



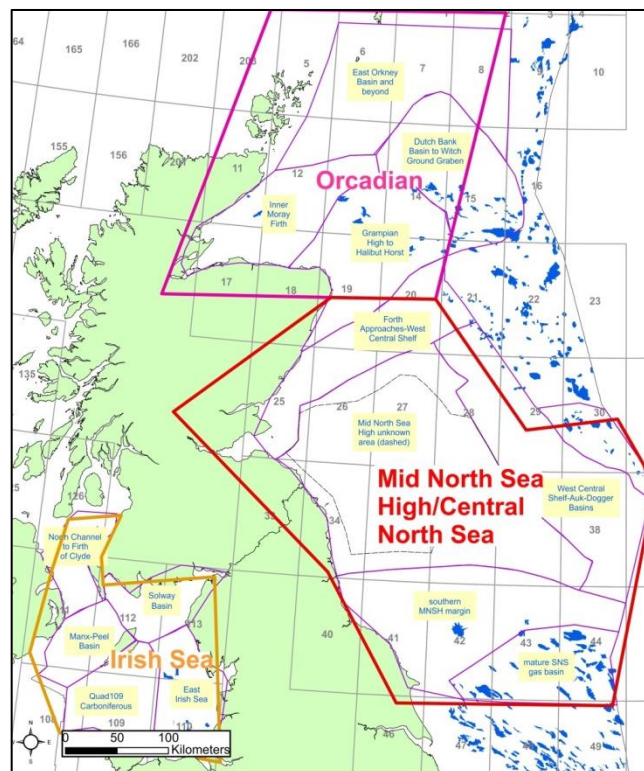
**British Geological Survey**

NATURAL ENVIRONMENT RESEARCH COUNCIL

# Overview of the 21CXRM Palaeozoic Project – a regional petroleum systems analysis of the offshore Carboniferous and Devonian of the UKCS

Energy and Marine Geoscience Programme

Commissioned Report CR/16/047





BRITISH GEOLOGICAL SURVEY

ENERGY AND MARINE GEOSCIENCE PROGRAMME

COMMISSIONED REPORT CR/16/047

# Overview of the 21CXRM Palaeozoic Project – a regional petroleum systems analysis of the offshore Carboniferous and Devonian of the UKCS

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A.A. Monaghan and the Project Team (S. Arsenikos, E Callaghan,  
R Ellen, C Gent, E Greenhalgh, S Hannis, A Henderson, G Leslie,  
K Johnson, M Kassyk, T Kearsey, A Kim, G Kimbell, K Kirk, M  
Quinn, W McLean, D Millward, T Pharaoh, M Sankey, N Smith, C  
Ugana, C Vane, C Vincent, O Wakefield, C Waters, P Williamson)

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### **BGS Central Enquiries Desk**

Tel 0115 936 3143 Fax 0115 936 3276  
email [enquiries@bgs.ac.uk](mailto:enquiries@bgs.ac.uk)

### **Environmental Science Centre, Keyworth, Nottingham NG12 5GG**

Tel 0115 936 3241 Fax 0115 936 3488  
email [sales@bgs.ac.uk](mailto:sales@bgs.ac.uk)

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

Tel 0131 667 1000 Fax 0131 668 2683  
email [scotsales@bgs.ac.uk](mailto:scotsales@bgs.ac.uk)

### **Natural History Museum, Cromwell Road, London SW7 5BD**

Tel 020 7589 4090 Fax 020 7584 8270  
Tel 020 7942 5344/45 email [bgs\\_london@bgs.ac.uk](mailto:bgs_london@bgs.ac.uk)

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

Tel 029 2052 1962 Fax 029 2052 1963

### **Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB**

Tel 01491 838800 Fax 01491 692345

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

Tel 028 9038 8462 Fax 028 9038 8461

[www.bgs.ac.uk/gsni/](http://www.bgs.ac.uk/gsni/)

### *Parent Body*

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

Tel 01793 411500 Fax 01793 411501  
[www.nerc.ac.uk](http://www.nerc.ac.uk)

Website [www.bgs.ac.uk](http://www.bgs.ac.uk)

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# Foreword and Acknowledgements

This report is a published product of the 21st Century Exploration Road Map (21CXRM) Palaeozoic project. This joint industry-Government-BGS project comprised a regional petroleum systems analysis of the offshore Devonian and Carboniferous in the North Sea and Irish Sea.

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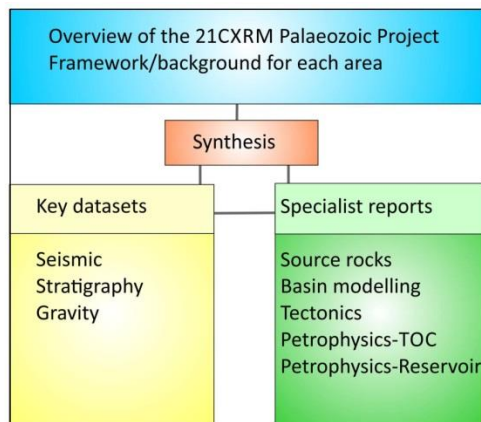
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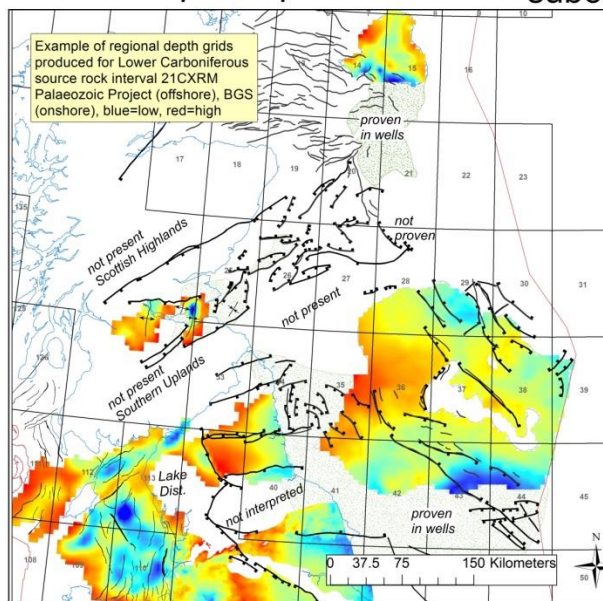
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# Summary

This report gives an overview of the 21CXRM Palaeozoic Project background, scope and products (Sections 1-3). It explains how the component reports and datasets of the project fit together. Overview technical information (e.g. key diagrams and charts applicable across the reports for each area) is reproduced in Sections 6 and 7 for reference, particularly as background for users of the specialist reports. A visual representation of the regional coverage and quantity of digital Palaeozoic Project products is given in Figure 1.



**Report topics**



**Regional grids**

**21CXR Palaeozoic Project - digital products**

25 peer-reviewed reports

21 regional TWTT and depth surfaces of the Devonian and Carboniferous over the CNS, Orcadian & Irish Sea areas, from over **125,000 line km** 2D seismic interpretation (plus some 3D)

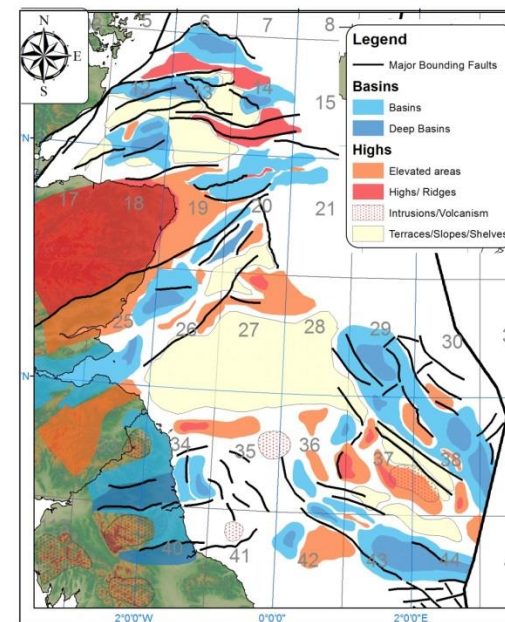
GIS with Devonian and Carboniferous extents, subcrop maps, well picks, gravity etc

Data spreadsheets

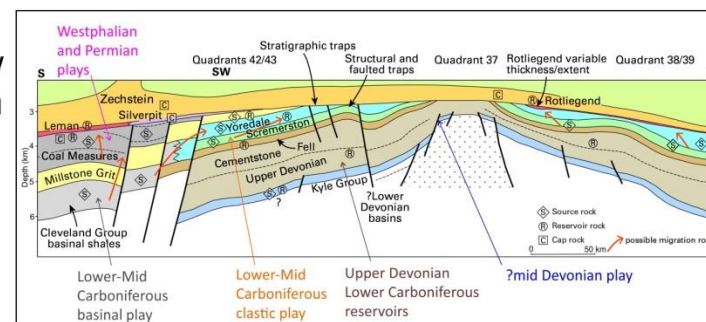
- well picks- **700** re-interpreted well tops
- organic geochemistry - over **3500** rows of data
- poroperm - over **12,500** rows of data

A regional digital dataset aligned to the Wood Review recommendations: to inform interpretation of the Government seismic data and 29th License Round studies

Budget = **£1.3 million**  
 BGS work days = **2500**  
 Nov. 2014 - May 2016  
**46** industry Sponsors



**Palaeozoic basin evolution**



**Play Cartoons**

**Figure 1 Overview of 21CXR Palaeozoic Project products**



# 1 Background

The Sir Ian Wood report ([UKCS Maximising Recovery Review](#)) proposed 29 Actions aimed at Maximising Economic Recovery from the UKCS (MER UK). The Palaeozoic Project was a response to Action 7: ‘An up-to-date readily accessible digital perspective on the prospectivity and geology of the UKCS’.

Oil & Gas UK, DECC and NERC funded a consultative study to seek views on new projects covering this Action and a Palaeozoic project was selected as the first regional project topic. The initial project proposal was developed by BGS and the 21<sup>st</sup> Century Exploration Roadmap/PILOT Project Board from across the industry. The work aimed to address some of the underlying challenges identified in the Wood Report, including collaboration across all sectors of the industry, identifying new plays and making better use of data.

The Palaeozoic project was focused on areas and Carboniferous and Devonian sequences outside the extent of Jurassic (Kimmeridge) source rocks and perceived as frontier and high risk, for which little systematic regional work and data existed in the public domain. Data quality and density over these areas was variable. The Mid North Sea High area was largely blank on many maps and, straddling the northern and southern Permian basins, was at the edges of both the Millennium Atlas and Southern Permian Basin Atlas study areas. However, with the success of the Breagh field on the southern flank of the Mid North Sea High (Quadrant 42) and the recognition of significant unconventional resources onshore UK, the Carboniferous play outside of the mature Southern North Sea clearly merited further work. Whilst known and potential Palaeozoic petroleum systems exist in areas of the UKCS such as west of Shetland (e.g. Clair Field), Cardigan Bay/Caernarfon Bay and on the northern edge of the London-Brabant massif (Quadrants 53, 54), the consultative study focussed the work of the Palaeozoic Project to the Central North Sea, Mid North Sea High, Orcadian Basin (east of Orkney) and the Irish Sea.

After Town Hall meetings in Aberdeen and London in January 2014 and support from DECC and Oil and Gas UK, company Sponsors began joining the project. As of March 2016, the project has 46 industry Sponsors from large to small companies from the UK and overseas, including a significant number of seismic data owners (Table 1).

Actis Oil and Gas Ltd	Conoco Phillips	MOL Operations UK
Alpha Petroleum Resources	Dana Petroleum	Nexen Petroleum U.K.
Antrim Resources	Dolphin Geophysical	Origo Exploration UK
Apache North Sea	Dong E & P	Parkmead (E & P)
Atlantic Petroleum UK	Dyas UK	PGS
Aurora Petroleum	E.ON E & P UK	Premier Oil Plc
Azinor Catalyst	EBN (Netherlands)	Shell
Bayerngas Europe	Edison/Euroil (UK)	Spectrum
BG Group	ENI	Statoil
BP	GDF Suez E & P UK	Talisman Sinopec
Cairn Energy	I H S	TGS-Nopec
Centrica Energy	Ineos	ThinkTank Maths Limited
CGG Veritas	Inpex	Total E & P
Chevron Upstream	LR Senergy	Verus Petroleum
Chrysaor	Maersk Oil North Sea UK	Western Geco / Schlumberger
Cluff Natural Resources		Upstream Consultants Ltd

**Table 1 Industry Sponsors of the 21CXRM Palaeozoic Project at March 2016 (in addition to DECC/OGA, BGS and Oil and Gas UK).**

During the project, the functions of DECC passed to the Oil and Gas Authority (OGA). In March 2015, the UK Government allocated £20 million to DECC/OGA for new seismic surveys across the Mid North Sea High and Rockall area. The BGS project team contributed to the positioning of the seismic lines, which were publically released in March 2016.

The OGA has announced its intention for a 29th ‘Frontier’ Licensing Round, including the Mid North Sea High and Rockall areas in 2016. Palaeozoic project reports and deliverables are commercial-in-confidence to Sponsors until the License Round closes or until July 2017 (whichever is earlier).

The 21XCRM Project Board determined the financial parameters, overall objectives, project boundaries, data management, release of results and publication protocol.

The Technical Steering Committee was open to technical representatives of Sponsor organisations. It acted as the technical discussion forum and facilitated peer review and collaboration, including contribution of opinions, knowledge and additional data. Seven well-attended Technical Steering Committee (TSC) meetings were held at BGS Edinburgh between February 2015 and March 2016.

## 2 Objectives

The overall objective of the Palaeozoic project was to stimulate exploration of under-explored Palaeozoic plays of the UKCS.

This was achieved by:

- Improving the regional-scale knowledge of the Palaeozoic petroleum system
- Delivering digital products for maximum use and accessibility
- Improving collaboration
- Gathering and synthesizing existing data and interpretations (subject to IP restrictions)
- Targeting new interpretations on the best quality, most up-to-date datasets (subject to IP restrictions)

Using the products, the predictive capability and understanding of prospective areas of the Palaeozoic at regional scale will be improved, to facilitate detailed studies and exploration in these areas of the UKCS.

In the original project plan, positive outcomes of the project and a measure of success were deemed to be that ‘further studies of the Palaeozoic are stimulated, leading on to seismic data collection and drilling. For example, key areas where new seismic is required may be identified.’ Also ‘a high level of engagement from industry at Technical Steering Committee meetings will indicate a positive collaboration and knowledge sharing. Collaborative workshops to examine onshore analogues are also envisaged.’

Further objectives were described during the course of the project, summarised as

- Searching deeper and wider than the conventional hydrocarbon horizons
- Develop a strong, consistent regional data-set to provide a platform for more specific oil & gas exploration studies
- Develop a solid regional geological understanding
  - that down-risks some of the critical play elements
  - that stimulates new ideas for plays and prospectivity

Provoking

- new data acquisition
- additional analysis and interpretation programmes

Leading to

- licence activity
- significant exploration well activity
- economic commercial success rates

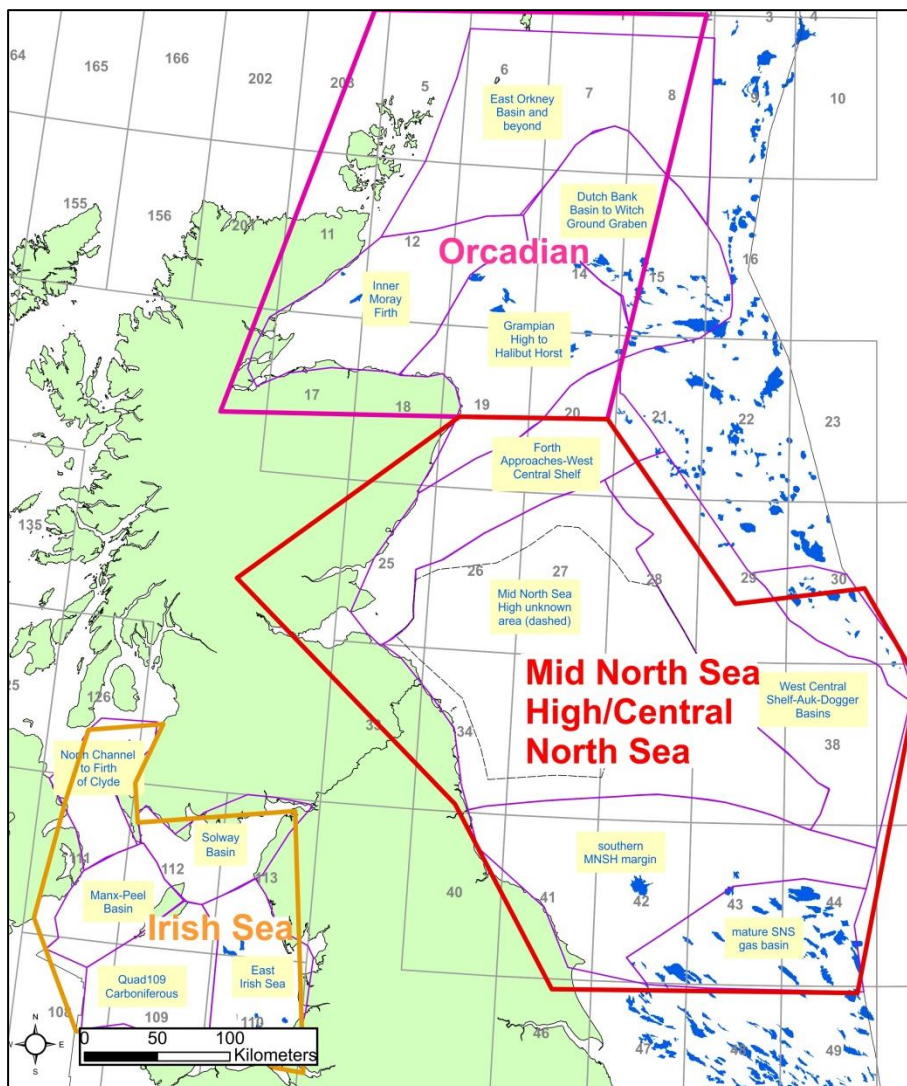
During the project the key drivers were summarised as:

- Achieving the best understanding we can to ensure that more, more successful wells are drilled by the industry
- Win-win arrangements for optimal seismic data use
- Expectation of a fully integrated approach with industry supporting and involved

### 3 Scope and products

The work focused on a synthesis of data resulting in a regional-scale tectono-stratigraphic and petroleum systems analysis. The scale is between that of the Millennium Atlas/Southern Permian Basin Atlas and block scale, so that play elements but not specific prospects were considered. Carboniferous strata were the main focus in the Central North Sea/Mid North Sea High and East Irish Sea (Figure 2). Devonian strata were also considered, with particular focus in the Orcadian Basin (Figure 2). Extensive BGS experience of working on the onshore Carboniferous was utilised.

The density, quality and vintage of datasets was very variable across the three study areas. BGS had access to all seismic and well data through the DECC/BGS contract. Seismic interpretation was focused on using the highest quality long-offset 2D and 3D data. A large quantity of legacy, proprietary and BGS data was used for well, source and reservoir studies. Project products using confidential seismic data or data/reports donated to the project were covered by Confidentiality Agreements. During the course of the Project, the UK Government funded new seismic acquisition across the Mid North Sea High and BGS provided key input to OGA on optimal line locations (the new seismic data was released at the same time as Project deliverables and is therefore not incorporated within the study).



**Figure 2 Summary of the three project areas (Mid North Sea High, Orcadian and Irish Sea) used in initial scoping, together with geological sub-areas studied (in purple, pale yellow and blue labels) delineated by scoping and consultation with the Technical Steering Committee.**

The Project workflow started with data gathering and seismic and well interpretation, then integration of those datasets with gravity-magnetic interpretation, source rock geochemistry, burial-history modelling etc to inform the location of prospective Carboniferous and Devonian play elements (Table 2). Whilst the results of these tasks have been reported separately, staff worked closely together and integration between tasks has been key.

Table 2 describes the project products, which comprise a report and in many cases an accompanying digital dataset (e.g. TWT and depth grids, well tops spreadsheet, GIS project etc). These are currently accessed by a password protected website.

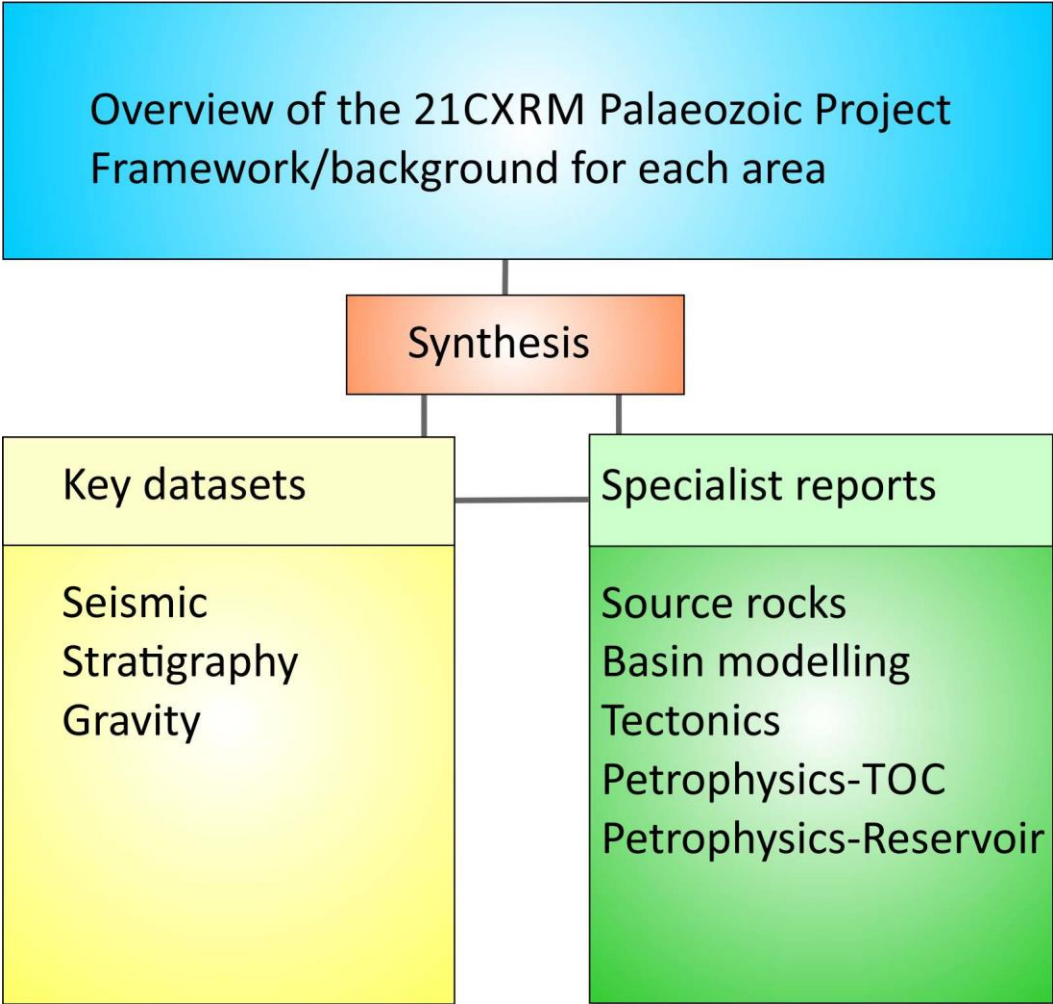
The reports and products are a regional scale interpretation with specialist studies obtaining and screening the datasets and interpretations for future, more detailed studies (Table 2, Figure 3). A different approach was taken than that which would be appropriate at block or prospect scale and was tailored to meet the budget and deadline requirements. Several peer report reviews have identified potential for more detailed work, or follow on work.

Task	Aim	Deliverable/product	Mid North Sea High/Central North Sea (Quadrants 25-44)	Orcadian study area, Quadrants 6-21	Irish Sea study area
Synthesis-petroleum systems	Summary of the petroleum system at regional scale	Report, diagrams	✓	✓	✓
<i>Key dataset interpretation</i>					
Well, stratigraphic and palaeogeographic (gross depositional environment) interpretation	Consistent framework for interpretation and time-slice maps for regional distribution of source, reservoir, seal facies	Well correlation panels, palaeogeography maps, report, well tops spreadsheet and GIS layers	✓	✓	✓
Seismic interpretation	Regional scale depth grids and understanding of basin distribution and development	Report containing selected line images. TWT and depth grids at 5 km resolution, GIS and other formats	✓	✓	✓
Gravity and magnetic interpretation	Presence of pre-Permian basins (also granites) in areas of poor seismic coverage	Interpreted grids and grav-mag images – GIS and other formats	✓	✓	Used existing work
<i>Specialist studies</i>					
Tectonic development	Regional scale framework for tectonic evolution	Report, diagrams	✓	✓	✓ in seismic report
Pre-Permian subcrop map	Define extents of stratigraphic units	Map image and GIS	✓	✓	✓
Source rock analysis - organic geochemistry	Regional well-based screening of quality and maturity of potential source rock intervals	Data spreadsheet. Report and images	✓	✓	✓
Petrophysical analysis-TOC content	Prediction of Total Organic Content throughout successions, regional screening	Derived LAS files. Report, images, tables	✓		
Petrophysical analysis-reservoir	Prediction of reservoir quality throughout successions, regional screening	Derived LAS files. Report, images, tables	✓	✓ limited number wells	✓ limited number wells
Thermal maturity, uplift/burial/migration	Have hydrocarbons been produced and when	Report, images	✓	✓ 1D well models only	✓ 1D well model only
<i>Data management</i>	Manage complex confidentiality of datasets used and donated. Enhance relevant CDA content.	Database of confidentiality constraints (BGS use only)	✓	✓	✓

**Table 2 Summary of the tasks and products of the 21CXRM Palaeozoic project**

The reports for each study area are intended to be used together. The synthesis draws the work together to examine the petroleum systems, having understood the key datasets that were used, and viewing the specialist reports as ‘appendices’ to the synthesis (Figure 3).

**Readers should first look at the petroleum synthesis report for the area of interest.** This will give the context for the key datasets and specialist reports, which are cited and integrated into the synthesis. The key dataset and specialist reports give the detailed results and methodology of the work undertaken.



**Figure 3 Summary of the structure of the Palaeozoic project reports. Readers should first look at the petroleum synthesis report for the area of interest and use that to signpost the detailed results and methodology contained within the key dataset and specialist reports.**

The project products highlight a clearer and detailed distribution of Carboniferous and Devonian source, reservoir and seal rocks with insights into source rock maturity and maturation history. The scope of the project was regional-scale. The project was focused on the Carboniferous and Devonian intervals of the Palaeozoic era. Permian (Zechstein) strata were interpreted on seismic data for the purposes of depth conversion and gravity modelling. However the petroleum system of the Permian strata was outside the scope of the current project, as was an examination of pre-Palaeozoic/basement plays.

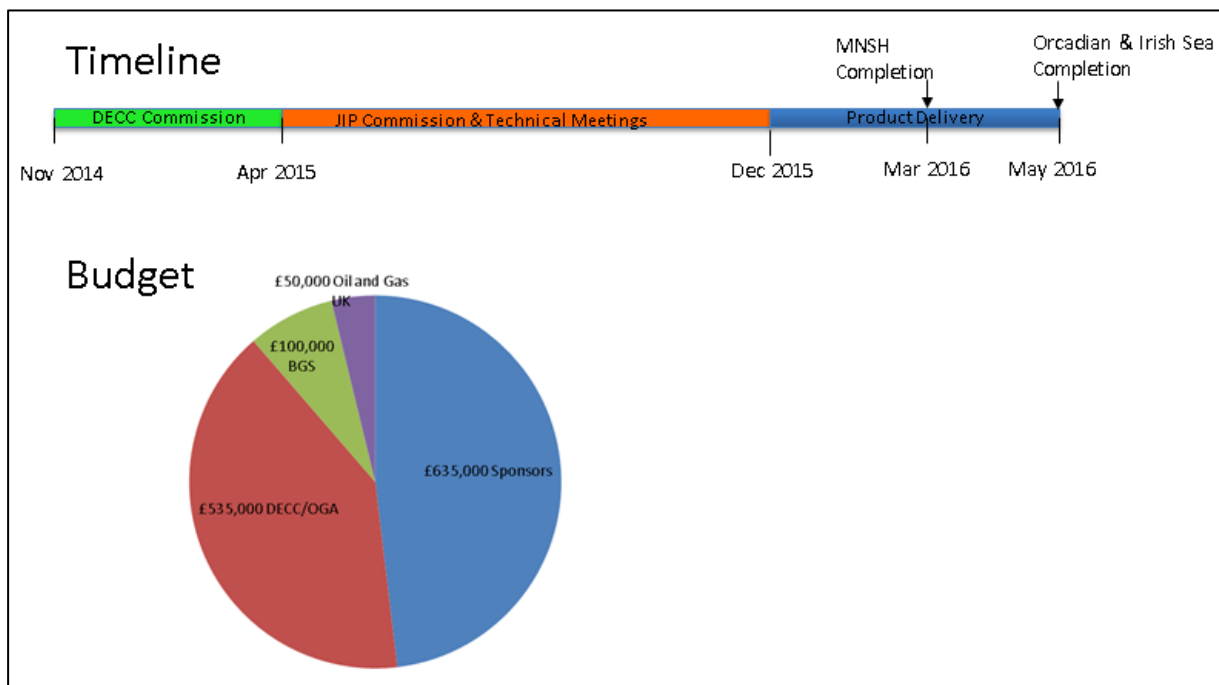
The project team considered all suggestions from the Technical Steering Committee and Project Board during the project and acted where appropriate and practicable. The short timeline and budget inevitably meant certain aspects remained out of scope of the current study (e.g. detailed study of reservoir properties, burial history and diagenesis).

## 4 Timeline and budget

The main phase of the Palaeozoic project ran from January 2015–March 2016. Planning and data gathering commenced from November 2014 and report review and editing of Orcadian and Irish Sea deliverables continued until May 2016 (Figure 4). The Mid North Sea High area was studied first.

The timeline for project results was challenging for a project of this scale and scope. Over 30 BGS staff contributed to the project, working in core teams for each study area in addition to specialist contributors. Data gathering was protracted and complicated by a number of IP issues. Donations of proprietary seismic interpretations were less than envisaged, requiring greater amounts of seismic interpretation to be undertaken. These aspects put particular pressure on project schedules and budgets.

The overall project budget at March 2016 was £1.32 million including a contribution in kind from Oil and Gas UK (Figure 4). Approximately half of the project budget was from industry sponsorship.



**Figure 4 Summary of 21CXR Palaeozoic Project timeline and budget**

## 5 Outcomes and future work

### 5.1 GENERAL

Positive outcomes included:

- Many companies with interests in the area/succession joined as Sponsors at a time of challenging company finances due to the low oil price.
- Technical Steering Committee meetings were well attended and stimulated discussion and collaboration
- The Palaeozoic Project provided scientific input to guide the new Government seismic data. OGA are now using both Project Results and new seismic data to further stimulate exploration interest and detailed studies.

- The reports and datasets produced provide a regional dataset on which to base further work (main outcomes described for each area in synthesis report).

## 5.2 DATA AND IP

Even with DECC/BGS arrangements for access to seismic and well data and many willing Sponsors the project team found:

- Highly variable accessibility to data
- No comprehensive view of what exists (e.g. for well reports on geochemistry, biostratigraphy, regional synthesis reports)
- Very complex ownership and confidentiality rights
- Non-basic well data was patchy in CDA; this has been improved with the significant release of data by Operators during the project
- High dependence on goodwill and memory of companies and individuals
- Restrictions created by the interim exclusivity undertaking in the sponsorship contract on this project
- Imperative to collaborate with seismic data owners and get sanction to communicate examples and generalised interpretations in the output

There was significant interaction with both CDA and the OGA on these issues and with respect to the formulation of the forward strategy and requirements for data archiving in the UK.

Positive outcomes relating to data and IP include:

- Willingness of seismic data owners to agree to the release of regional resolution grids, including interpretations from their most modern data
- Willingness of many Operators to release components of a large set of non-basic well data on the CDA, enabling compilation of datasheets for released data to improve efficiencies such that each company does not have to re-digitise basic data
- Donations to the project from many companies willing to share reports and interpretations



### 5.3 EXPLORATION HIGHLIGHTS

Some key highlights of the work include:

*On and surrounding the Mid North Sea High:* A clearer mapping of widespread Carboniferous source rock intervals and calibration of the stratigraphy and depositional environment with the onshore sequence, with the potential for similar petroleum systems to the Breagh Field

*In the Orcadian study area:* Recognition of the widespread possibilities of Devonian and Carboniferous reservoir intervals to host Jurassic-sourced oil, as well as a more extensive and detailed mapping of potential Devonian and Carboniferous source rocks, with a large variety of possible traps.

*In the Irish Sea:* Detailed tectono-stratigraphic development of Carboniferous source and reservoir intervals with strong links to onshore knowledge.

### 5.4 FUTURE WORK

Aside from detailed and prospect level studies, there are some fundamental themes that it would be beneficial to consider for future work:

*Mid North Sea High/Central North Sea area*

- Regional study of the Rotliegend and Zechstein – critical reservoir and seal intervals for the Carboniferous plays. For example, detailed mapping of thin/patchy Rotliegend over the Mid North Sea High.
- Tight gas, intraformational seals, stratigraphic traps, particularly within the lower–mid Carboniferous basinal play
- Further work with the adjoining Dutch, Norwegian etc sectors
- Further work linking onshore and nearshore, perhaps with a focus on unconventional and tight gas
- Integration of the 2016 Government-funded seismic dataset
- Further release/sharing of data and interpretations and to continue building on collaborative working/knowledge sharing.
- Pilot seabed geochemical sampling programme over ‘gas chimney’ area of Quadrant 29
- New vitrinite reflectance and ATFA data to further define burial/uplift history and maturity

*Orcadian area*

A ‘deep frontier’ of stacked plays has been highlighted in the Outer Moray Firth. Further work on Jurassic sourced/Palaeozoic reservoirs and Devonian – Carboniferous sourced/post-Carboniferous reservoir prospectivity is recommended;

- Extending to the east and north of the current study area (Quadrants 8, 9, 16, 21, 22)
- New organic geochemistry/maturity sample analysis to better constrain regional scale basin modelling in Quadrants 14, 15, 20 and 21
- Typing of oil and gas from fields and discoveries could determine whether there is a component of Palaeozoic co-sourcing more widely than the Inner Moray Firth, and give evidence for migration pathways.

From the Inner Moray Firth to the northern side of the Halibut Horst/East Orkney Basin, (Quadrants 11, 12, 13, 14W), future work could focus on wider basin modelling of maturity, migration routes and trapping/fault leakage, given the extensive Devonian source rock intervals mapped.

Further source rock and reservoir property core analysis would be particularly useful in future work evaluating and modelling the potential prospectivity of migrated Palaeozoic and Jurassic sourced-plays in southern Quadrants 13, 14 and Quadrants 19, 20 to basement or Devonian or

younger reservoirs. Interpretation of the 2016 Government-funded seismic dataset over this area is recommended.

#### *Irish Sea area*

Further additional core analysis on reservoir and source rock quality would be beneficial, along with maturity and apatite fission track data for burial history. Other themes for future work include:

- Regional study of the Permian Appleby and Cumbrian Coast groups as reservoir and seal intervals for the Carboniferous-sourced hydrocarbons.
- More detailed mapping of the intra-Namurian and top Namurian picks, which are the key to understanding the geometry of Variscan inversion structures.
- Further work linking the onshore and the nearshore, perhaps with a focus on unconventional resources and tight gas
- New seismic acquisition to include a denser network of 2D data in Quadrant 109, and a patch of 3D south of the Isle of Man to map the key Variscan inversion structures there.
- Section balancing to analyse the magnitudes and vectors of the multiple phases of inversion recognised from the seismic study
- Extension of the study to include Northern Ireland, Cardigan Bay and the Bristol Channel.

## 6 Technical information to support specialist reports

Very brief summaries are given to give background context in the following geological setting and exploration history sections. Readers are referred to Glennie (1998), The Millennium Atlas (2003), Underhill (2003), the Southern Basin Permian Atlas (2010) for details, links to references etc.

### 6.1 GEOLOGICAL SETTING

A very brief summary of the geological/tectonic setting of the North Sea, as applicable to the Palaeozoic of the study areas is given here.

- In Early Palaeozoic times, basement terranes were amalgamated with the closure of the Iapetus Ocean during the Caledonian Orogeny, and the closure of the Tornquist Ocean.
- A mid Devonian unconformity is widespread in some onshore parts of the UK whilst marine (Central North Sea) and fluvio-lacustrine (Orcadian) deposition was prevalent in parts of the offshore.
- Upper Devonian-Carboniferous extension and strike-slip basins formed in the Central North Sea and to Orcadian areas, north of the Variscan Orogeny, with Variscan transpression and inversion at end Carboniferous times. Carboniferous coal and mudstone source rocks were deposited in a variety of non-marine and marine environments.
- Permian extension and volcanism occurred with the development of the southern and northern Permian basins, separated by the Mid North Sea High. Rotliegend sandstone, mudstones and volcanic rocks were followed by widespread deposition of Zechstein marine carbonates and evaporites.
- A phase of Triassic extension and rifting occurred.
- The Late Jurassic North Sea trilete rift system of the Central, Viking and Moray Firth grabens was preceded by volcanism and uplift. Kimmeridge Clay source rocks were deposited within the rift system.
- In the north (Orcadian area) Cretaceous to Cenozoic post-rift thermal subsidence was affected by Palaeocene uplift to the north-west of the area, as was Mesozoic

sedimentation in the Irish Sea. In the south of the Central North Sea and in the Irish Sea, inversion related to the Alpine orogeny can be observed.

## **6.2 SUMMARY OF DEVONIAN AND CARBONIFEROUS EXPLORATION HISTORY - CENTRAL NORTH SEA/MID NORTH SEA HIGH**

Onshore exploration of the Carboniferous sequence began as early as 1919, with small fields producing in the East Midlands and Yorkshire (1940's to present day; Pharaoh et al., 2011) and Midland Valley of Scotland (1960's, Hallett et al., 1985)

In the early days of North Sea exploration, 1965-1970, wells were drilled across the Central North Sea/Mid North Sea high. Apart from a few notable exceptions, these exploration wells remain the only dataset reaching the Devonian and Carboniferous sequence in Quadrants 27, 28, 29, 36, 37 and 38 (information from DECC well shapefile).

The Argyll and Auk fields in Quadrant 30 were discovered in the 1970's, Argyll utilising a naturally fractured upper Devonian reservoir. Exploration in the Forth Approaches resulted in 5 wells being drilled between 1985 and 2001. A number of wells were drilled across the area in the 1980's and 1990's, some of proved shows and discoveries (e.g. 42/10b- 2) in the Carboniferous of northern Quadrants 41-44.

Many significant gas discoveries in the Carboniferous Southern North Sea play were made between 1984 and 2000, almost all at valid closures on the base Permian unconformity (Cameron et al., 2005 their Figures 3 and 4). More recently, the Cygnus Field has been developed in a Westphalian and Rotliegend play (Taggart, 2015). Outside of the Westphalian play, gas shows in well 42/13- 2 were first identified in 1997, and were later reappraised from 2007 onwards resulting in the Breagh gas field coming onstream in 2013. This field has been critical in proving the pre-Westphalian play.

Well 37/25- 1 was drilled in 2009 to test the Devonian, Kyle Limestone play (Corbenic prospect) but the target strata were absent. The Devonian interval was also tested as dry by well 37/12- 1 in 1985.

Seismic data across the area varies in age, density and quality from some good, regional 1980's lines to modern long-offset 2D data and modern 3D data (see Arsenikos et al. 2015).

## **6.3 SUMMARY OF DEVONIAN AND CARBONIFEROUS EXPLORATION HISTORY – ORCADIAN AREA**

The Buchan Field (Quadrants 20/21 fractured Upper Devonian-Lower Carboniferous reservoir) was discovered in 1974 (Edwards, 1991) and the Beatrice oil field (mid Jurassic reservoir, Jurassic plus Devonian source, Quadrant 11) was discovered in 1976 (Stevens, 1991). The Stirling Field (Quadrant 16) produces from an Upper Devonian reservoir (Gambaro and Currie, 2003) and Carboniferous sandstones form a minor reservoir in the Claymore Field (Quadrant 14; Harker et al., 2003).

Many of the wells in the Inner Moray Firth (Quadrants 11-13) were drilled in the 1980-1990's. In the Outer Moray Firth (Quadrants 14-16), wells continued to be drilled post-2000 due to the development of Mesozoic and Cenozoic fields, however Devonian and Carboniferous penetrations in these wells is limited. There are very sparse or no well penetrations in Quadrants 6, 7, 8 and 19.

A good coverage of 2D seismic data, including modern long offset data, is available for the Inner and Outer Moray Firth, with 3D seismic data prevalent in the Outer Moray Firth (see Arsenikos et al., 2016). However, in areas of the East Orkney Basin, Grampian High and northern end of the Forth Approaches, 1980-1990's 2D seismic data is widely spaced and poorly constrained by well data.

#### **6.4 SUMMARY OF PALAEOZOIC EXPLORATION HISTORY- IRISH SEA**

The Triassic-reservoired Morecambe fields were first drilled in 1969 and discovered in the 1970's (Cowan, 1996). Renewed drilling activity in the East Irish Sea from 1989 resulted in the discovery of oil and gas fields such as Hamilton, Douglas and Lennox (e.g. Haig et al., 1997; Yaliz, 1997).

The main focus of exploration has been in the East Irish Sea, though only 24 wells drilled from 1969 – 1990's penetrate the Carboniferous succession in that area. Outside the East Irish Sea, well data is very sparse with only 5 wells drilled in the 1990's reaching the Carboniferous interval.

2D seismic data of 1980-1990's vintage is fairly extensive across the East Irish Sea and Solway Basin with some regional surveys in the Manx-Peel Basin and North Channel. 3D seismic data is available in parts of the East Irish Sea (see Pharaoh et al., 2016a).

## 6.5 CARBONIFEROUS TIMESCALE

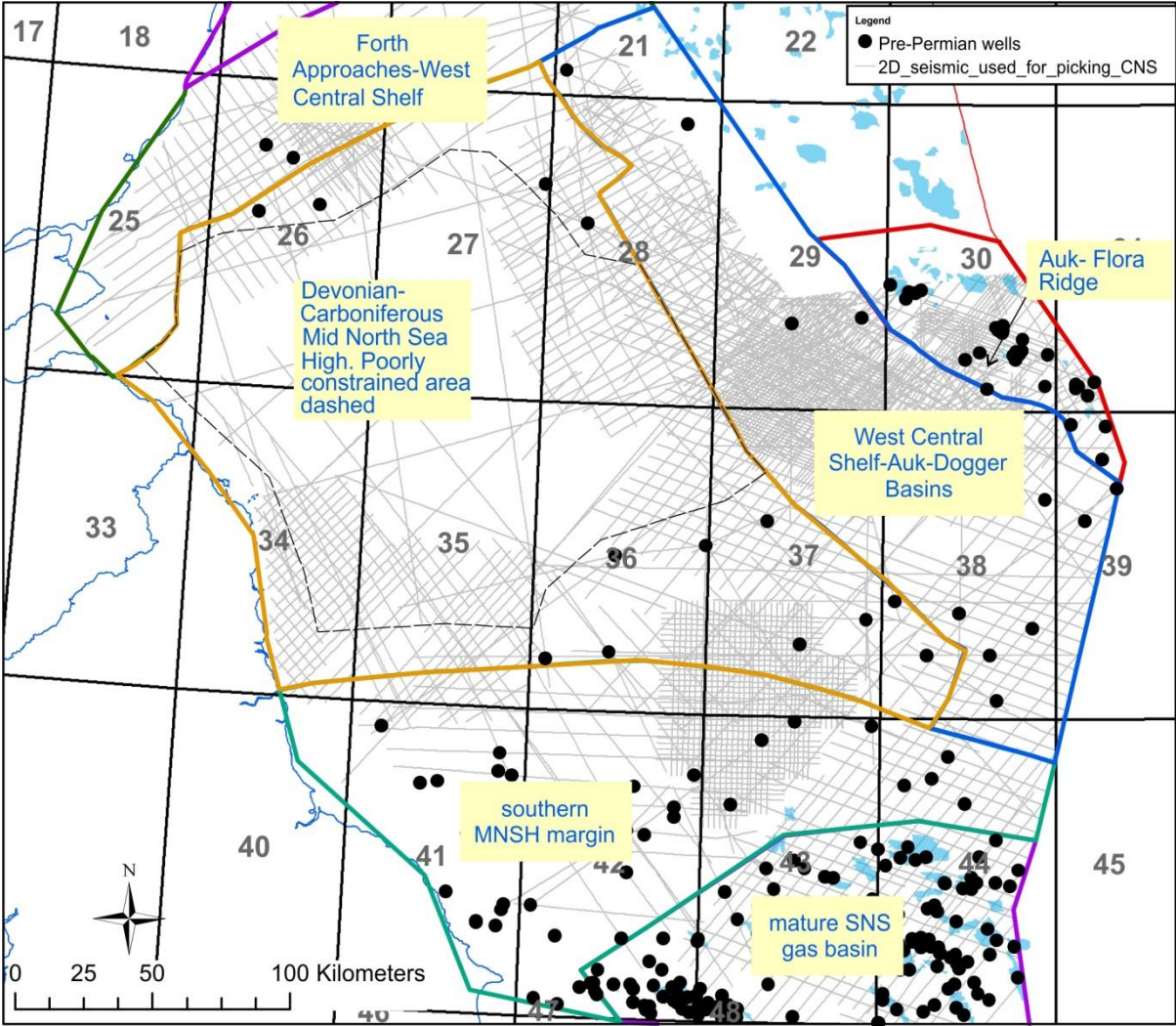
The Carboniferous timescale has undergone significant revision in the last 20 years such that terms such as ‘Dinantian’ are no longer in use and are replaced by Mississippian etc. In this study we have used the Western European stages and substages shown below (Figure 5) and informally used lower, mid and upper Carboniferous to indicate the relative position of key source and reservoir intervals.

STANDARD DIVISIONS			REGIONAL DIVISIONS (W. Europe)		OBSOLETE TERMS	
Sub System	Series	Stage	Stage	Substage		
PENNSYLVANIAN	UPPER	Gzhelian	Autunian ( <i>pars</i> )	Kuzel	SILESIA (UPPER CARBONIFEROUS)	
		Kasimovian	Stephanian	Stephanian C		
				Stephanian B		
	MIDDLE	Moscovian	Westphalian	A Barruelian		
				Cantabrian		
				D Asturian		
				C Bolsovian		
	LOWER	Bashkirian	Namurian	B Duckmantian		
				A Langsettian		
				Yeadonian		
				Marsdenian		
				Kinderscoutian		
				Alportian		
MISSISSIPPIAN	UPPER	Serpukhovian	DINANTIAN (LOWER CARBONIFEROUS)	Chokierian		
	MIDDLE	Visean		Visean	Arnsbergian	
					Pendleian	
					Brigantian	
					Asbian	
					Holkerian	
	LOWER	Tournaisian		Tournaisian	Arundian	
					Chadian	
					Courseyan	Ivorian
						Hastarian

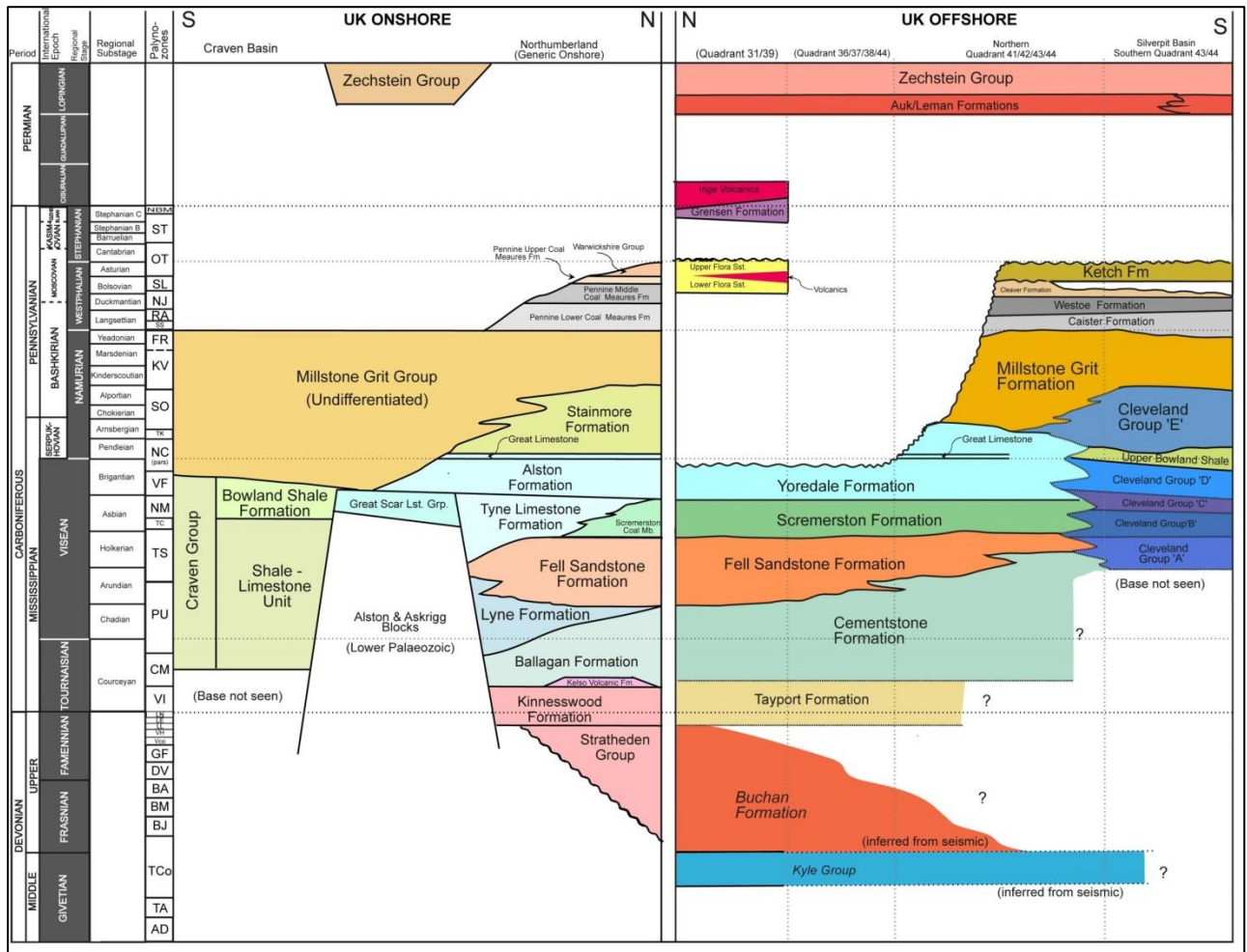
Fig. 1. Chart showing recently ratified global subdivisions of the Carboniferous System and their approximately regional equivalents currently adopted in western Europe, derived from a wide variety of sources. Note that the former western European series are now regarded as stages, and the former stages as substages. Many of the subdivisions shown have not yet been fully formally defined, and in several instances the correlations of series and stage boundaries shown are presently approximate or uncertain. For example, the base of the Chadian substage does not precisely coincide with the base of the Visean, and the precise level of the base of the Kasimovian has yet to be decided.

**Figure 5 Carboniferous timescale nomenclature and equivalence with older terminology, from Holliday & Molyneux 2006. Editorial statement: new official names for the subsystems, series and stages of the Carboniferous System. Reproduced with permission of the Yorkshire Geological Society.**

# 7 Reference images for the Mid North Sea High/Central North Sea study area

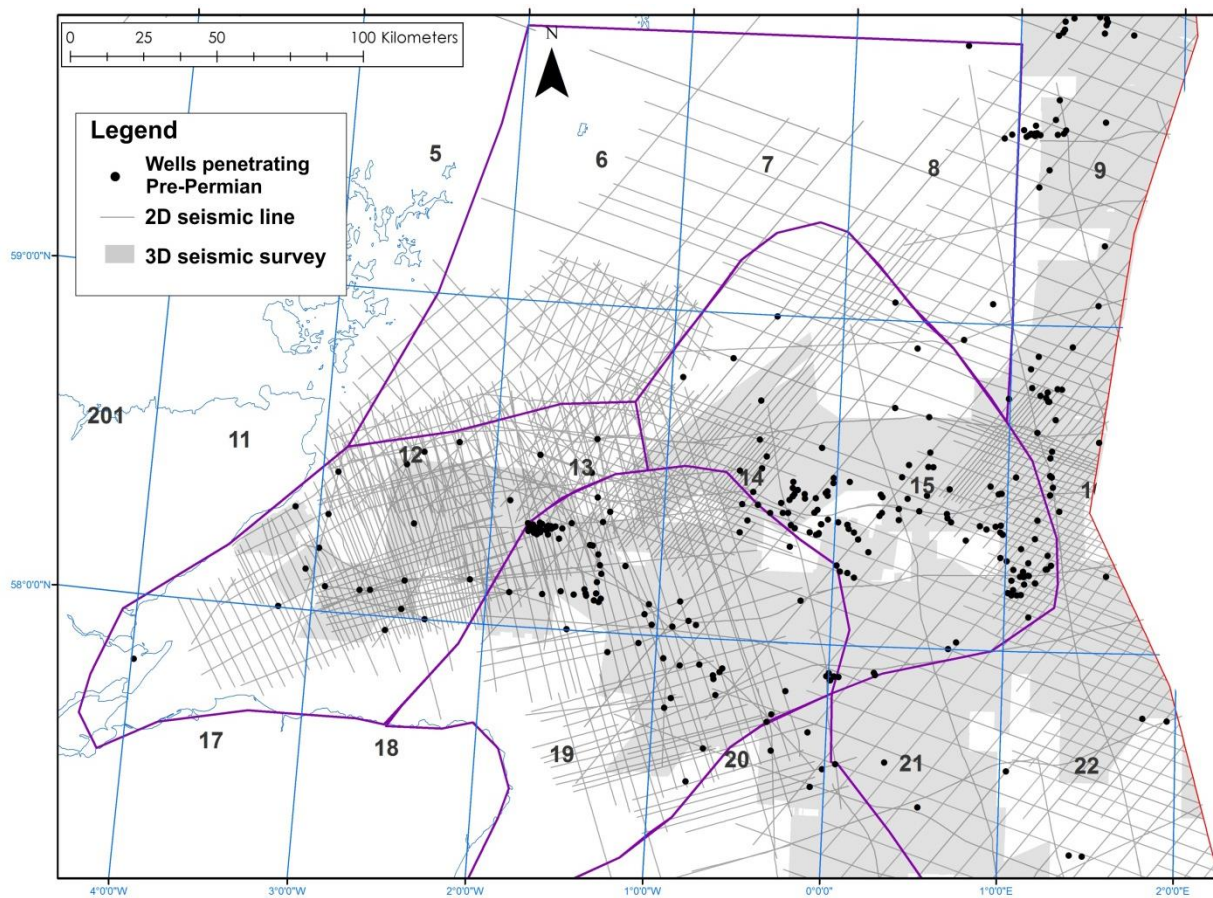


**Figure 6 Summary of seismic and well data used for the Mid North Sea High/Central North Sea area, together with the terminology used for the sub-areas of study.**



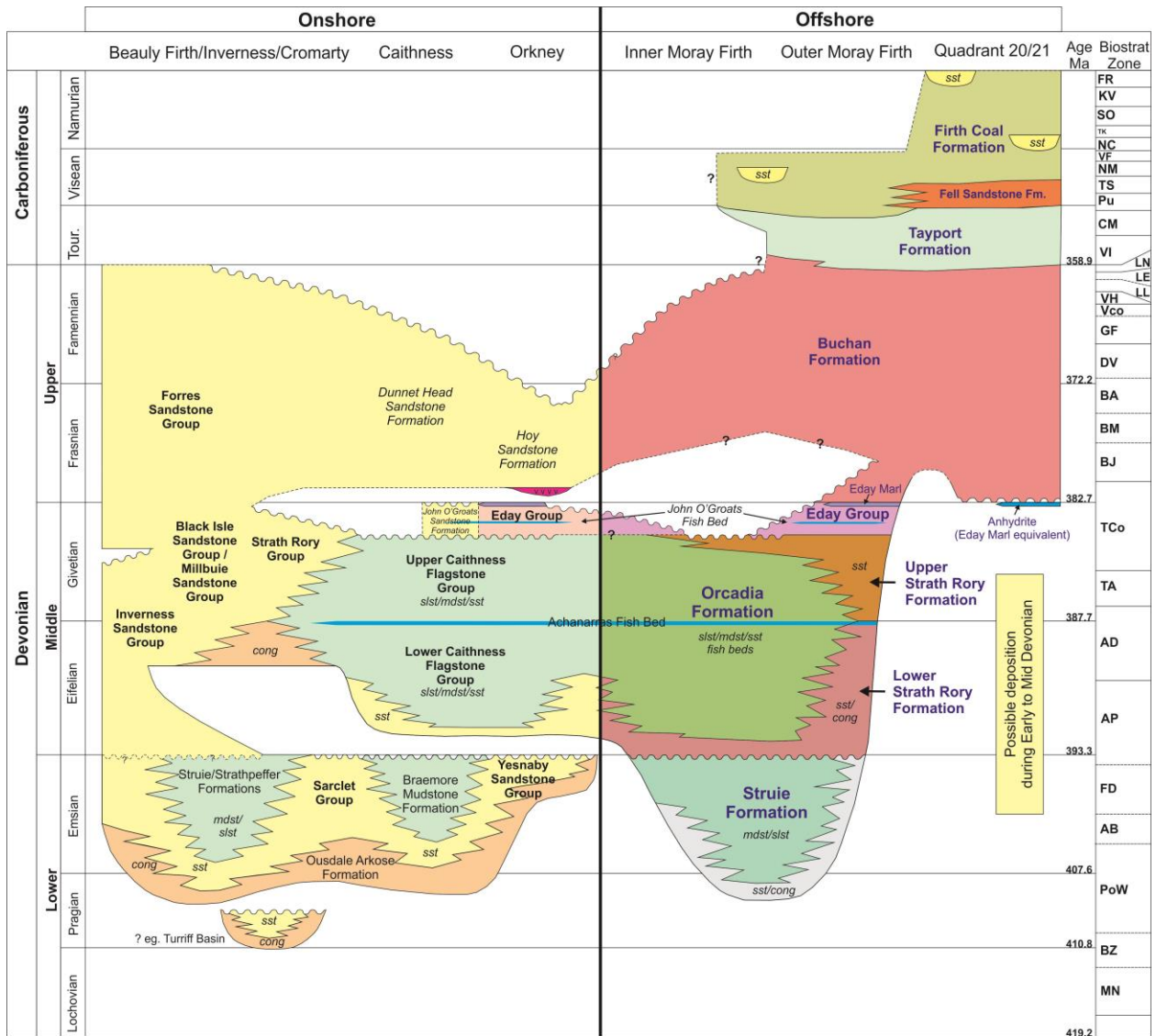
**Figure 7 Summary of stratigraphic terminology for the Mid North Sea High/Central North Sea area. Note that the Cleveland Group units are newly defined in Kearsley et al. (2015).**

## 8 Reference images for the Orcadian study area

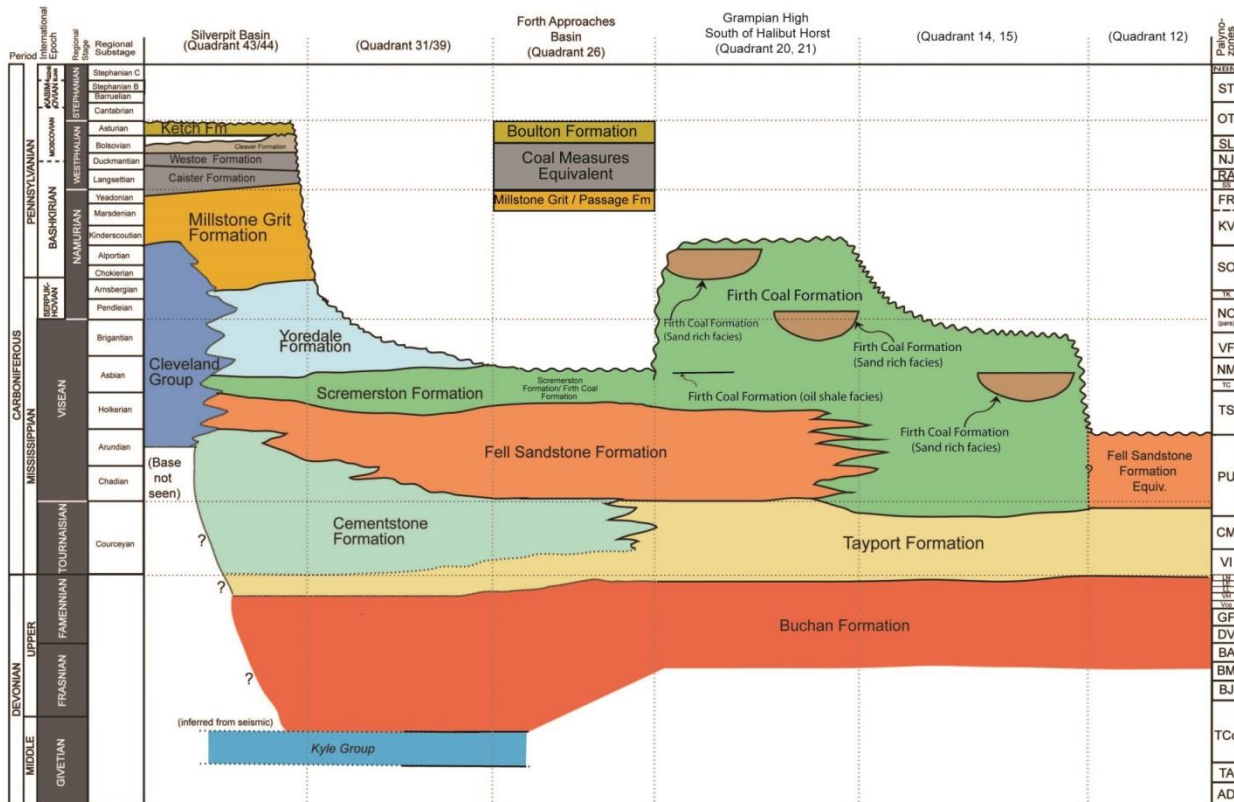


**Figure 8 Summary of seismic and well data used for the Orcadian area, together with the terminology used for the sub-areas of study.**





**Figure 9 Summary of stratigraphic terminology for the Orcadian area from Whitbread and Kearsy, 2016.**



**Figure 10 Stratigraphical relationship of Late Devonian to Early Carboniferous strata between the Orcadian area and the Central North Sea from Whitbread and Kearsy, 2016.**



<b>Chronostratigraphy</b>	<b>Current lithostratigraphic name</b>		<b>Former lithostratigraphic name<sup>1</sup></b>
Upper Permian	Cumbrian Coast Group		Cumbrian Coast Group (includes St Bees Shales & Manchester Marls)
Middle Permian	Appleby Group		Appleby Group (includes Collyhurst Sandstone & Manchester Marls)
Stephanian	Warwickshire Group		Kidston Group
Westphalian	Pennine Coal Measures Group		
Namurian	Millstone Grit Group		Bisat Group
	Yoredale Group	Craven Group	
Visean	Border Group	Carboniferous Limestone Supergroup	Garwood Group
Tournaisian	Inverclyde/Ravenstonedale groups		

**Table 3 Summary of old and new stratigraphical nomenclature, Irish Sea area from Wakefield et al., 2016**

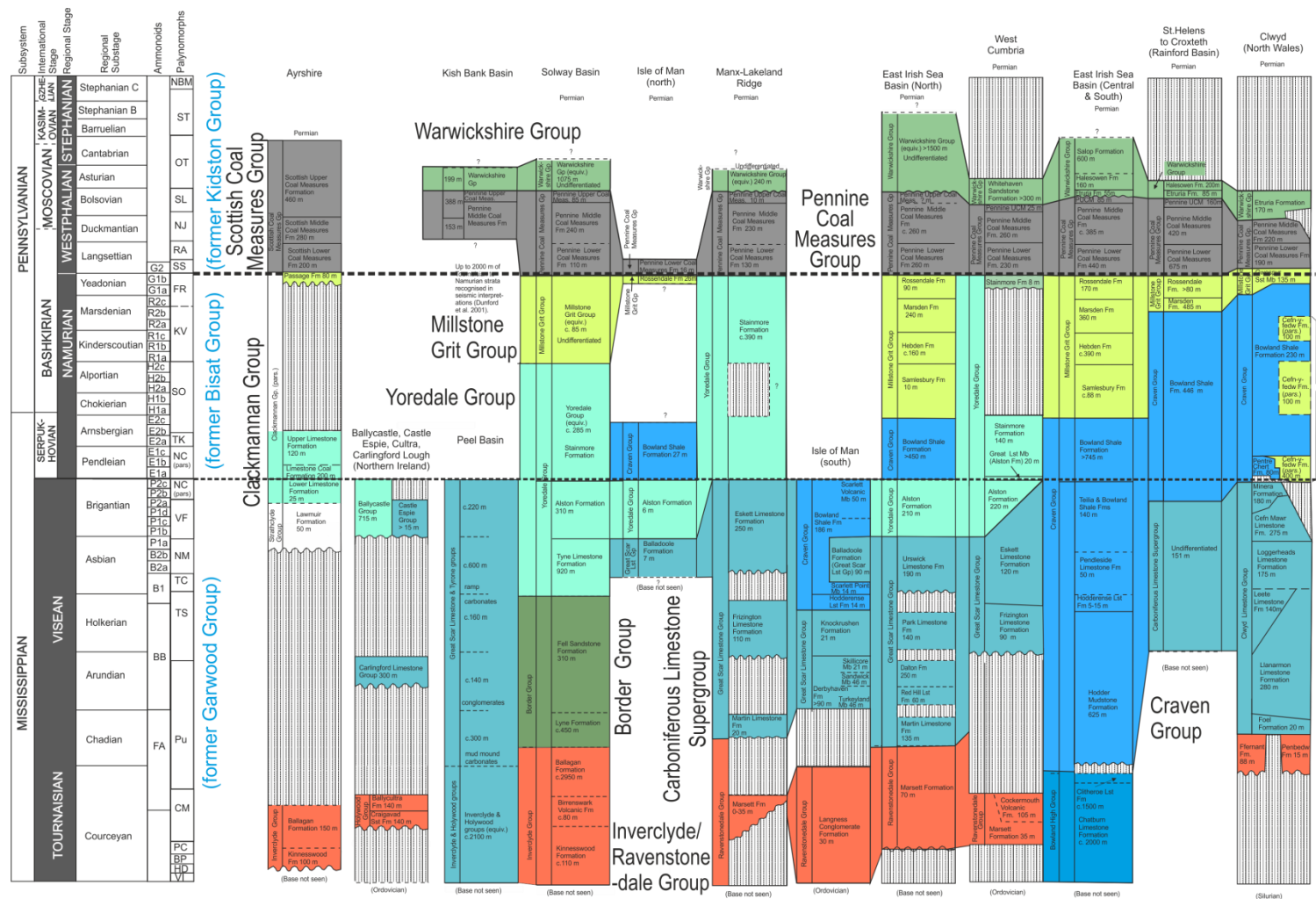


Figure 12 Carboniferous stratigraphical successions and correlation of the onshore UK and adjacent quadrants in the Irish Sea. The nomenclature, distribution and maximum thicknesses are those published in component chapters of the Geological Society Special Report on the Carboniferous, see Wakefield et al., 2016.

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