Lower Cretaceous**
-	Base Cretaceous UC	various	various	**Base Cretaceous Unconformity (BCU)**
-	Mid Cimmerian UC	various	various	**Mid Cimmerian Unconformity (MCU)**
-	-	Top Upper Triassic	various	**Top Upper Triassic**
-	-	Top Lower Triassic	Top BactonGroup	**Top Lower Triassic**
Upper Permian (Zechstein)	-	Top Upper Permian	Top Zechstein Group	**Top Permian Zechstein Group**
Base Zechstein	-	Intra Upper Permian	Base Zechstein / Top Rotliegend	**Top Permian Rotliegend Group**
-	Base Permian UC	various	various	**Base Permian Unconformity (BPU)**
-	Basement	Top Mid Devonian	Top Basement	**Basement**

Table 1: *Surfaces interpreted in this study. Noted are the surfaces provided in the original Oil and Gas Authority (OGA) Mid North Sea High data pack. *Top Chalk is picked as Top Upper Cretaceous Chalk in this study.*

Figure Captions

Figure 1: *The tectonic setting, and Basement Terranes of the North Sea. Location of the Mid North Sea High study area indicated by blue AOI (area of interest) polygon. Modified from Evans et al. (2003), Glennie (1998) and Frogtech (2016).*

Figure 2: *The exploration history of the Greater Mid North Sea High region over time. License blocks shaded grey and wells drilled are indicated. Study area highlighted by blue polygon. Gas (red) and oil (green) discoveries are highlighted in addition to unsanctioned discovery Crosgan. Highlighted wells 28/29-1 and 44/02-1 are the first and second exploration wells to be drilled offshore the UKCS.*

Figure 3: *The data used in this study including well and seismic data. Location of seismic lines shown in Figure 4 indicated.*

Figure 4: *(**A**) Seismic Line OGA_2015 L58 and (**B**) OGA_2015 L18. Upper panel shows OGA_2015 seismic data and well locations. Lower panels show the interpretation of the seismic data and key observations. Line locations indicated on Figure 3. Colours indicate geological age (see Fig. 5).*

Figure 5: *The chronostratigraphy of the Mid North Sea High. Interpreted seismic horizons are highlighted. The seismic loop picked is indicated. Data is zero phase, normal polarity, therefore peaks represent a hard acoustic impedance.*

Figure 6: *Isochron maps with interpretation for the four key Tectonostratigraphic Units A to D.*

Figure 7: *Main Devono-Carboniferous depocentres and structural highs with well penetrations. Basement Terranes from Frogtech (2016).*

Figure 8: *Seismic cross section illustrating the high amplitude Kyle Limestone package. Seismic line location shown in Figure 9.*

Figure 9: *Seismofacies mapping of the Kyle Limestone with associated well penetrations. Unknown indicates that the well did not penetrate this stratigraphic level.*

Figure 10: *Base Permian UC and Carboniferous seismic facies and fault blocks. Seismic section location indicated in Figure 7.*

Figure 11: *Pre-Zechstein well penetrations for two well sections across the southern MNSH. Section locations indicated in Figure 7.*

Figure 12: *(**A**) Permian Rotliegend isochron thickness map. (**B**) Seismic and well facies mapping for the Permian Rotliegend Group. Well facies sticks are shown in true vertical thickness.*

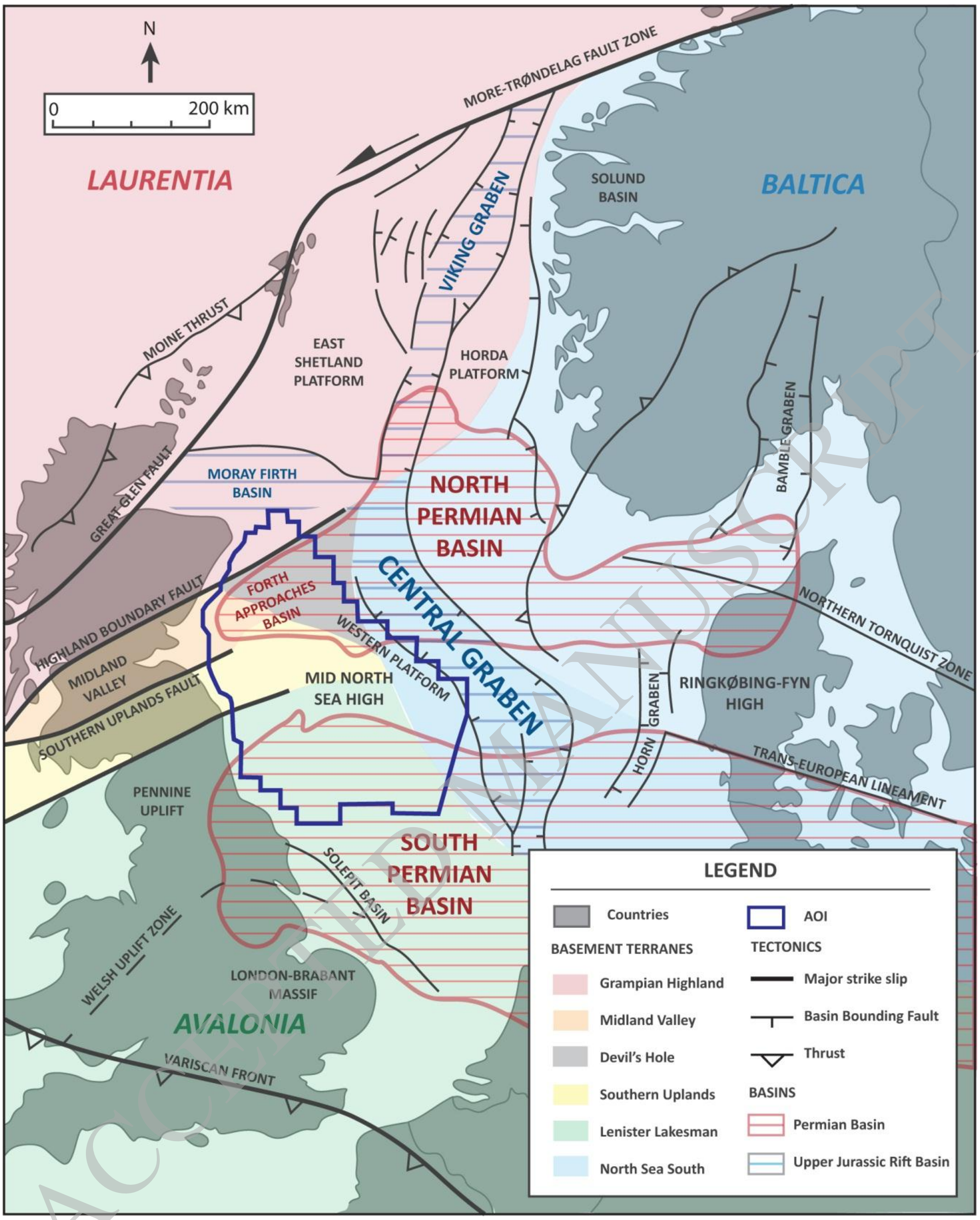
Figure 13: *(**A**) Permian Zechstein isochron thickness map. A) – D) seismic sections shown in Fig. 14. (**B**) Zechstein facies mapping and well data. Where wells are 'unknown or absent' the well is likely to have TD-ed in the Cenozoic / Mesozoic, of the Zechstein is locally eroded away. Mapping reveals carbonate margin, isolated platforms and salt basins with extensive salt pillowing and diapirism. Map created using seismic facies mapping, with isochron and well data.*

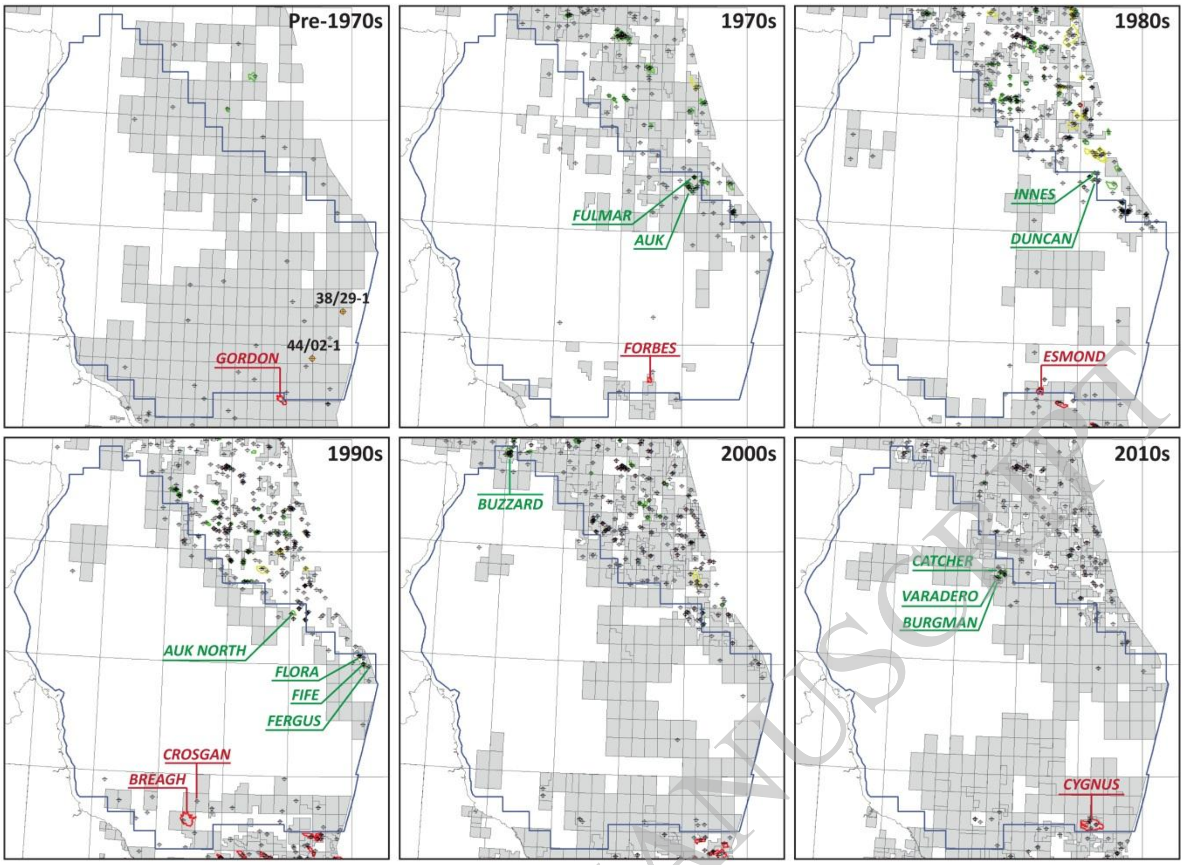
Figure 14: *Example cross sections across the Zechstein showing the changing facies of the supergroup. Section localities indicated in Figure 13.*

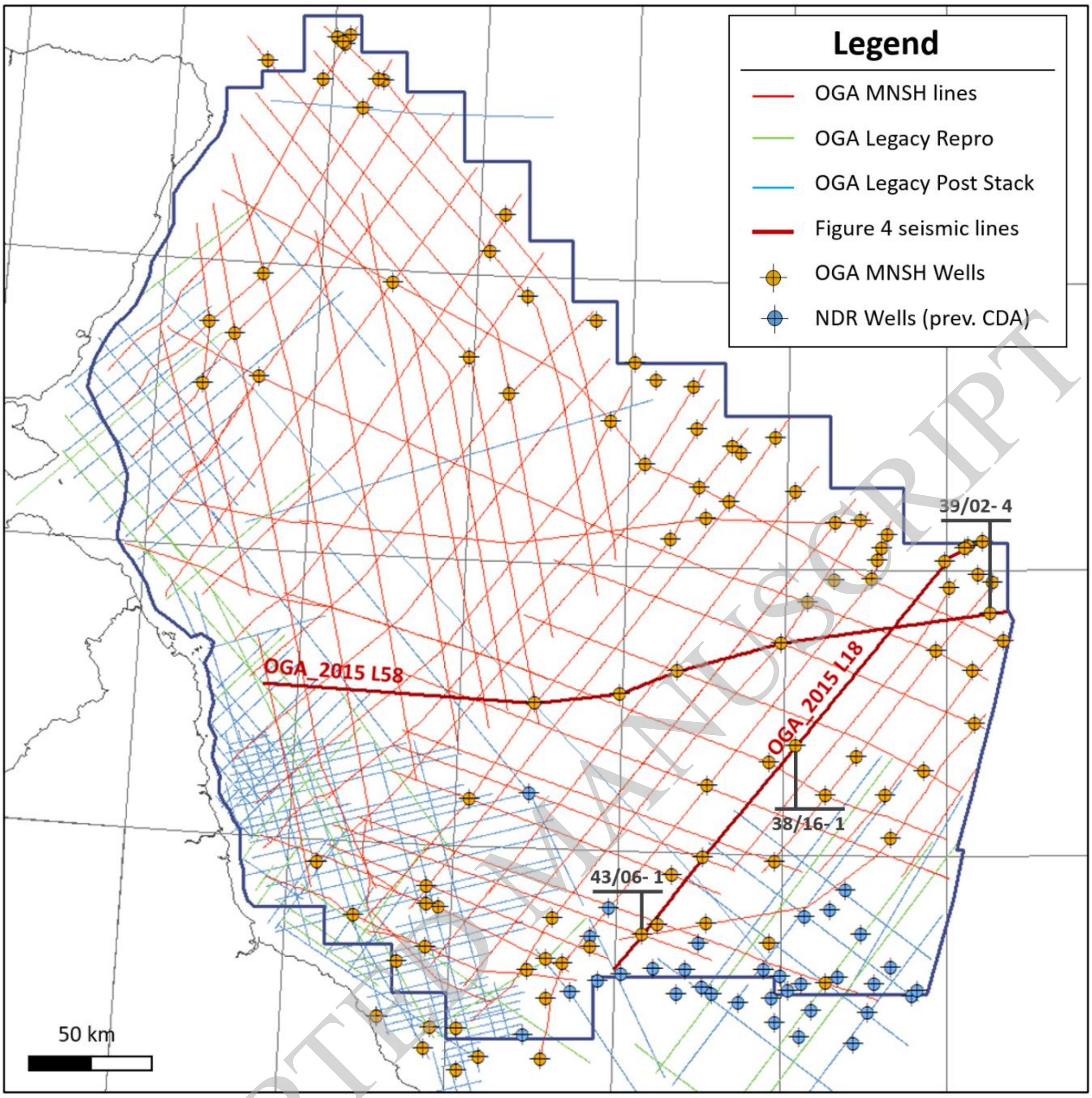
Figure 15: *(**A**) Lower Triassic and (**B**) Upper Jurassic Isochron thickness maps. These maps demonstrate the extensive erosion by the MCU and BCU over the MNSH. (**C**) Base Cretaceous and (**D**) Mid Cimmerian Unconformity Subcrop maps with well penetrations. The MCU becomes conformable with the BCU in the south and west.*

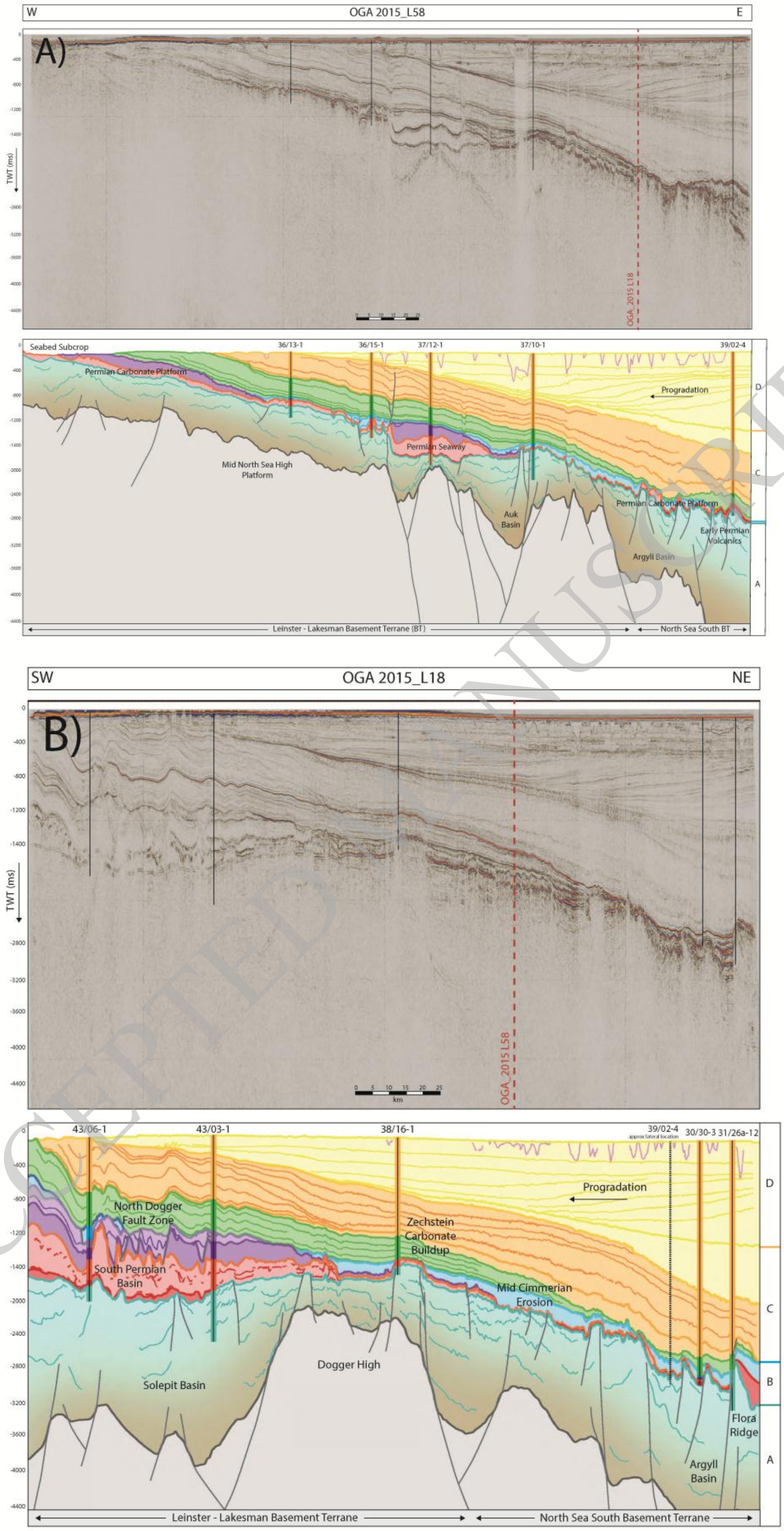
Figure 16: *Wheeler Diagram SW-NE across the Mid North Sea High with burial curves. The figure demonstrates the evolution from localized highs in the Devono-Carboniferous, to a more regional Mid North Sea High during the Permian. Jurassic footwall flank uplift formed the Western Platform in the Mesozoic. Finally, Cenozoic tilting to the west reconfigures the region.*

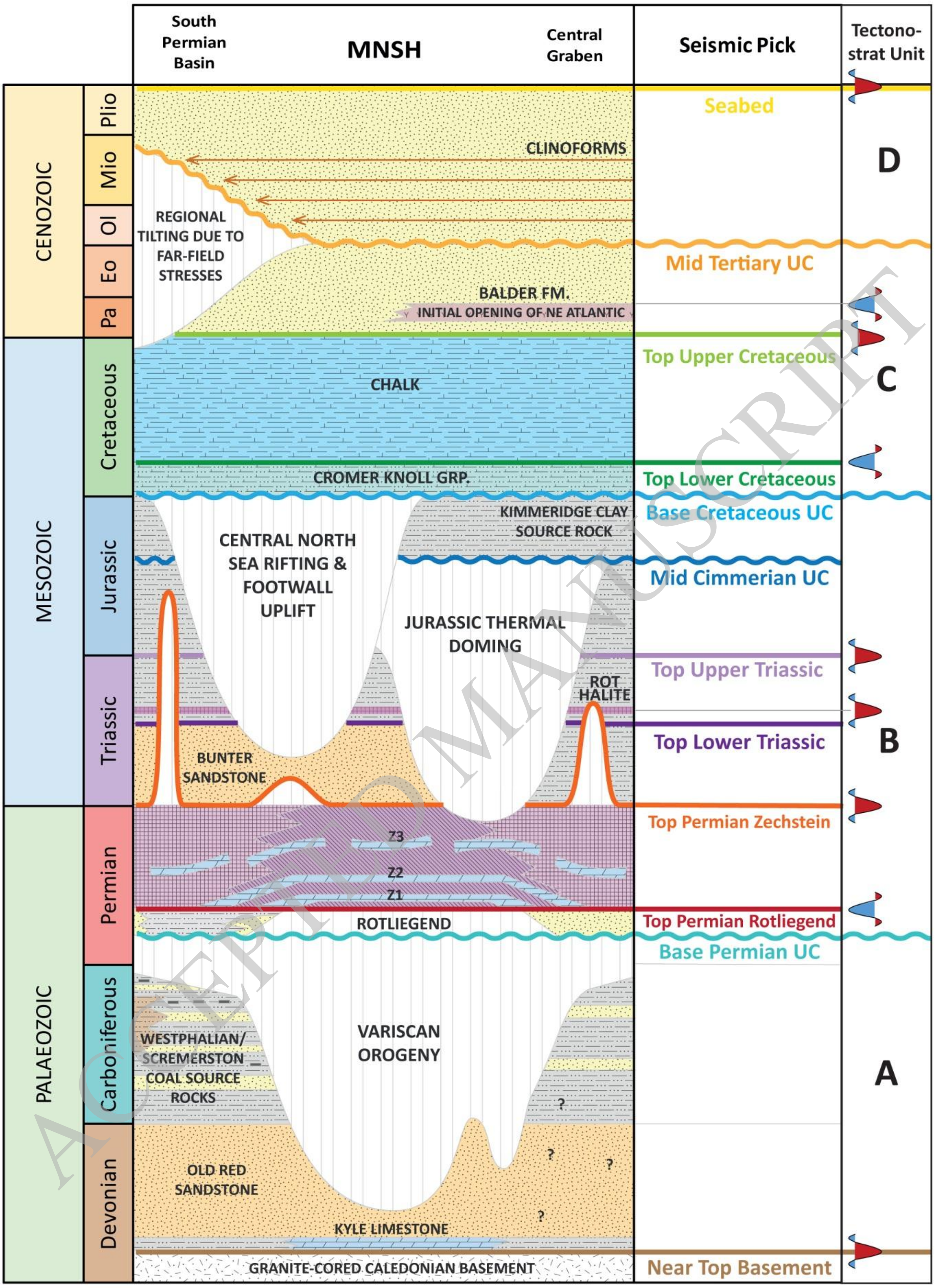
Figure 17: *Effect of the Mid Tertiary tilting on the petroleum systems in the region. Maps show the Base Permian Unconformity surface (Top Carboniferous source rock) prior to regional tilting of the region in the Mid Tertiary, and at present day.*


N
0
200 km
LAURENTIA
BALTICA
AVALONIA
MORE-TRØNDELAG FAULT ZONE
VIKING GRABEN
SOLUND BASIN
EAST SHETLAND PLATFORM
HORDA PLATFORM
MOINE THRUST
GREAT GLEN FAULT
MORAY FIRTH BASIN
NORTH PERMIAN BASIN
BAMBLE GRABEN
FORTH APPROACHES BASIN
CENTRAL GRABEN
HIGHLAND BOUNDARY FAULT
MIDLAND VALLEY
WESTERN PLATFORM
MID NORTH SEA HIGH
SOUTHERN UPLANDS FAULT
NORTHERN TORNQUIST ZONE
RINGKØBING-FYN HIGH
HORN GRABEN
TRANS-EUROPEAN LINEAMENT
PENNINE UPLIFT
SOUTH PERMIAN BASIN
SOLEPIT BASIN
WELSH UPLIFT ZONE
LONDON-BRABANT MASSIF
VARISCAN FRONT
LEGEND
Countries
AOI
BASEMENT TERRANES
TECTONICS
Grampian Highland
Major strike slip
Midland Valley
Basin Bounding Fault
Devil's Hole
Thrust
Southern Uplands
BASINS
Lenister Lakesman
Permian Basin
North Sea South
Upper Jurassic Rift Basin

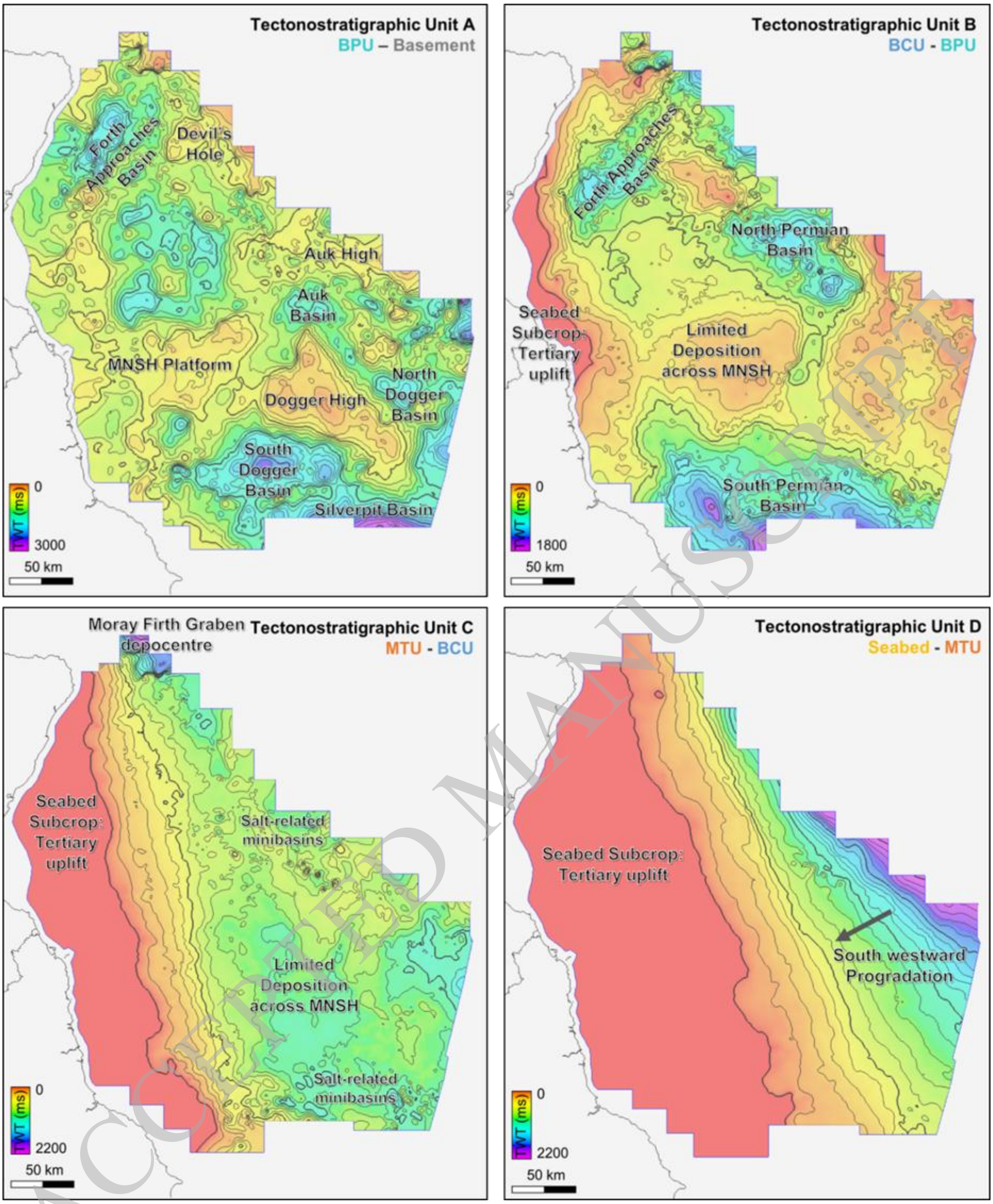

Pre-1970s
38/29-1
44/02-1
GORDON
1970s
FULMAR
AUK
FORBES
1980s
INNES
DUNCAN
ESMOND
1990s
AUK NORTH
FLORA
FIFE
FERGUS
CROSGAN
BREAGH
2000s
BUZZARD
2010s
CATCHER
VARADERO
BURGMAN
CYGNUS


Legend
OGA MNSH lines
OGA Legacy Repro
OGA Legacy Post Stack
Figure 4 seismic lines
OGA MNSH Wells
NDR Wells (prev. CDA)
39/02- 4
OGA_2015 L58
OGA_2015 L18
38/16- 1
43/06- 1
50 km

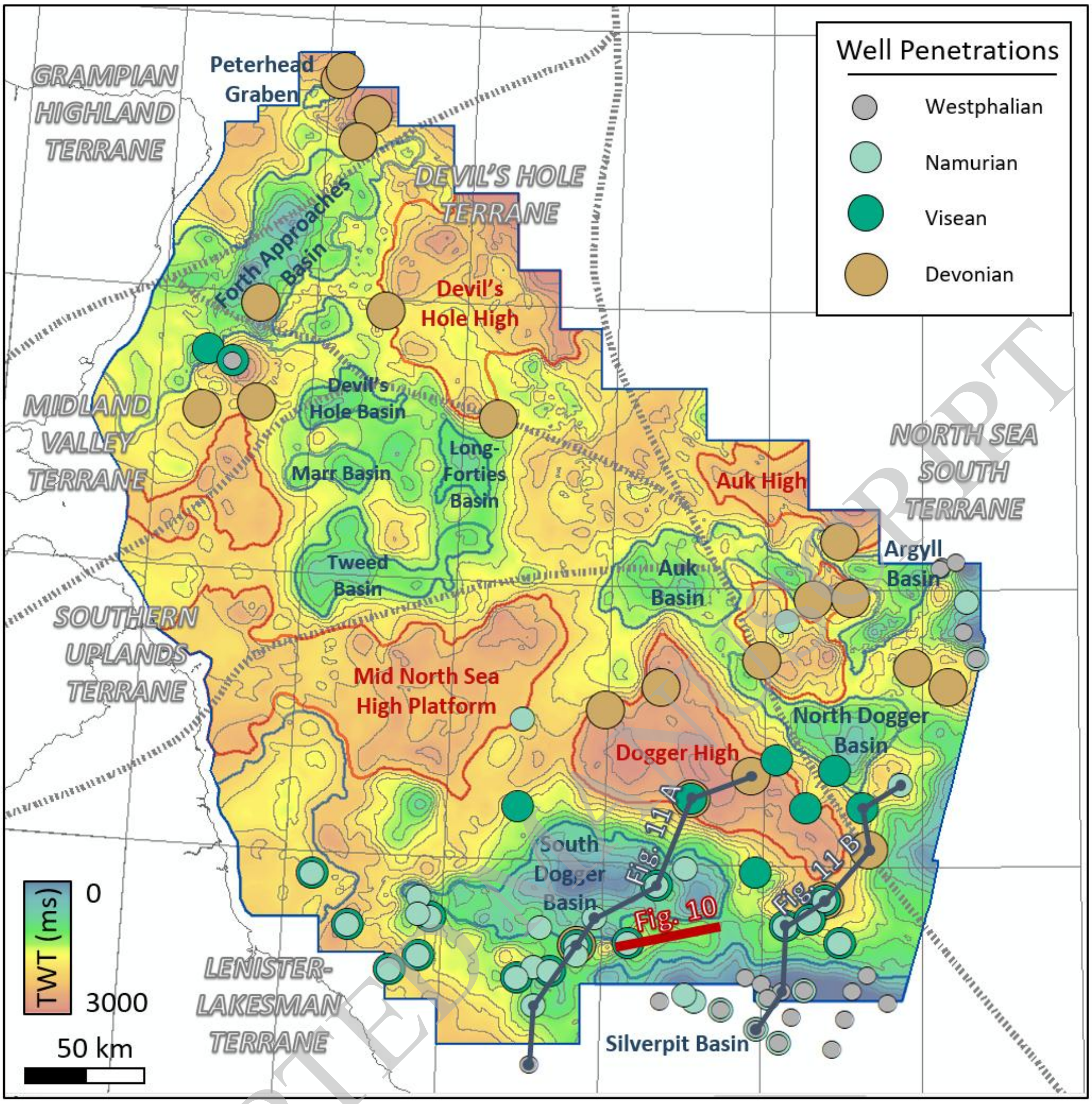

W
OGA 2015_L58
E
A)
TWT (ms)
OGA_2015 L18
Seabed Subcrop
36/13-1
36/15-1
37/12-1
37/10-1
39/02-4
Permian Carbonate Platform
Progradation
Permian Seaway
Mid North Sea High Platform
Auk Basin
Permian Carbonate Platform
Early Permian Volcanics
Argyll Basin
D
C
A
Leinster - Lakesman Basement Terrane (BT)
North Sea South BT
SW
OGA 2015_L18
NE
B)
TWT (ms)
OGA_2015 L58
km
43/06-1
43/03-1
38/16-1
39/02-4
30/30-3
31/26a-12
Progradation
North Dogger Fault Zone
Zechstein Carbonate Buildup
South Permian Basin
Mid Cimmerian Erosion
Dogger High
Solepit Basin
Flora Ridge
Argyll Basin
D
C
B
A
Leinster - Lakesman Basement Terrane
North Sea South Basement Terrane



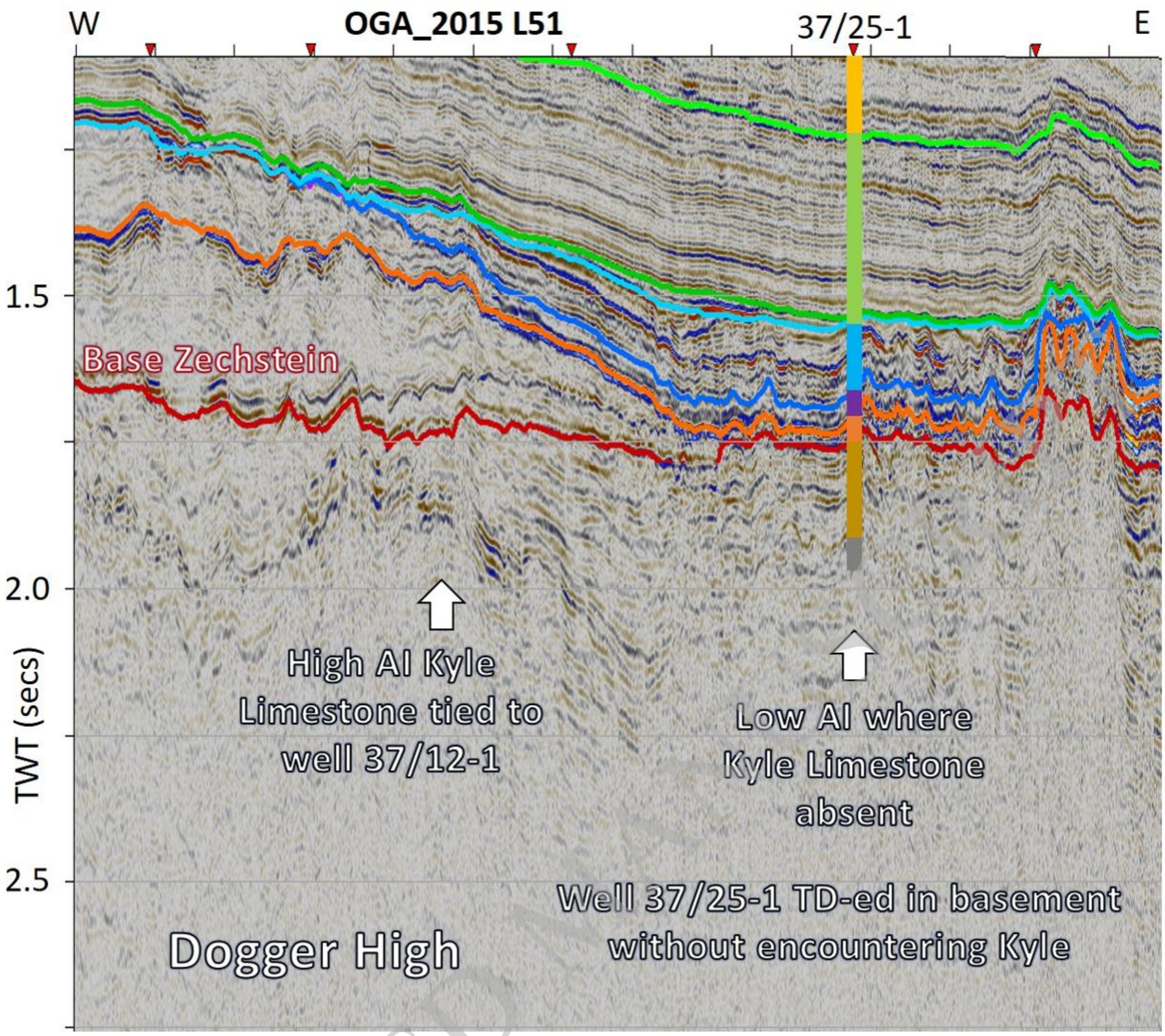
South Permian Basin
MNSH
Central Graben
Seismic Pick
Tectono-strat Unit
CENOZOIC
MESOZOIC
PALAEOZOIC
Plio
Mio
Ol
Eo
Pa
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
CLINOFORMS
REGIONAL TILTING DUE TO FAR-FIELD STRESSES
BALDER FM.
INITIAL OPENING OF NE ATLANTIC
CHALK
CROMER KNOLL GRP.
KIMMERIDGE CLAY SOURCE ROCK
CENTRAL NORTH SEA RIFTING & FOOTWALL UPLIFT
JURASSIC THERMAL DOMING
ROT HALITE
BUNTER SANDSTONE
Z3
Z2
Z1
ROTLIEGEND
VARISCAN OROGENY
WESTPHALIAN/ SCREMERSTON COAL SOURCE ROCKS
OLD RED SANDSTONE
KYLE LIMESTONE
GRANITE-CORED CALEDONIAN BASEMENT
Seabed
Mid Tertiary UC
Top Upper Cretaceous
Top Lower Cretaceous
Base Cretaceous UC
Mid Cimmerian UC
Top Upper Triassic
Top Lower Triassic
Top Permian Zechstein
Top Permian Rotliegend
Base Permian UC
Near Top Basement
D
C
B
A

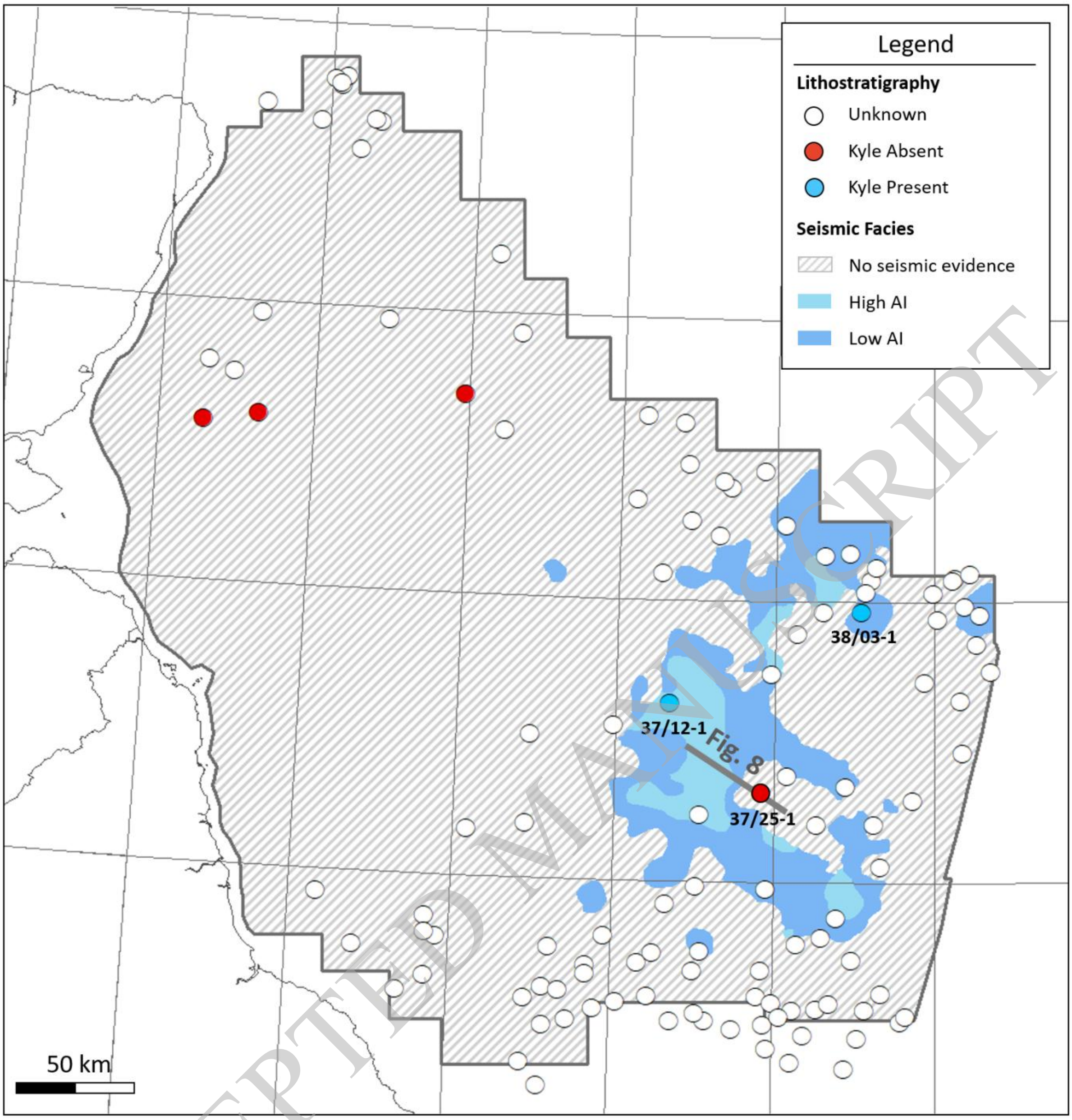


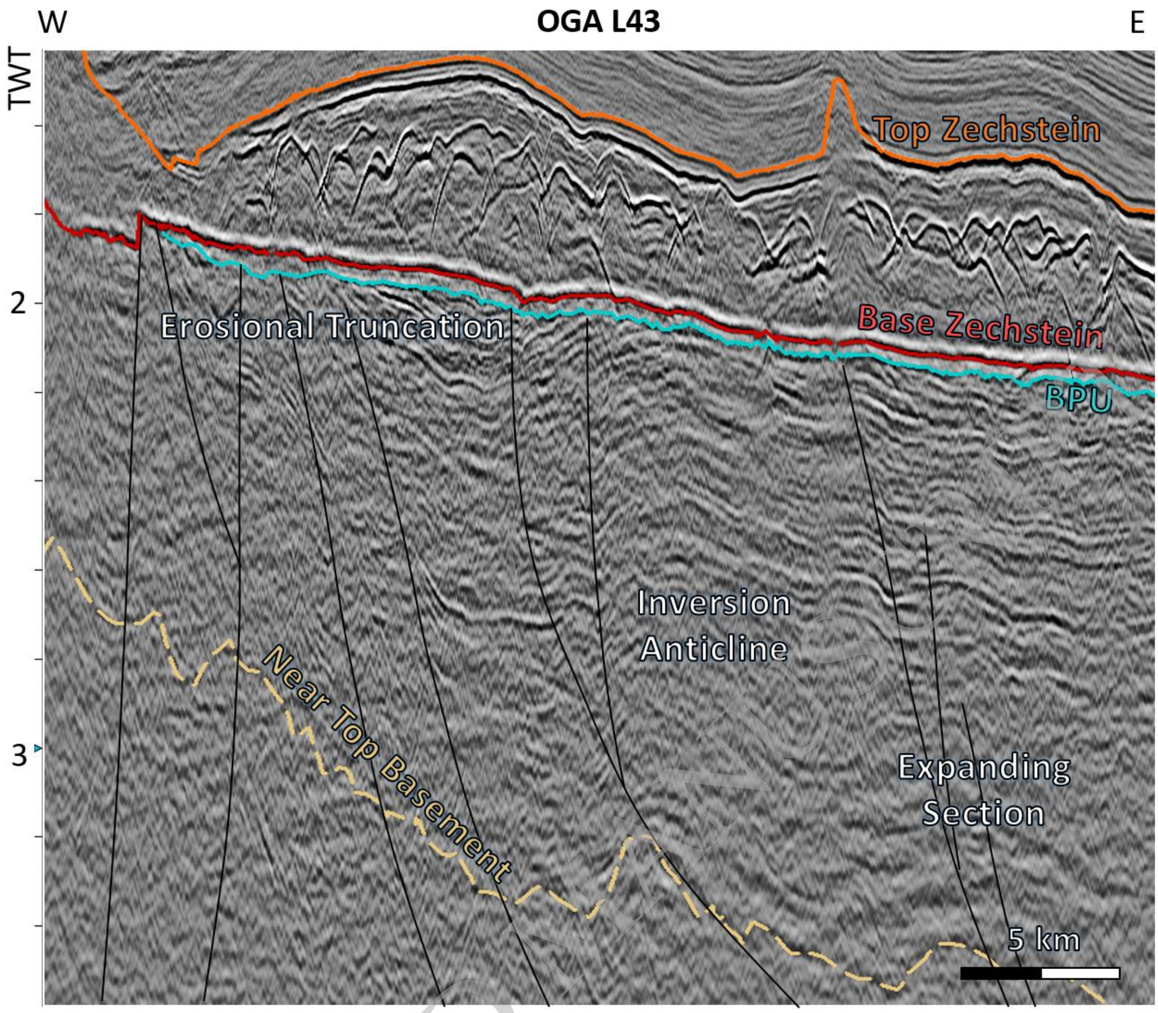
Tectonostratigraphic Unit A
BPU – Basement
Forth Approaches Basin
Devil's Hole
Auk High
Auk Basin
MNSH Platform
North Dogger Basin
Dogger High
South Dogger Basin
Silverpit Basin
TWT (ms)
0
3000
50 km
Tectonostratigraphic Unit B
BCU - BPU
Forth Approaches Basin
North Permian Basin
Seabed Subcrop: Tertiary uplift
Limited Deposition across MNSH
South Permian Basin
TWT (ms)
0
1800
50 km
Moray Firth Graben depocentre
Tectonostratigraphic Unit C
MTU - BCU
Seabed Subcrop: Tertiary uplift
Salt-related minibasins
Limited Deposition across MNSH
Salt-related minibasins
TWT (ms)
0
2200
50 km
Tectonostratigraphic Unit D
Seabed - MTU
Seabed Subcrop: Tertiary uplift
South westward Progradation
TWT (ms)
0
2200
50 km

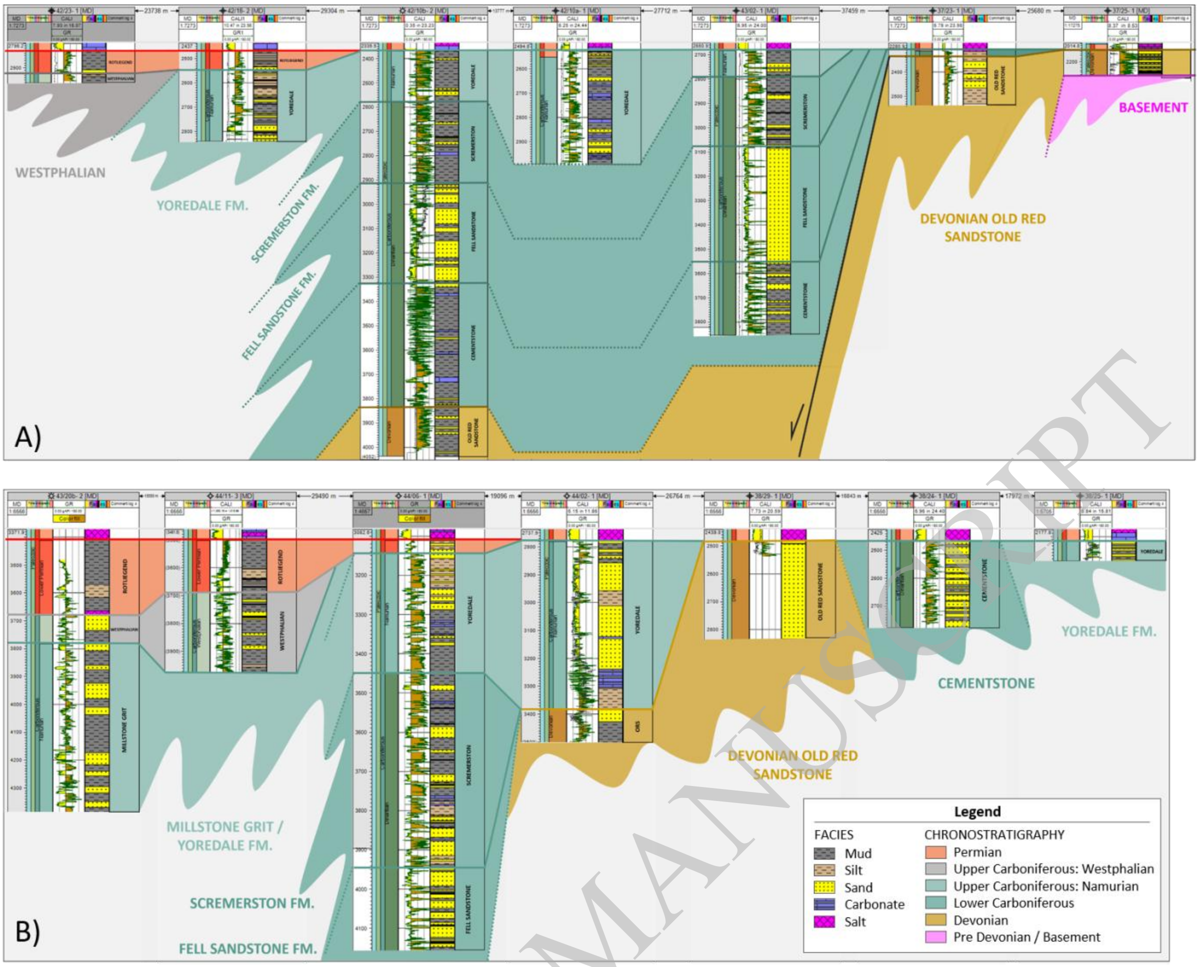


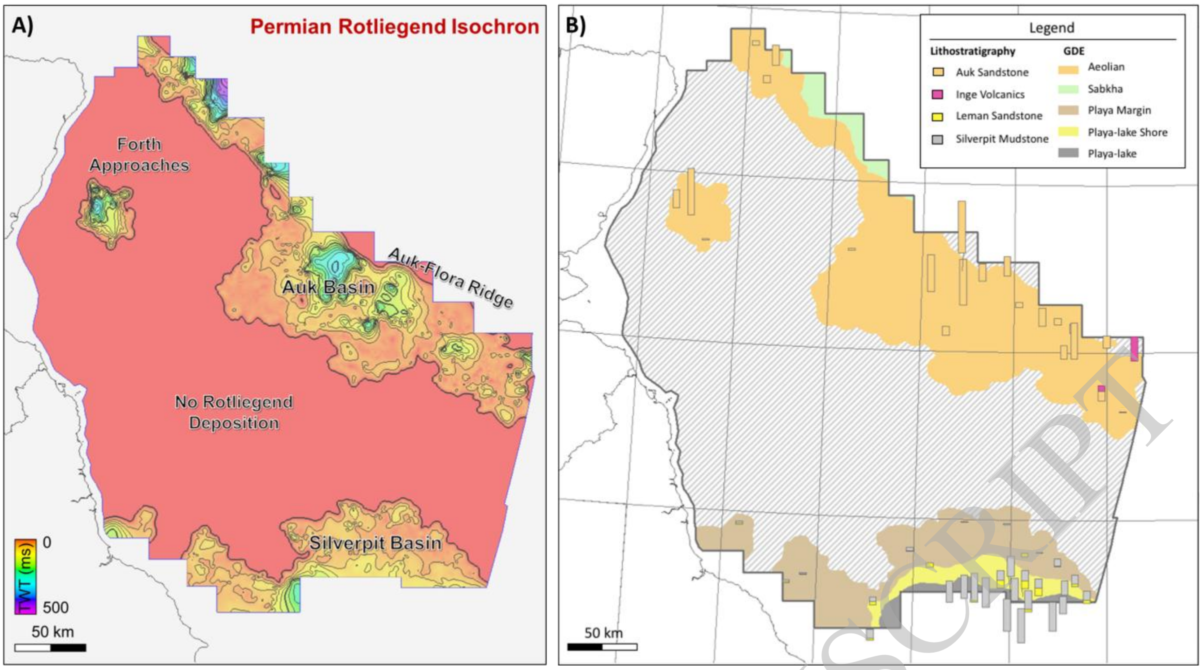
Well Penetrations
Westphalian
Namurian
Visean
Devonian
GRAMPIAN HIGHLAND TERRANE
Peterhead Graben
DEVIL'S HOLE TERRANE
Forth Approaches Basin
Devil's Hole High
MIDLAND VALLEY TERRANE
Devil's Hole Basin
Marr Basin
Long-Forties Basin
Auk High
NORTH SEA SOUTH TERRANE
Argyll Basin
Tweed Basin
Auk Basin
SOUTHERN UPLANDS TERRANE
Mid North Sea High Platform
North Dogger Basin
Dogger High
Fig. 11 A
Fig. 11 B
South Dogger Basin
Fig. 10
TWT (ms)
0
3000
50 km
LENISTER-LAKESMAN TERRANE
Silverpit Basin

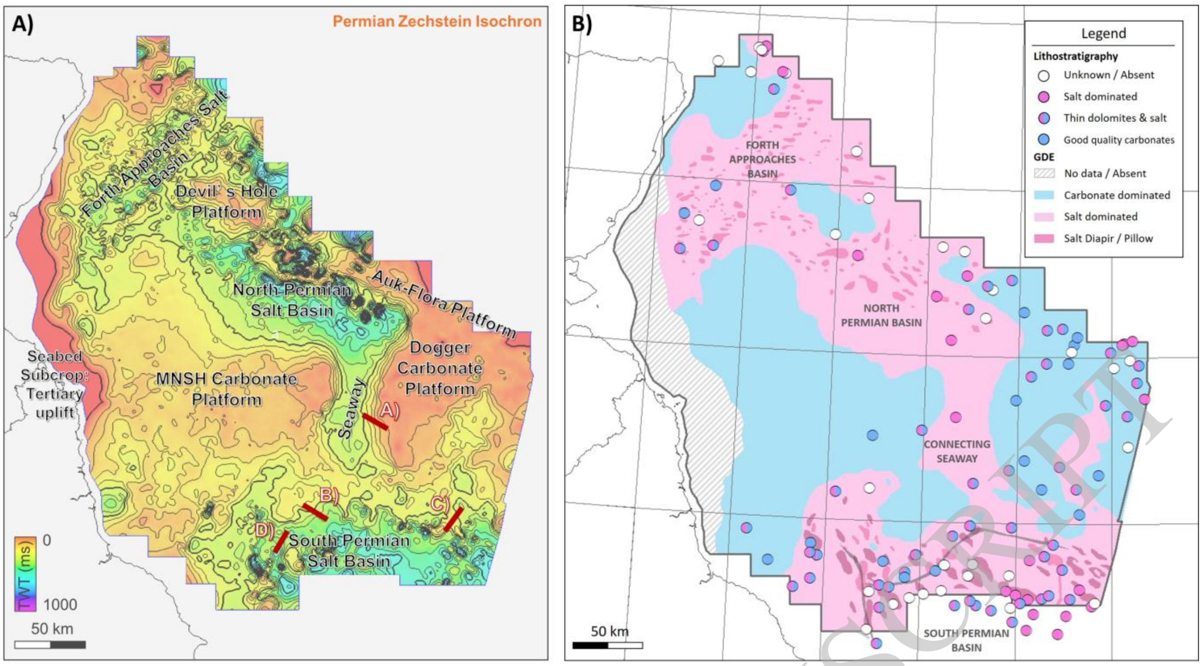

W
OGA_2015 L51
37/25-1
E
1.5
2.0
2.5
TWT (secs)
Base Zechstein
High AI Kyle
Limestone tied to
well 37/12-1
Low AI where
Kyle Limestone
absent
Well 37/25-1 TD-ed in basement
without encountering Kyle
Dogger High

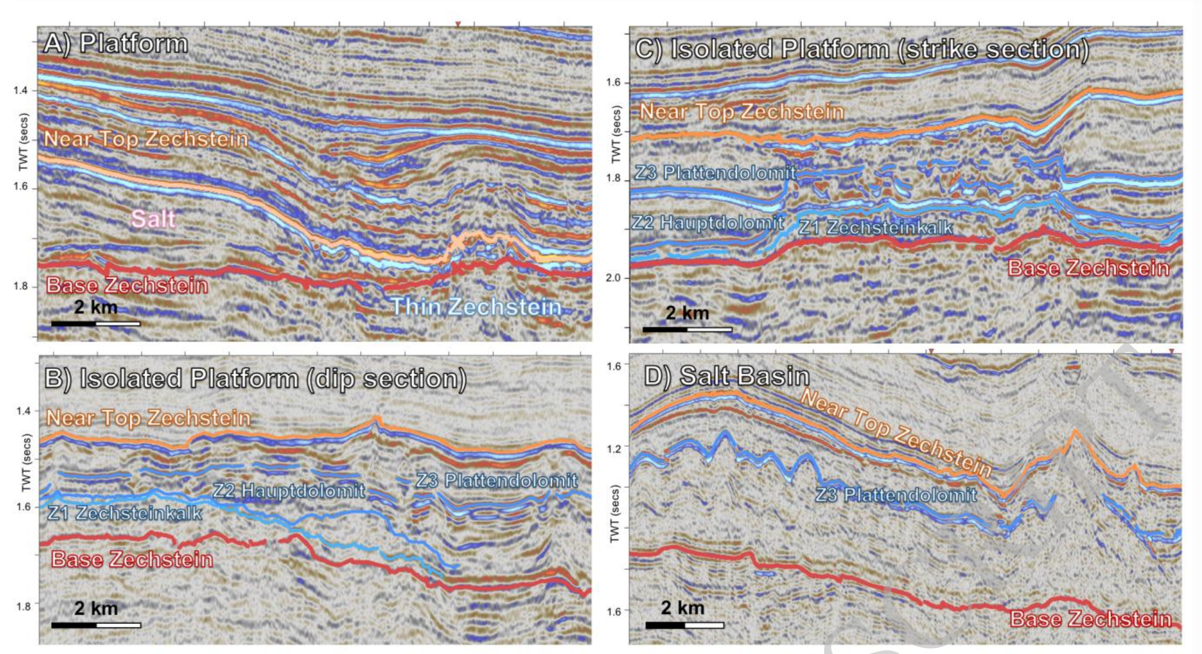

Legend
Lithostratigraphy
Unknown
Kyle Absent
Kyle Present
Seismic Facies
No seismic evidence
High AI
Low AI
38/03-1
37/12-1
Fig. 8
37/25-1
50 km

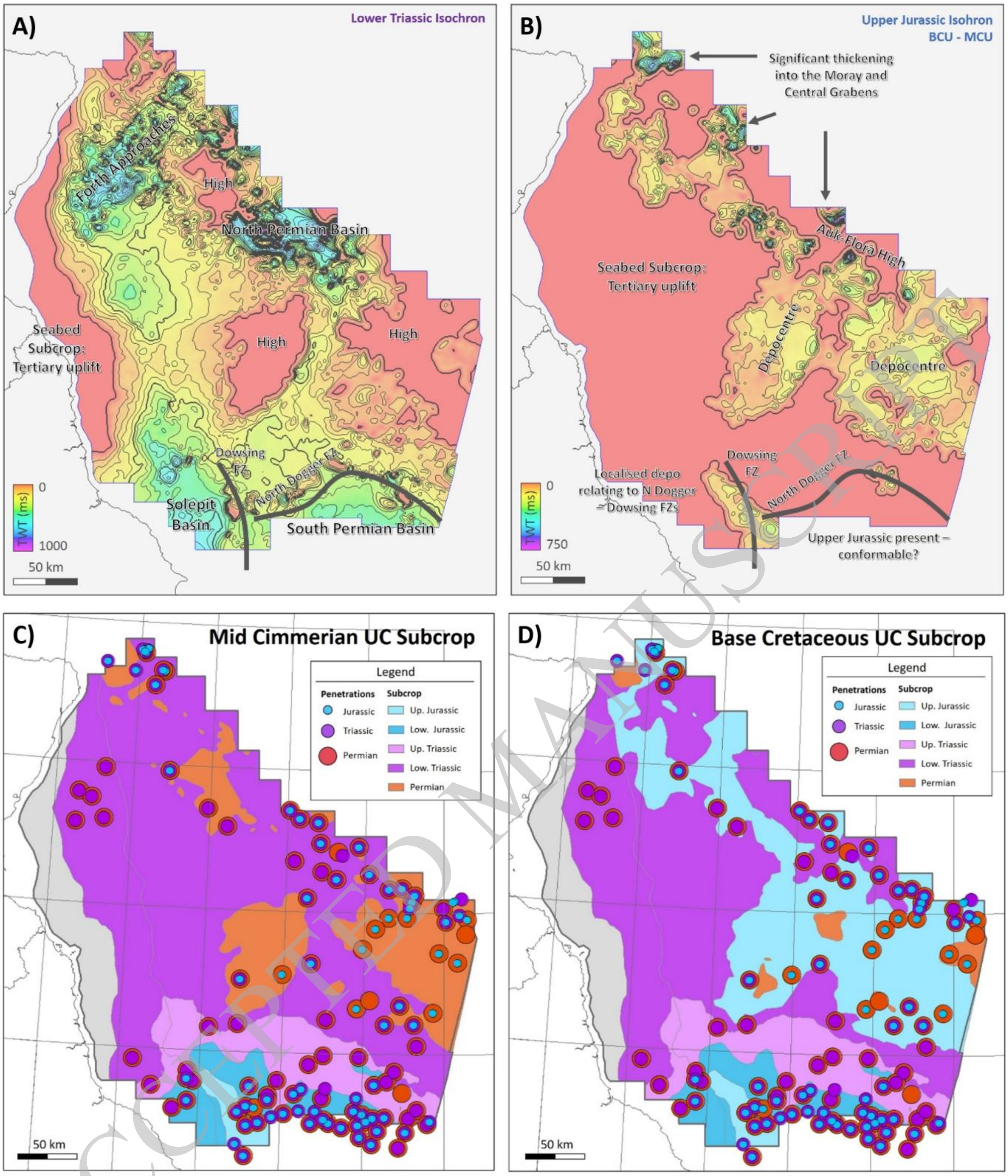

W
OGA L43
E
TWT
2
3
Top Zechstein
Base Zechstein
BPU
Erosional Truncation
Inversion
Anticline
Expanding
Section
Near Top Basement
5 km

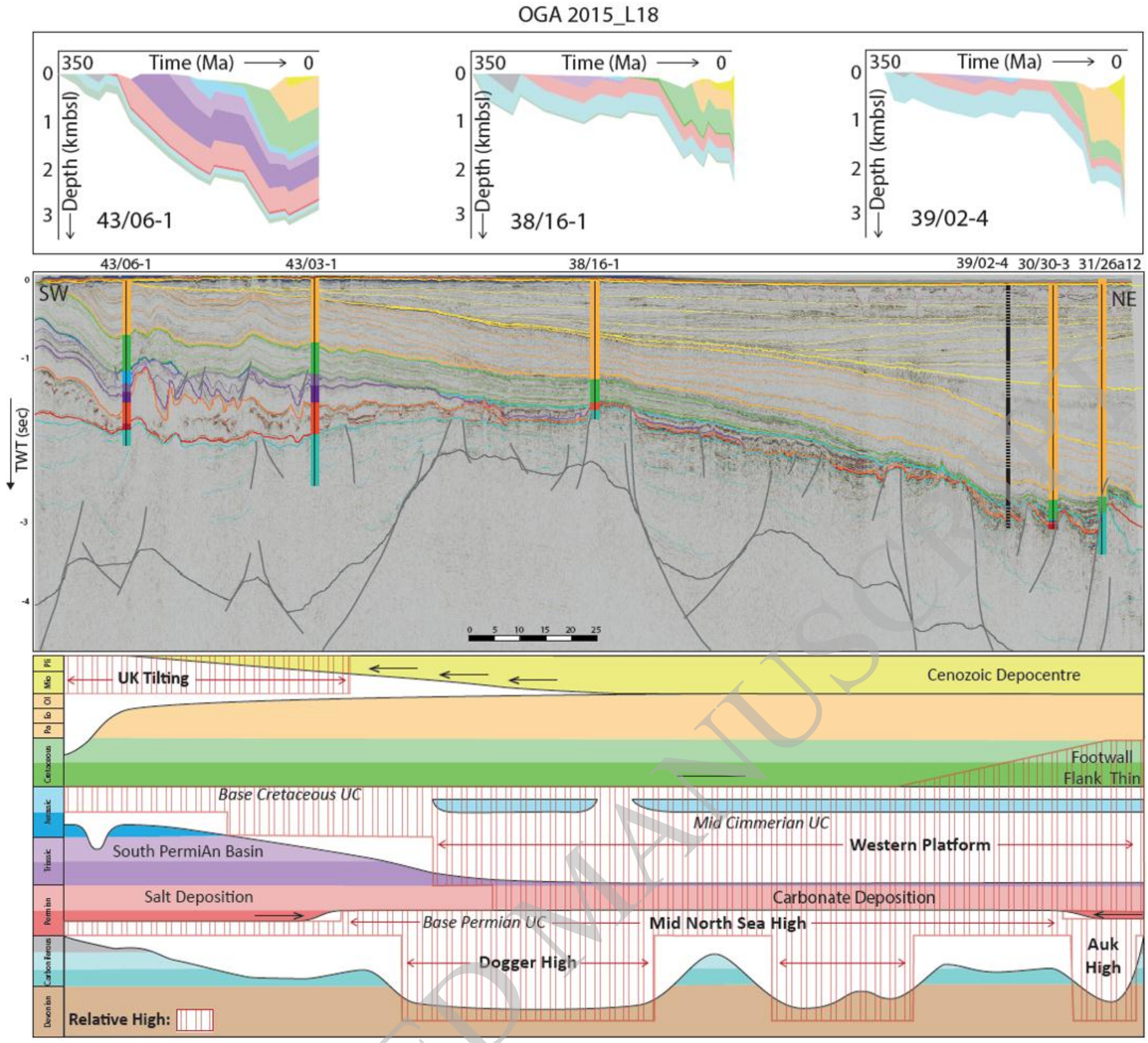

WESTPHALIAN
YOREDALE FM.
SCREMERSTON FM.
FELL SANDSTONE FM.
DEVONIAN OLD RED SANDSTONE
BASEMENT
A)
MILLSTONE GRIT / YOREDALE FM.
SCREMERSTON FM.
FELL SANDSTONE FM.
DEVONIAN OLD RED SANDSTONE
CEMENTSTONE
YOREDALE FM.
B)
Legend
FACIES
Mud
Silt
Sand
Carbonate
Salt
CHRONOSTRATIGRAPHY
Permian
Upper Carboniferous: Westphalian
Upper Carboniferous: Namurian
Lower Carboniferous
Devonian
Pre Devonian / Basement

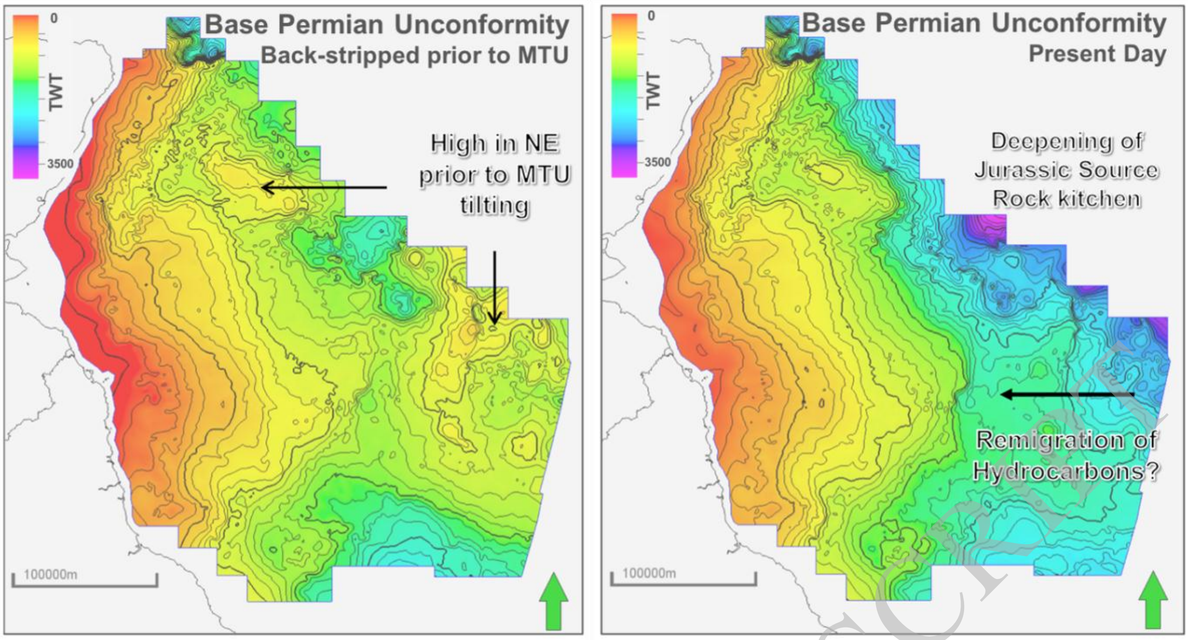

A)
Permian Rotliegend Isochron
Forth Approaches
Auk Basin
Auk-Flora Ridge
No Rotliegend Deposition
Silverpit Basin
TWT (ms)
0
500
50 km
B)
Legend
Lithostratigraphy
Auk Sandstone
Inge Volcanics
Leman Sandstone
Silverpit Mudstone
GDE
Aeolian
Sabkha
Playa Margin
Playa-lake Shore
Playa-lake
50 km


A)
Permian Zechstein Isochron
Forth Approaches Salt Basin
Devil's Hole Platform
North Permian Salt Basin
Auk-Flora Platform
Dogger Carbonate Platform
Seabed Subcrop Tertiary uplift
MNSH Carbonate Platform
Seaway
South Permian Salt Basin
TWT (ms)
0
1000
50 km
B)
FORTH APPROACHES BASIN
NORTH PERMIAN BASIN
CONNECTING SEAWAY
SOUTH PERMIAN BASIN
50 km
Legend
Lithostratigraphy
Unknown / Absent
Salt dominated
Thin dolomites & salt
Good quality carbonates
GDE
No data / Absent
Carbonate dominated
Salt dominated
Salt Diapir / Pillow


A) Platform
Near Top Zechstein
Salt
Base Zechstein
Thin Zechstein
2 km
TWT (secs)
1.4
1.6
1.8
B) Isolated Platform (dip section)
Near Top Zechstein
Z2 Hauptdolomit
Z3 Plattendolomit
Z1 Zechsteinkalk
Base Zechstein
2 km
C) Isolated Platform (strike section)
Near Top Zechstein
Z3 Plattendolomit
Z2 Hauptdolomit
Z1 Zechsteinkalk
Base Zechstein
2.0
D) Salt Basin
Near Top Zechstein
Z3 Plattendolomit
Base Zechstein
1.2


A)
Lower Triassic Isochron
Forth Approaches
High
North Permian Basin
High
High
Seabed
Subcrop:
Tertiary uplift
Dowsing
FZ
North Dogger FZ
Solepit
Basin
South Permian Basin
0
TWT (ms)
1000
50 km
B)
Upper Jurassic Isohron
BCU - MCU
Significant thickening
into the Moray and
Central Grabens
Auk-Flora High
Seabed Subcrop:
Tertiary uplift
Depocentre
Depocentre
Dowsing
FZ
North Dogger FZ
Localised depo
relating to N Dogger
- Dowsing FZs
Upper Jurassic present –
conformable?
0
TWT (ms)
750
50 km
C)
Mid Cimmerian UC Subcrop
Legend
Penetrations
Subcrop
Jurassic
Triassic
Permian
Up. Jurassic
Low. Jurassic
Up. Triassic
Low. Triassic
Permian
50 km
D)
Base Cretaceous UC Subcrop
Legend
Penetrations
Subcrop
Jurassic
Triassic
Permian
Up. Jurassic
Low. Jurassic
Up. Triassic
Low. Triassic
Permian
50 km


OGA 2015_L18
350
Time (Ma)
0
Depth (kmbsl)
43/06-1
38/16-1
39/02-4
43/03-1
30/30-3
31/26a12
SW
NE
TWT (sec)
UK Tilting
Cenozoic Depocentre
Footwall Flank Thin
Base Cretaceous UC
Mid Cimmerian UC
South PermiAn Basin
Western Platform
Salt Deposition
Carbonate Deposition
Base Permian UC
Mid North Sea High
Dogger High
Auk High
Relative High:


Base Permian Unconformity
Back-stripped prior to MTU
TWT
0
3500
High in NE
prior to MTU
tilting
100000m
Base Permian Unconformity
Present Day
TWT
0
3500
Deepening of
Jurassic Source
Rock kitchen
Remigration of
Hydrocarbons?
100000m