The Standard Stratigraphic Nomenclature of Offshore Ireland:

An Integrated Lithostratigraphic, Biostratigraphic and Sequence Stratigraphic Framework

Project Atlas

Prepared By

Merlin Energy Resources Consortium

(Merlin Energy Resourced Ltd, in association with Palaeodate Ltd, Network Stratigraphic Consulting Ltd, Riley Geoscience Ltd, Integrated Geochemical Interpretation Ltd)

For

PIP (Petroleum Infrastructure Programme)

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A number of companies and individuals assisted in retrieving additional historical data that was incorporated in this project including Marathon International Oil UK Ltd., BP Exploration Operating Company Limited, Esso UK Ltd., Shell UK Ltd., Chevron North Sea Ltd., Equinor UK Ltd., ExxonMobil International Ltd., PSE Kinsale Energy Ltd., Providence Resources Plc, RPS Ichron UK Ltd., Robertson UK Ltd., PetroStrat Ltd. and Millennia Stratigraphic Consultants Ltd.

Additional acknowledgements are due to, Dr Martyn Stoker (Australian School of Petroleum), Professor Stephen J. Daly (University College Dublin), Dr Stephen McCarron (Maynooth University), Professor Peter Coxon (Trinity College Dublin), Katie Hernon (PAD), Oonagh O'Loughlin (PAD), Darren Wallace (PAD), Nick Boldy (PAD), John O'Brien (PAD), Mojibola Aramide (PAD), Niamh Walsh (PAD), Callum Gilchrist (PAD), Graham Pritchard (Serica Energy), Paleolab Ltd., Rockwash Ltd., the iCRAG research group, the Geological Survey of Ireland and the British Geological Survey. Professor Patrick Shannon, Michael Hanrahan and Kara English are acknowledged for their work in reviewing and approving the Atlas content.

This system is accepted for use by the Stratigraphic Committee and the stratigraphic nomenclature system for offshore Ireland presented here is endorsed by the Petroleum Affairs Division of the Department of Communications, Climate Action and Environment and is to be used by all involved in working the geology of the Irish basins.

FOREWORD

Any geoscientist who has worked the Irish offshore basins to date is acutely aware that a standard stratigraphic nomenclature was not available. I am delighted to report that this is no longer the case and this identified gap has now been filled. It has been recognised for some time that it would be important to establish a formal, rigorous and publicly available system for naming geological units offshore Ireland which will better enable data analysis and interpretation.

The Standard Stratigraphic Nomenclature of Offshore Ireland: An Integrated Lithostratigraphic, Biostratigraphic and Sequence Stratigraphic Framework is a milestone project. The multi-year study, initiated by the Petroleum Affairs Division (PAD) and Petroleum Infrastructure Programme (PIP) members in 2016 was a major undertaking. The scale of the project is impressive, covering all basins offshore Ireland and involving the immense task of trawling and compiling varied datasets over a 50 year exploration period to create a new national stratigraphic framework. The substantial detail, the methodology, the workflow, the extensive quantity and range of multi-sourced datasets of variable quality together with the integrated nature of the study, provides a robust project deliverable.

The objective of the project was twofold – firstly to compile all existing biostratigraphic data from offshore Ireland wells and secondly to propose a new chrono-lithological framework to be presented to the geoscience community. The study aimed to provide a common geological nomenclature for the use of offshore operating companies and their partners, government departments, academia and contractors. This is achieved through seismic sequence recognition, sequence stratigraphy, biostratigraphy, lithostratigraphy, geochemistry, palaeofacies maps, rock unit distribution, sub-divisions and stratigraphic columns.

Hydrocarbon exploration began offshore Ireland in the 1960s. The first seismic survey was acquired in 1965 in the Porcupine Basin and the first well drilled offshore was 48/25-1 in 1970 in the North Celtic Sea Basin. Exploration to date has resulted in four commercial gas discoveries and numerous oil, gas and condensate discoveries. The exploration success includes the discovery of the Kinsale gas field in 1971 off our south coast. The Corrib gas field, located in the Slyne Basin, first produced gas in 2015 and is an important contributor to Ireland's energy security, and proves the attractiveness of the Atlantic margin. In more recent years, improvements in seismic acquisition and processing have provided higher resolution images of the subsurface, and analogues from conjugate margin discoveries have significantly assisted exploration efforts offshore Ireland.

This project is also directly aligned and integrally linked with previous PIP sponsored projects; for example, it dovetails with the Trans-Atlantic source rock geochemistry study (PIP project IS16/01) completed in 2018 and the earlier Structural Elements Special Publications (1999 and 2002) that are useful companion studies. The completed stratigraphic framework facilitates comparison to the geology of surrounding jurisdictions include offshore East Canada (Newfoundland), UK basins and Norway North Sea.

The stratigraphic nomenclature involved much iteration. Names were selected according to Irish based themes and consideration was given towards the ease of pronunciation and the avoidance of repetition with existing names. Rationale behind the definition of sequences, groups, formations and members are also provided in the project deliverables. Over 250 lithostratigraphic units are officially named for the first time, of which 63 existing names have been used from the UK, and a further 50 units are informally named, amounting to a total of over 300 defined rock units that comprise the Atlas.

The study was overseen by the Project Steering Group, under the direction of the PAD and the PIP Secretariat. Following a tendering process the Atlas/study was prepared by an expert consortium led by Merlin Energy Resources Limited. The framework and nomenclature was overseen by a newly formed Stratigraphic Committee that comprised members from industry, prominent academics in the sector and PAD government geoscientists. The individual and combined expertise of the entire project group was pronounced, with regular positive engagement and each individual's input and time surrendered to project steer was generous and very much appreciated.

I would like to acknowledge the substantial input by many individuals into the successful completion of the project. Special thanks are due to the Project Coordinator & Atlas Editor Dr Philip Copestake of Merlin Energy Resources, the Departmental Project Lead Dr. Kara English and Michael Hanrahan, the Stratigraphic Steering Committee, chaired by Professor Patrick Shannon and the PIP Secretariat Nick O' Neill.

I offer my sincere thanks to the PIP member companies for not only supporting the project but for generously providing valuable input during the technical meetings and for data provision. I also wish to thank PIP members who gave approval for the public release of the results. I am also grateful to the academic community for sharing results of their research. I witnessed first-hand the collaborative effort in progressing the project. This completed work is a very tangible example of the way PAD, the petroleum industry and academia are able to work together in partnership.

As with any project of this scale, the final product does not totally capture the behind-scene forensic search for data, substantial interpretation discussions, interim reporting and presentations, the timeline charts, drafting, IT and the sleepless nights! The lively enthusiastic healthy debate and the good engagement with all players throughout the multi-year period helped shape a robust stratigraphic framework and nomenclature. The project has generated a quality document of tremendous importance to the geoscience community.

The design layout of an Atlas, in high-resolution format, was deliberately chosen for convenience to the end user. This illustrative deliverable provides a reference tool for all geoscientists whether industry, researchers or government based, and this unique document will be utilised for many years and decades into the future.

Clare P. Morgan

Clare Morgan
Head of Technical Section
Petroleum Affairs Division
Department of Communications, Climate Action and Environment

March 2020

ATLAS TABLE OF CONTENTS

EXECUTIVE SUMMARY

This atlas (and accompanying executive summary report) presents the results of project IS16/04 funded by the Irish Shelf Petroleum Studies Group (ISPSG) of the Petroleum Infrastructure Programme (PIP). The project has been carried out by a consortium of companies, led by Merlin Energy Resources Ltd, incorporating Palaeodate Ltd, Network Stratigraphic Consulting Ltd, Riley Geoscience Ltd, and Integrated Geochemical Interpretation Ltd. The study area includes the Rockall, Slyne, Erris, Donegal, Macdara/Bróna, Porcupine, Goban Spur, Fastnet, North Celtic Sea, South Celtic Sea, Kish Bank and Central Irish Sea basins of the offshore Ireland region.

The atlas presents new lithostratigraphic, chronostratigraphic, biostratigraphic and sequence stratigraphic frameworks for drilled Phanerozoic section of the Ireland offshore region. These are based on an extensive legacy data set, and published research, supplemented by a significant amount of new data generation and interpretation. The new lithostratigraphic scheme has been developed in association with a newly established Stratigraphic Committee. It is intended that, in addition to this atlas, the new lithostratigraphic scheme will be published as a Petroleum Affairs Division Special Publication.

A total of 309 lithostratigraphic units (groups, formations, members, units) are recognised in the study. Of these, 259 rock units are formally named and described and a further 50 units are informally named. Of the total, 196 new names are introduced in the documented lithostratigraphic scheme and 63 previously existing names are utilised from the UK (offshore and onshore). The final set of rock unit names was agreed between members of the Stratigraphic Committee and the PAD. Maps have been produced showing the interpreted distributions of all defined lithostratigraphic units, based on a considered interpretation of the likely extent of each unit, utilising all well and borehole penetrations, integrated with seismic interpretations.

The reservoir intervals for all producing hydrocarbon fields and discoveries in offshore Ireland have been placed into the new lithostratigraphic nomenclature. All test intervals have been incorporated into the project and are plotted against the new stratigraphy on the project well and borehole summary logs provided as a digital Atlas Appendix C.

Stratigraphic sequences have been recognised and defined in this study, both from interpretations of well and seismic data, over the Triassic-Quaternary interval. In total, sequences have been interpreted in 116 wells and boreholes in the project. New schemes are defined and described for most of these intervals and are integrated and compared with previously documented schemes for the region. Existing schemes are utilised for parts of the Jurassic and Cretaceous intervals. These schemes are described in the individual stratigraphic chapters in the Atlas (sections D.5-D10).

New biozonation schemes are defined for the Jurassic, Cretaceous and Cenozoic of the offshore area, based on a thorough review of all legacy data integrated with a significant body of new data generated in this study from new sample analysis (involving over 3000 new sample analyses from 106 wells) (Atlas Appendix B). For the Carboniferous and Triassic, existing published palynology biozonation schemes have been applied.

The new Ireland stratigraphy has been compared to adjacent regions of offshore Eastern Canada, the UK Continental Shelf and the North Sea. This is illustrated in a series of stratigraphic charts.

The well and borehole database for offshore Ireland, at the time of the study, comprised 264 released wells and boreholes; this includes 219 oil and gas wells, 31 DSDP/ODP/IODP boreholes and 14 shallow/mining boreholes. In addition, a small number of UK wells that are close to the median line with Ireland, have been tied to the evaluations. New stratigraphic interpretations, including tops and stratigraphic summary logs for 197 wells and boreholes are provided in the study.

The well interpretations have been tied to an extensive seismic database across the region. From the seismic interpretations, a set of around 60 significant seismic horizons were interpreted in the offshore areas of Ireland in this project. These have been named in a consistent manner and will provide a good basis for future work in the area. A set of 10 key regional seismic lines illustrates the regional stratigraphy and seismic horizon development (Atlas Section E). In addition, ties between the seismic and the wells and boreholes are provided in numerous figures within the atlas. A small number of synthetic seismograms have been produced to illustrate particular well-seismic ties. 55 figures showing seismic lines and well ties are illustrated in the Atlas, in addition to the 10 regional seismic lines.

A regional evaluation of the source rock potential for offshore Ireland has identified 21 formations with hydrocarbon generation potential based on the newly developed stratigraphy of this project. Identified source rock formations are mainly of Early Cretaceous to Early Jurassic age, although the Paleogene Gweedore Formation and Carboniferous Blackthorn Group also show significant source potential. None of the Upper Cretaceous or Triassic formations showed hydrocarbon generative potential.

Volcanic rocks occur throughout the offshore Ireland area, at many stratigraphic levels and are of both intrusive (plutonic rocks, sills and dykes) and extrusive (lava flows, including pillow lavas and tuffs) origin. Several extrusive igneous rock units are named and described in the new lithostratigraphic scheme. To assist the evaluation of the age of these igneous rock units, 10 new radiometric dating (Ar-Ar) analyses were carried out. Most of the results of the new analysis were inconclusive due to high alteration of the samples analysed.

Most geological periods and stages are represented in offshore Ireland, from Palaeozoic to Recent, however, many significant unconformities are present, some over very wide areas. There is no strong evidence for the presence of Callovian aged sediments in the region.

A revision of the structural elements of offshore Ireland has been carried out, utilising seismic and gravity data. This includes a new definition for the boundary between the Fastnet and North Celtic Sea basins.

Digital outputs derived from the project include *Stratabugs* and *IC* databases containing all stratigraphic data, including tops, raw and interpreted biostratigraphic data (all legacy data combined with newly generated data), biozones, biostratigraphic comments (key biostratigraphic markers), chronostratigraphy, groups, formations, members, wireline logs, test data, geochemistry data (TOC, HI values) and stratigraphic sequences. The original data sets, well displays and correlations that have been used in the Atlas are provided in the *IC* database. A set of 197 well and borehole stratigraphic summary logs is provided in pdf or png form, within the Digital Addenda to this atlas, which have been generated from the original files in the *IC* database.

An *ArcGIS* database has been developed that contains all maps generated in the project. A full listing of all biostratigraphic reports available from the area is provided as an *Excel* spreadsheet (within the Digital Addenda).

DISCLAIMER

Merlin Energy Resources Ltd., in association with Palaeodate Ltd, Riley Geoscience Ltd, Network Stratigraphic Consulting Ltd and Integrated Geochemical Interpretation Ltd, has prepared this report using principles and methods of geoscientific investigation that are widely accepted as good practice by the hydrocarbon exploration and production industry. However, all interpretations made and contained within this report are matters of opinion rather than proven fact and should be regarded as such.

Merlin Energy Resources Ltd., its Directors, employees or sub-contractors shall have no liability arising out of the use of this report or anything contained within it.

A. INTRODUCTION

PROJECT OBJECTIVES & STUDY AREA

This atlas presents the results of project IS16/04 funded by the Irish Shelf Petroleum Studies Group (ISPSG) of the Petroleum Infrastructure Programme (PIP).

The objectives of the study were as follows:-

- Establish new biostratigraphic and chronostratigraphic framework and updated well interpretations of offshore Ireland for use by the geoscience community
  - Based upon interpretation of existing and new stratigraphic data from all offshore key wells and boreholes.
  - Integrated with new interpretations of all available seismic data
- Review existing data, gaps and uncertainties in the current offshore stratigraphic database.
- Recommend and carry out new analysis of selected intervals in key wells, addressing identified data gaps and stratigraphic issues.
- Compile all existing and new data into stratigraphic database(s).
- Establish a new lithostratigraphic nomenclature scheme to be adopted as a standard for the offshore area
- Establish new sequence stratigraphic scheme(s) for the region integrating well based and seismic based sequences
- Generate palaeofacies maps
- Provide maps showing the distribution of rock units, tied to the updated stratigraphic schemes.
- Incorporate results of the PIP Project IS16/01 Trans-Atlantic Source Rock Geochemical Study (BeicipFranlab, 2017) and update ages of source rock intervals with new interpretations
- Compare results with the geology of offshore East Canada (Newfoundland), UK North Sea and Norway North Sea where appropriate.

The study area includes the Rockall, Slyne, Erris, Donegal, Macdara, Bróna, Porcupine, Goban Spur, Fastnet, North Celtic Sea, South Celtic Sea, Kish Bank and Central Irish Sea basins (**Figure A.1**), in which the study wells and boreholes are located. In addition, the Conall and Rónán basins were included, based on a seismic interpretation and extrapolation from ODP holes and wells on the eastern flank of the Rockall Basin. There are several basins within the overall project bounds that are currently undrilled; these include the Cockburn and Little Sole basins, to the south east of the Fastnet Basin, and many small basins on the eastern flank of the Rockall Basin, including the Colm, Fursa, Padraig, South Bróna and Cillian basins. These basins have not been inteprrted in any detail as they sit outside the agreed project scope. No detailed mapping has been carried out that incorporates these basins, though some of them are mentioned where relevant.

The project data and results are reported via an atlas (this document), a Summary Report and by a set of accompanying supplementary databases and addenda, as follows:-

- **Atlas** containing the bulk of the project results, together with project background, description of the project database, descriptions of lithostratigraphic units, illustrated with well displays, correlations and maps, sequence stratigraphy, description of biostratigraphy (including biozonations), geochemistry, unit extent maps, palaeofacies maps and comparisons between offshore Ireland and Eastern Canada and the North Sea, regional seismic lines tying key wells across the offshore area, montages of geochemistry results and source rock distribution maps.
- **Summary report** containing a summary of the project results.
- **Chronostratigraphic and lithostratigraphic tops listing.**
- **ArcGIS database** containing all project maps including palaeofacies maps, lithostratigraphic unit extent maps and set of stratigraphic summary well logs.
- **Stratabugs** database of all new and legacy biostratigraphic data, including quantitative distribution data.
- **IC** database of new and legacy biostratigraphic database comments (key biostratigraphic events), biozones, sequence stratigraphic subdivisions (project interpretations and legacy interpretations of other authors), lithostratigraphic (group, formation, member) subdivisions, lithologies, cored intervals, casing points, DST data, geochemistry data (updated source intervals based on data from the IS16/01 project), well summary logs, lithologies and well correlation panels.
- **Digital Addenda**, including
  - spreadsheet listing of all legacy biostratigraphic reports
  - spreadsheet listing of all type and reference wells
  - spreadsheet listing of all seismic lines interpreted in the project
  - igneous rocks report by Stevenson (2017)
  - radiometric dating report by ActLabs (2017)
  - charophytes report by Closas (2018)
  - lithostratigraphic tops (and thicknesses) spreadsheet.
  - "Gap Analysis" spreadsheet
  - A new standard lithostratigraphic framework for offshore Ireland; regional chronostratigraphic summary chart.

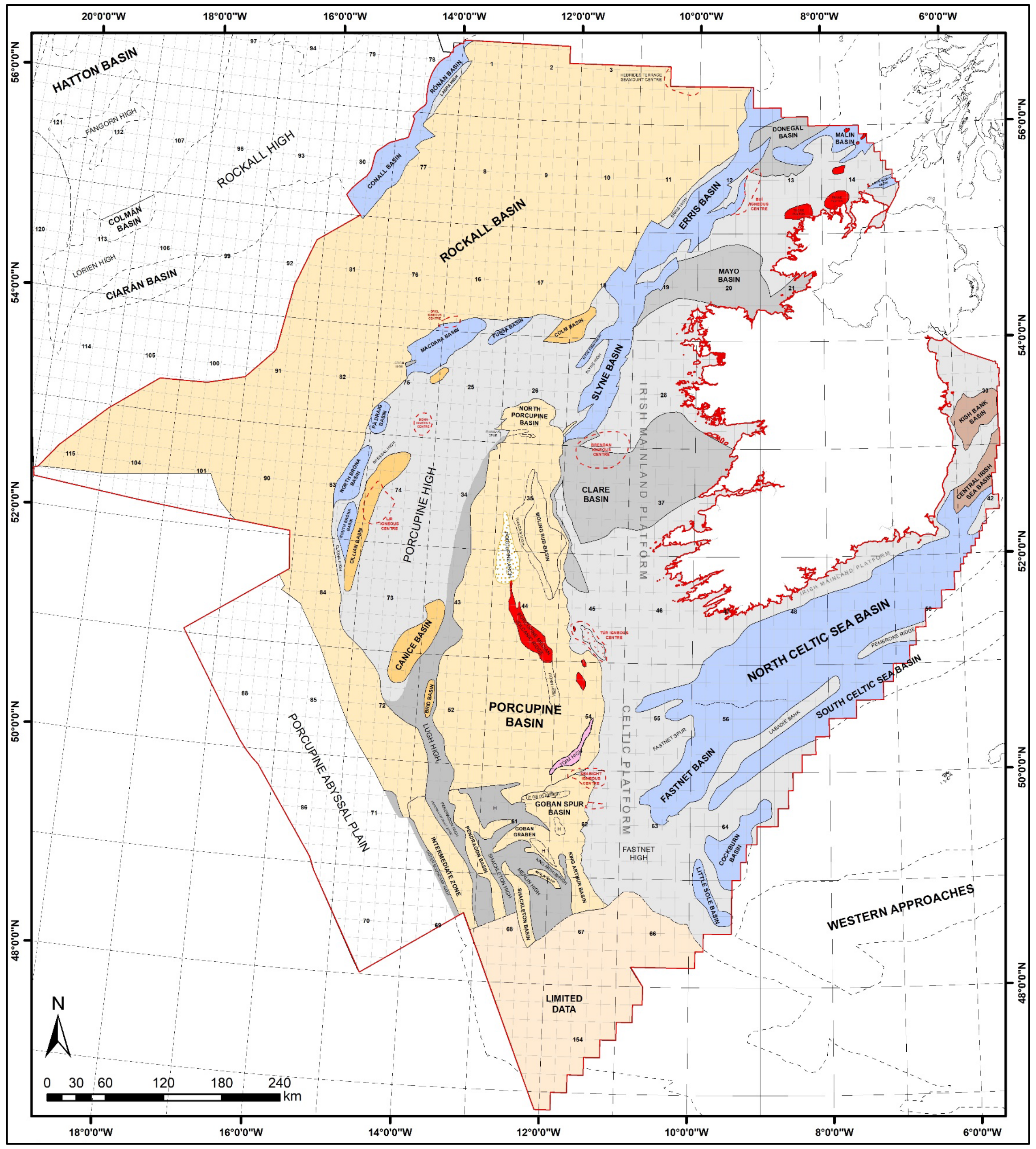


Figure A.1. ***Project area (red outline), relative to basins and major structural features. See Figure A.7 for legend.***

ATLAS STRUCTURE & AUTHORSHIP

The Atlas comprises the following sections:-

- ***A. Introduction**; executive summary, project objectives, scope, background, structural framework, database, methodologies.
- ***B. Geochemistry**; summary of geochemistry results.
- ***C. Stratigraphic Columns**;
  - set of stratigraphic summaries for each interval show main lithostratigraphic units and sequences, with column for each basin offshore Ireland.
  - Set of stratigraphic summaries comparing Ireland offshore stratigraphy with Eastern Canada, UKCS and Norway North Sea.
- ***D. Stratigraphic Intervals**; lithostratigraphy, sequence stratigraphy, source rocks, palaeofacies, illustrated with type wells, seismic lines, well correlation panels, distribution maps.
  - D1. Precambrian-Lower Palaeozoic (Pre-Devonian).
  - D2. Devonian
  - D3. Carboniferous
  - D4. Permian
  - D5. Triassic
  - D6. Lower-Middle Jurassic
  - D7. Upper Jurassic
  - D8. Lower Cretaceous
  - D9. Upper Cretaceous
  - D10. Cenozoic
- ***E. Regional Seismic Lines**; set of 10 regional seismic lines (interpreted and uninterpreted displays).
- ***F. Future Directions**; Areas for future work and general recommendations.
- ***G. References**; listing of all publications and reports referenced in the Atlas.
- ***Appendix A – Database**; database listings and discussion.
- ***Appendix B – Biostratigraphy**; listing of new sample analyses carried out, biozonation schemes, biostratigraphic zonation charts.
- **Appendix C – Stratigraphic Summary Logs**; for 197 wells and boreholes with legacy or newly generated biostratigraphic data, displaying stratigraphic interpretations, wireline logs, lithology, sample points, DST data, sequences, key biostratigraphic markers.
- **Appendix D – Radiometric Dating**; radiometric dating report, petrography and description of all new samples analysed radiometrically.
- **Appendix E – Geochemistry**; source rock characterisation plots for 10 formations with only limited source potential.

Those atlas sections indicated with an * will be publicly released upon project completion. The ISPSG Secretariat (noneill@pip.ie) may be contacted with any enquiries about accessing project data.

The authors of the various Atlas chapters and Appendices are as follows:-

Atlas Section	*Primary Authors*	*Additional Authors*	*Additional Technical/Editorial Input*
A. Introduction	P. Copestake	N. Ainsworth, M. Gehlen	O. Lavis, G. Lockham
B. Geochemistry Results Summary	M. Gehlen	P. Copestake	
C. Stratigraphic Columns	P. Copestake (compiler)	All chapter authors	
D. Stratigraphic Intervals			
D1. Precambrian-Lower Palaeozoic (Pre-Devonian)	P. Copestake, N. R. Ainsworth		K. Gueinn
D2. Devonian	P. Copestake, N. R. Ainsworth		K. Gueinn
D3. Carboniferous	N. R. Ainsworth, P. Copestake		K. Gueinn
D4. Permian	N. R. Ainsworth, P. Copestake		K. Gueinn
D5. Triassic	N. R. Ainsworth, P. Copestake		K. Gueinn
D6. Lower-Middle Jurassic	N. R. Ainsworth, P. Copestake		L. A. Riley
D7. Upper Jurassic	N. R. Ainsworth, P. Copestake		L. A. Riley
D8. Lower Cretaceous	N. R. Ainsworth, P. Copestake		L. A. Riley
D9. Upper Cretaceous	L. T. Gallagher, N. R. Ainsworth	P. Copestake, M. Hampton	H. W. Bailey, T. Loy, L. A. Riley
D10. Cenozoic	M. Hampton, P. Copestake	L. T. Gallagher	H. W. Bailey, K. Gueinn
E. Regional Seismic Lines	T. D. Wright, P. Copestake		G. Lockham
F. Future Directions	P. Copestake	N. R. Ainsworth	
Appendix A, Database	P. Copestake, J. A. Donato	N. R. Ainsworth	
Appendix B, Biostratigraphy	P. Copestake (compiler), N. R. Ainsworth, H. W. Bailey, L. T. Gallagher, K. Gueinn, M. Hampton, T. Loy, L. A. Riley		
Appendix C, Stratigraphic Summary Logs	P. Copestake (compiler), N. R. Ainsworth, H. W. Bailey, L. T. Gallagher, K. Gueinn, M. Hampton, T. Loy, L. A. Riley		O. Lavis, G. Lockham
Appendix D, Radiometric Dating	T. D. Wright, P. Copestake		

Appendix E, Geochemistry	M. Gehlen		P. Copestake

Table A.1. ***Atlas authorship credits.***

The summary Report was compiled by P. Copestake, based on the results of the Atlas chapters. Overall editor of the Atlas and summary Report was P. Copestake. All written content was reviewed in detail and approved by M. Hanrahan, P. Shannon and K. English. Drafting support was provided by G. Warmington, with assistance from G. Lockham and E. Lashko. T. Loy carried out an additional editorial role on all chapters and assisted in the compilation of lithostratigraphic unit figures (montages).

All atlas maps were generated from the ArcGIS project and created by O. Lavis and G. Lockham. All well displays, including stratigraphic summary logs, were generated from *IC*. All seismic images were captured from the *IHS Markit Kingdom* seismic project and annotated and labelled in *Microsoft Powerpoint*. All Atlas images were compiled in *Microsoft Powerpoint*. The Atlas and Report were written in *Microsoft Word*. Drafted figures were created in *Adobe Freehand 9*.

The final Atlas (excluding the Digital Addenda) was delivered in *Microsoft Word* format. The final well and borehole summary logs (Appendix C) were provided in pdf and png formats.

PROJECT HISTORY & BACKGROUND

The first Irish offshore exploration well, 48/25-1, was drilled in the North Celtic Sea Basin in 1970. Since then, a total of 132 exploration and 28 appraisal wells have been drilled, resulting in four producing gas fields (Corrib, Seven Heads, Kinsale Head and Ballycotton) and 11 oil, gas and condensate discoveries (Hanrahan & Morgan, 2013; Morgan, 2017; Shannon, 2018). These, together with wells that encountered significant shows, are listed in **Table A.2**, with the reservoirs assigned to the new lithostratigraphic nomenclature and ages as interpreted in the current project.

Name	*Rig release date*	*Discovery well*	*Status*	*Basin*	*Reservoir (new lithostratigraphic nomenclature)*	*Reservoir Age*	*Fluid*
Kinsale Head	1971	48/25-2	Field	North Celtic Sea	Gault Fm (Agone Sandstone Mbr, Bream Sandstone Member)	Early Cretaceous	Gas
Hook Head	1971	50/11-1	Discovery	North Celtic Sea	Wealden Gp	Early Cretaceous	Oil & gas
Seven Heads	1974	48/24-1	Field	North Celtic Sea	Wealden Gp (Eel Fm)	Early Cretaceous (Late Aptian)	Gas
Seven Heads Oil	1974	48/24-1	Field	North Celtic Sea	Wealden Gp	Early Cretaceous	Oil & gas
Ardmore	1975	49/14-1	Discovery	North Celtic Sea	Wealden Gp	Early Cretaceous	Gas
Nemo	1974	49/14-1	Discovery	North Celtic Sea	Wealden Gp	Early Cretaceous	Oil
Ram Head	1974	49/13-1	Discovery	North Celtic Sea	Purbeck Gp (Pike Fm)	Early Cretaceous (Early Valanginian-Late Berriasian)	Gas
Burren	1978	35/8-1	Discovery	Porcupine	Bradán Fm (Boladh Sandstone Mbr)	Early Cretaceous (Late Aptian)	Oil
Connemara	1979	26/28-1	Discovery	Porcupine	Dursey Fm (Streedagh Sandstone Mbr) & Minard Fm (Renard, Dooneragh & Tonakeera Mbrs)	Late Jurassic (Tithonian, Oxfordian)	Oil & gas
63/10-1 Discovery	1981	63/10-1	Discovery	Fastnet	Glenbeg Fm (Gara Sandstone Mbr)	Early Jurassic (Late Sinemurian)	Oil & gas
Spanish Point	1981	35/8-2	Discovery	Porcupine	Dursey Fm (Leck Sandstone Mbr)	Late Jurassic (Tithonian)	Gas & condensate
Helvick	1983	49/9-2	Discovery	North Celtic Sea	Galley Fm, Dunbrattin Fm (Dunworly Sandstone Mbr), Peregrine Fm	Late Jurassic (Kimmeridgian, Oxfordian), Middle Jurassic (Bathonian)	Oil & gas
57/9-1 Discovery	1984	57/9-1	Discovery	North Celtic Sea	Wealden Gp (Eel Formation)	Early Cretaceous (Late Aptian)	Oil & gas
Galley Head	1985	48/18-1	Discovery	North Celtic Sea	Gault Fm (Agone Sandstone Mbr, Char Sandstone Mbr), Wealden Gp	Early Cretaceous (Late Albian)	Oil & gas
Dunmore	1986	50/6-1	Discovery	North Celtic Sea	Dunbrattin Fm (Dunworly Sandstone Mbr)	Late Jurassic (Oxfordian)	Oil & gas
49/13-2 Discovery	1986	49/13-2	Discovery	North Celtic Sea	Dunbrattin Fm (Dunworly Sandstone Mbr)	Late Jurassic (Oxfordian)	Oil (heavy)
Schull	1987	57/2-2	Discovery	North Celtic Sea	Gault Fm (Bream Sandstone Mbr)	Early Cretaceous (Late Albian)	Gas
Ballycotton	1989	48/20-2	Discovery	North Celtic Sea	Gault Fm (Agone Sandstone Mbr)	Early Cretaceous (Late Albian)	Gas
Barryroe	1990	48/24-3	Field	North Celtic Sea	Wealden Gp	Early Cretaceous	Oil & gas
Carrigaline	1990	48/24-4	Discovery	North Celtic Sea	Gault Fm (Bream Sandstone Mbr) & Wealden Gp	Early Cretaceous	Gas
Baltimore	1992	48/19-2	Discovery	North Celtic Sea	Gault Fm (Agone Sandstone Mbr, Bream Sandstone Mbr) & Wealden Gp	Early Cretaceous	Oil
Southwest Kinsale	1995	48/25-3	Discovery	North Celtic Sea	Gault Fm (Bream Sandstone Mbr)	Early Cretaceous (Late Albian)	Gas
Corrib	1996	18/20-1	Field	Slyne	Corrib Sandstone Fm	Early Triassic	Gas
Dooish	2002	12/2-1z	Discovery	Rockall	Cot Sandstone Fm, Foxglove Fm	?Early Triassic, Carboniferous (Pennsylvanian)	Gas condensate
Old Head of Kinsale	2006	49/23-1	Discovery	North Celtic Sea	Gault Fm (Bream Sandstone Mbr) & Wealden Gp	Early Cretaceous	Gas
Bandon	2009	27/4-1	Discovery	Slyne	Inagh Fm (Neaskin Mbr)	Early Jurassic (Late Sinemurian)	Oil & gas

Table A.2. ***Ireland fields, discoveries and wells with significant shows, listed by rig release date. New reservoir***

lithostratigraphic nomenclature shown.

In addition, a relevant discovery on the UK offshore areas was that of the Dragon gas and condensate discovery which was proven by the UK103/1-1 well, that was drilled by Marathon Oil in the North Celtic Sea Basin in 1994 (Providence Resources, 2016). The hydrocarbons in this discovery are reservoired in the Dunbrattin Formation (Dunworly Sandstone Member). The hydrocarbon bearing structure has been considered by some to extend in to Irish offshore waters.

Although much has been published on the region since the first wells were drilled offshore Ireland, in numerous papers and conference proceedings, no official standard stratigraphy for the whole offshore Ireland region has ever been defined. Following the entry of a significant number of new companies into the Ireland offshore area following the 2011 and 2015 licensing rounds, the need to establish a standard nomenclature became ever more necessary to provide a common geological nomenclature for the use of offshore companies, government departments, academia and contractors. Furthermore, with a strong research initiative focusing on the offshore area, for example via the Irish Centre for Research in Applied Geosciences (iCRAG), a standard stratigraphy is required to provide a stratigraphic framework for current and future research projects in the region. To create an appropriate framework, this project re-evaluated all existing stratigraphic data to provide a consistent interpretation across all wells and boreholes, supplemented by new data where necessary to address data gaps or to improve existing data.

There is also an interest in understanding how the Atlantic Margin of offshore Ireland compares to the conjugate margin of Eastern Canada. The palaeojuxtaposition of offshore Ireland with Eastern Canada is evident from plate reconstructions, and the extent to which the two areas compare in terms of basin evolution and stratigraphic development is important to understand.

The project has been carried out by a consortium of companies, led by Merlin Energy Resources Ltd (hereafter referred to as "Merlin"), also incorporating Palaeodate Ltd, Riley Geoscience Ltd, Network Stratigraphic Consulting Ltd (hereafter referred to as "Network") and Integrated Geochemical Interpretation Ltd (hereafter referred to as "IGI"). Geoscience advice was provided by G. Dunford Exploration Ltd.

The project team members and their roles within the project are set out below:-

Personnel	***Company***	***Role in project***
Dr Philip Copestake	Merlin	Project manager, Atlas & report editor. Biostratigraphic, lithostratigraphic and sequence stratigraphic interpretation (Palaeozoic-Cenozoic).
Dr Nigel Ainsworth	Palaeodate	Biostratigraphic co-ordinator, biostratigrapher; micropalaeontologist (Jurassic, Cretaceous); comparisons with Eastern Canada; lithostratigraphic interpretation (Palaeozoic-Lower Cretaceous).
Dr Haydon Bailey	Network	Biostratigrapher; micropalaeontologist (Upper Cretaceous – Cenozoic). Lithostratigraphic interpretation (Upper Cretaceous, Cenozoic).
Dr John Donato	Merlin	Geophysicist. Seismic interpretation, gravity interpretation. Focus on Fastnet, Celtic Sea, Central Irish Sea & Kish Bank basins.
Dr Paul Farrimond	IGI	Supervising Geochemist. Source rock data interpretation & integration with updated stratigraphy.
Dr Liam Gallagher	Network	Biostratigrapher; calcareous nannoplankton (Mesozoic-Cenozoic). Supervision of lithological data entry and digitisation of legacy biostratigraphic database; lithostratigraphic interpretation (Upper Cretaceous-Cenozoic).
Mr Mischa Gehlen	IGI	Lead Geochemist. Source rock data interpretation & integration with updated stratigraphy.
Dr Keith Gueinn	Riley Geoscience	Biostratigrapher; palynologist (Palaeozoic, Triassic, Cenozoic). Lithostratigraphic interpretation (Palaeozoic).
Dr Matt Hampton	Network	Biostratigrapher; calcareous nanoplankton (Mesozoic/Cenozoic). Lithostratigraphic interpretation (Upper Cretaceous, Cenozoic).
Mr Owain Lavis, Ms Georgina Lockham and Ms Elle Lashko	Merlin	Geoscience Support. Management of GIS database and mapping; palaeofacies mapping; structural elements definition; database management; DST data import; import of data from *Stratabugs* into *IC* and *Kingdom*. Well displays in IC. General geoscience support.
Dr Tony Loy	Merlin	Biostratigrapher, Geoscientist. Geoscience support, lithological interpretations, palynological interpretations and QC
Ms Eleanor Oldham	Merlin	Geophysicist. Seismic interpretation of the western Rockall, Conall and Rónán basins.
Dr Les Riley	Riley Geoscience	Biostratigrapher; palynologist (Jurassic, Cretaceous); comparisons with Eastern Canada.
Dr Tim Wright	Merlin	Geophysicist, Structural Geologist. Seismic interpretation, structural evaluation, mapping. Focus on Rockall, Slyne, Erris, Porcupine and Goban Spur basins.
Ms Sarah Dominey	Merlin	Support Geoscientist. GIS database development, lithological interpretation.
Mr Gerry Dunford	G. Dunford Exploration	Geoscience Advisor. Advice on seismic interpretation and structural geological interpretation.
Mr Gary Warmington	Merlin	Draftsman. Drafting selected Atlas figures.
Stratigraphic assistants	Network	Entry of biostratigraphic data (from legacy hard copy data) into *Stratabugs*, interpretation of lithology data and entry into IC database

Table A.3. ***Summary of technical project team, company affiliation, expertise & project roles***.

In addition, specialist evaluations were subcontracted, including study of igneous rocks selected for new radiometric dating (Dr Carl Stevenson, University of Birmingham), and study of charophytes (Dr Carles Closas, University of Barcelona; Closas, 2018).

The project was funded by the Irish Shelf Petroleum Studies Group comprising the following companies; AzEire Petroleum Ltd, BP Exploration Operating Co Ltd, Cairn Energy Plc, Chevron North Sea Limited, ENI Ireland BV, Europa Oil & Gas Plc, ExxonMobil E&P Ireland (Offshore) Ltd, Equinor Energy Ireland Ltd, Nexen Petroleum UK Ltd, Petroleum Affairs Division (PAD) of the Department of Communications, Climate Action and Environment, Providence Resources plc, Repsol Exploración SA, San Leon Energy Plc, Serica Energy Plc, Shell E&P Ireland Ltd, Sosina Exploration Ltd, Total E&P Ireland B.V., Tullow Oil Plc and Woodside Energy (Ireland) Pty Ltd.

The technical mentoring of the project on behalf of the PAD was performed by Dr Kara English and Michael Hanrahan, who provided overall guidance during the project, technical input and advice, and editorial input. The overall ISPSG Project Manager within PIP was Nick O'Neill, with Martin Davies (supported by Charlie Carlisle and, latterly, Lloyd Vaz) acting as overall ISPSG Projects Coordinator for PIP. Clare Morgan, of the PAD, attended meetings and assisted with the project guidance.

The project was overseen by the Steering Committee who collectively provided guidance, advice and steer of the project. This committee comprised the following representatives; Paul Gannon (Cairn Energy), Annemarie Smyth (Providence Resources), David Hulks, Adam Sultan, Chris Leppard, Karla Kane, Simon Haynes and Catherine Allsop (Equinor) and Richard England (Woodside), in addition to PAD and PIP staff mentioned above, together with Professor Pat Shannon

(University College, Dublin). We acknowledge the support of all the aforementioned persons in facilitating the successful completion of the project and for provision of technical feedback and discussion on many aspects of the study.

The generation of the new lithostratigraphic scheme for offshore Ireland, that was a key aspect of this project, was supervised by the Stratigraphic Committee, chaired by Professor Pat Shannon, and which comprised; Dr Tony Doré, Professor Peter Haughton, Dr David Naylor, Professor George Sevastopulo, Dr Shane Tyrell, Clare Morgan, Dr Kara English, Michael Hanrahan, Dr Philip Copestake and Dr Nigel Ainsworth.

During the course of the project, several technical discussions were held between the project team and members of the iCRAG hydrocarbons research spoke, headed by Professor Peter Haughton. We are grateful to the iCRAG team for sharing results of their research. Additional acknowledgements are listed on page ii.

A range of interim results have been issued during the time of the project. Following the completion of the first interpretation phase of the project, involving the initial stratigraphic interpretation of the legacy biostratigraphic database, a "Gap Analysis" was carried out. This involved the compilation of a spreadsheet showing the stratigraphic ages of the intervals drilled in each studied well and borehole across the study area. The spreadsheet also showed the type of biostratigraphic analysis that had been carried out on each interval. This spreadsheet was issued to PIP and ISPSG in April 2018 and a copy is provided as part of the Digital Addenda for this project. It should be noted that the ages interpreted in this spreadsheet are now in many instances out of date.

Following the completion of the final stratigraphic interpretations, including the definition of new lithostratigraphic units for all studied intervals, a listing of stratigraphic tops was provided. This was made freely available by the PAD on a memory stick at the Atlantic Ireland 2018 conference (late October 2018) and has since been available at PAD stands at various conferences. An updated version of this listing is provided as part of the Digital Addenda to this Atlas as a final project deliverable.

Interim results and presentations on the project have been made at four Atlantic Ireland conferences in 2016, 2017, 2018 and 2019. Six presentations of the project have been made at the 2016-2019 Atlantic Ireland conferences by members of the project team, including Copestake *et al*. (2017, project overview and interim results), Copestake *et al*. (2018; overview of new lithostratigraphic and sequence stratigraphic framework), Gehlen *et al*. (2019; source rocks in context of new lithostratigraphic framework) and Wright & Copestake (2019; significance of new framework for exploration within offshore Ireland and internationally). In addition, an overview of the philosophy behind the lithostratigraphic nomenclature that has been applied in the study was presented by Shannon *et al*. (2019).

In addition, posters, summarising interim project results, were presented at the first three of these conferences. The poster at the 2018 conference incorporated a large scale stratigraphic chart which set out all the new lithostratigraphic units, shown against a standard chronostratigraphy and tied to a set of regional seismic horizons. This chart was also made publicly available at that conference by the PAD, and since at other conferences and exhibitions. An updated version of this chart is included in this Atlas.

Earlier versions of most of the Atlas chapters and appendices have been made available to the ISPSG members during the later stages of the project, as they have become approved for issue by the PAD and PIP, during 2019 and 2020.

Progress reports outlining the progress of the project have been issued monthly to PIP throughout the duration of the project.

STRUCTURAL FRAMEWORK

The locations and limits of the major structural elements for offshore Ireland initially utilised in this study was based on the public domain shape file available from the PAD website. During the course of the project it became necessary to update and edit this on the basis of published information from the area together with interpretations being carried out as part of the current project. The structural elements have been revised to ensure the most up-to-date interpretations of basin boundaries are used for plotting palaeofacies and lithostratigraphic unit distribution maps and all other base maps **(see Figure A.1).** The offshore geology symbology, constrained by basins, reflects that of generalised basin geological fill/strata, all of which are detailed in associated legends.

For the **Rockall Basin**, **Porcupine Basin** and **Goban Spur Basin** and surrounding area, definitions and maps of the major structural elements are available in two PAD Special Publications (Naylor *et al*., 1999; Rockall Basin; Naylor *et al*., 2002; Porcupine-Goban region), and further discussed by Naylor & Shannon (2005) in the context of the basin evolution of these regions. For these areas, these publications have generally been followed, with minor modifications, in the current study. Note that the term "North Porcupine Basin" has been used (Naylor & Shannon, 1982; Naylor *et al*., 2002), as a "structurally complex small basin extending northwards from the Porcupine Basin" (Naylor *et al*., 2002). In the current study it has been considered in many of the chapters essentially as a part of the Porcupine Basin.

Other published sources have been used for the structural configuration and outlines of other basins that have been described, for instance Dancer *et al*. (1999) for the **Slyne Basin** and Dunford *et al*. (2001) for the **Kish Bank Basin**. A further source of structural information was the 'Structural Framework of the North Sea and Atlantic Margin' map published by the Petroleum Exploration Society of Great Britain (2017).

The **Fastnet Basin** was described by Robinson *et al*. (1981), however, the basin limits, particularly the boundary between this basin and the North Celtic Sea Basin, were not clearly defined by these authors. For this study we have recognised a major deep seated structural high, in the northern part of Quadrant 56 that is associated with some significant stratigraphic changes. While the definition of this area ideally requires more work, particularly utilising higher quality seismic data than was available to this project, there is a clear structural feature in this area that can be used to delimit the boundary between the Fastnet Basin and the North Celtic Sea Basin. The southern edge of this structural high marks the northern limit of major Jurassic (mainly Lower-Middle Jurassic) deposition, the southern limit of significant inversion (bringing Upper Cretaceous Chalk to sea bed), the northern limit of Cenozoic (Eocene-Miocene) deposition, and also affected depositional changes within the Lower Cretaceous. In addition, this area appears to have also marked, and most likely influenced, the passage from marginal to non marine Pliocene to marine Pliocene. These facts suggest that this was a structural feature that influenced sedimentation over a long period of geological time. In light of these observations, further study of the changes taking place in this region, and the underlying controls, would certainly be warranted.

The **Clare Basin** was proposed by Croker (1995) as a Carboniferous basin that was considered to be an extension of the onshore west of Ireland West Clare Namurian Basin into the offshore area, based on an interpretation of limited seismic data together with Bouguer gravity and combined aeromagnetic data. This was supported by a correlation of the Carboniferous stratigraphy in the 36/16-1A offshore well with the Doonbeg 1 borehole, drilled onshore western County Clare. The outline of the "Clare Basin" so proposed was subsequently followed by Naylor *et al*. (2002) and Johnston *et al*. (2001). The basin was referred to as the Shannon Basin by Cope *et al*. (1992), which is the name used by Sevastopulo (2009) for the onshore basin in County Clare. Well 36/16-1A sits on the western extremity of the "Clare Basin" as conceived by Croker (1995), updip and east of the Porcupine Basin bounding fault, and penetrated the thickest known Mississippian (Blackthorn Group) section in offshore Ireland, underlain by the Muirín Group. In this report, we have considered to what extent the Carboniferous succession in the 36/16-1A well (Blackthorn and Muirín groups) may be extrapolated eastwards of this well into the offshore part of the "Clare Basin".

Croker (1995) reported that the quality of the limited number of seismic lines over the "Clare Basin" area is very poor with very strong water bottom multiples as well as steeply dipping (surface generated) noise trains and the series of gravity and magnetic highs along the eastern margin of the Porcupine Basin were interpreted to be igneous intrusive centres. The quality of the more recently acquired PAD regional Survey (2013/2014) in the area east of the Porcupine Basin is also poor with a large amount of multiple reflections throughout. Therefore, extending the Carboniferous section eastwards from well 36/16-1A towards the Irish mainland is challenging. For the maps in the current report, the easterly limits of those Carboniferous lithostratigraphic units that are present in the 36/16-1A well are taken only a short distance east of the well due to the great uncertainty on their easterly extent. For these reasons, the use of the "Clare Basin" as defined by Croker (1995) is not followed herein and, instead, reference is made to the western edge of the Irish Mainland Platform upon which the 36/16-1A well sits. The location of this well is clearly separate from the main Porcupine Basin, the bounding fault of which lies to the west of this well.

In addition, published gravity data has been used to aid the definition of selected basins and their basin bounding faults for basins to the south and east of Ireland, including the North/South Celtic Sea Basins, Kish Bank Basin and their surrounding areas. Such basin bounding faults integrated with published literature and Merlin interpretations have aided the definitions of these basin boundaries.

Outlines for the Kish Bank Basin, **Little Sole Basin** and **Cockburn Basin**, the latter two located to the south of the Fastnet Basin, have been cross-checked with available seismic data and published interpretations (for example, Smith, 1995 for the Cockburn Basin). The structural nomenclature utilised comprises that previously used in the industry and in published sources.

The area to the immediate south of the **Shackleton Basin** lacks available data, therefore has been labelled on maps in this atlas as 'limited data – possible basins'.

It should be noted that the revision of the structural elements carried out for this project was undertaken only as a brief update of the existing structural elements base map and future work with updated seismic will be required.

LITHOSTRATIGRAPHIC NOMENCLATURE

A primary objective of the current project was to define and publish a standard lithostratigraphy for offshore Ireland, which will significantly help communication and understanding between oil companies, contractors, researchers and government departments. It will provide a common terminology of rock units that all parties can use in future work in the area, whether as a basis for naming reservoirs, source rocks and seal units in commercial exploration and development evaluations, or as a framework for geoscience research on subsurface successions.

No overall standard lithostratigraphic scheme has been previously published for the whole of the Ireland offshore area. A small number of schemes have been previously defined for particular areas of offshore Ireland, either in publications (for example, Murphy & Ainsworth, 1991 for the Triassic, Lower Jurassic and Middle Jurassic of the Fastnet Basin; Caston, 1995 for the Upper Jurassic of the Helvick Field, North Celtic Sea Basin or industry reports (some of which are in the public domain; for example, Ternan, 2006). Many of these pre-existing names are informal and not appropriate for formal usage; those that have been adopted have been renamed in the new lithostratigraphic scheme. The new lithostratigraphy has been defined for the Palaeozoic, Mesozoic, Cenozoic and Quaternary (excluding the Holocene).

Comparisons have been made between the offshore Ireland lithostratigraphic succession and onshore Ireland lithostratigraphic subdivisions. However, due to the relatively limited range of stratigraphic units developed onshore Ireland, with most of the rocks exposed being of Palaeozoic age, there are relatively few cases in which it is possible to apply onshore Irish names to the offshore stratigraphic units.

Neighbouring countries have published standard lithostratigraphic schemes for offshore exploration regions, that the hydrocarbon industry and researchers in those areas are encouraged to adopt. These are of obvious relevance to offshore Ireland as UK offshore waters border offshore Ireland over a large part of the median lines between the two jurisdictions. In the UK this includes the various British Geological Survey/UK Offshore Operators Association (UKOOA) publications for the offshore area, including the North Sea (for example, Richards *et al*., 1993 for the Jurassic of the Central and Northern North Sea), East Irish Sea (Jackson & Johnson, 1996; Jackson *et al*., 1997) and UK Rockall areas (Stoker *et al*., 2007), as well as numerous publications documenting the lithostratigraphy of onshore Britain some of which can be applied to offshore Ireland. For onshore British lithostratigraphic nomenclature, reference has been made to the British Geological Survey (BGS) Lexicon of Named Rock Units (http://www.bgs.ac.uk/lexicon/lexicon_intro.html) which provides definitions for all lithostratigraphic terms found on current BGS geological maps. In addition, a number of useful BGS publications summarise the current UK onshore lithostratigraphic nomenclature, for instance, for the Carboniferous (Waters *et al*., 2007), Triassic (Howard, 2008; Ambrose *et al*., 2014), Lower Jurassic (Cox *et al*., 1999) and Lower Cretaceous (Hopson *et al*., 2008).

For the Norwegian North Sea area, a number of publications define the standard lithostratigraphic terminology (for example, Deegan & Scull, 1977, updated by Vollset & Doré, 1984 for the Jurassic and Cretaceous; Isaksen & Tonstad, 1989 for the Cenozoic, later further updated by Brunstad *et al*., 2013, updated for the Cretaceous by Gradstein & Waters, 2016). Other standard lithostratigraphic nomenclature schemes have been established for other sectors of the North Sea, including Denmark (Jensen *et al*., 1986; Michelsen *et al*., 2003) and the Netherlands (van Adrichem Boogaert & Kouwe, 1993, Munsterman *et al*., 2012). In offshore East Canada, no formal lithostratigraphic scheme exists for the Flemish Pass Basin, though an informal scheme has been presented (Ainsworth *et al*., 2015). For the Labrador Shelf, lithostratigraphic schemes have been documented by Balkwill & McMillan (1990), and for the Jeanne d'Arc Basin by McAlpine (1990), Ainsworth *et al*. (2005) and Deptuck *et al*. (2003).

For comparisons with the neighbouring countries mentioned above, the knowledge and experience of the consortium members has also been applied.

For the procedures that underpin the establishment of the new lithostratigraphic scheme documented in this atlas, the stratigraphic code of Murphy & Salvador (1999) has been followed in most respects. Regarding lithostratigraphic subdivisions, these are categorised into the following hierarchy of units;- group, formation, member, unit. The appropriate hierarchical position for a given rock unit is determined by the lateral relationships between rock units revealed by well to well and well to seismic correlations. For instance, if a sandstone, limestone or extrusive volcanic unit can be shown to be a lateral equivalent to, and is encased by argillaceous sediments, then the unit may be recognised as a member of an argillaceous dominated formation. In most cases in this project, formations are aggregated into groups and each member is assigned to a single formation.

Following Murphy & Salvador (1999) in the newly defined lithostratigraphic scheme, we have not extended formations across known major unconformities. While uncertainty exists in deciding which unconformities are regional, major or local; lithostratigraphic boundaries are placed at major and regional unconformities wherever possible. In cases where similar or identical lithologies are developed both below and above a major unconformity, other criteria were used to define the lithostratigraphic unit boundary such as wireline log characteristics and biostratigraphic (chronostratigraphic, i.e. age) character. In these instances, the interpreted presence of a seismic horizon/sequence boundary/unconformity at a given well location was used to help recognise and define a lithostratigraphic boundary at an unconformity.

The generation of the new lithostratigraphic scheme for offshore Ireland was supervised by the Stratigraphic Committee, chaired by Professor Pat Shannon. The role of this committee was to review, guide and ratify the stratigraphic subdivision proposals made by the Merlin consortium stratigraphic team, and to name individual rock unit names for the new scheme. The overall objective was to ensure the stratigraphic framework was robust and workable by industry, government and academia, and retained an 'Irish flavour' where possible. The concepts and rationale behind the newly defined scheme were presented by Shannon *et al.* (2019) at the Atlantic Ireland 2019 Conference.

A total of 309 rock units are recognised in the study. Of these, 259 rock units are formally named and described and a further 50 units are informally named (for example, "26/28 Basal Conglomerate"). Of the total, 196 new names are introduced in the documented lithostratigraphic scheme and 63 previously existing names are utilised from the UK (offshore and onshore). Maps have been produced showing the interpreted distributions of all formally defined lithostratigraphic units, based on a considered interpretation of the likely extent of each unit, utilising all well and borehole penetrations, integrated with seismic interpretation. The final set of rock unit names was agreed between members of the Stratigraphic Committee and the PAD. None of the members of the Merlin consortium were involved in the choice of new lithostratigraphic names.

Existing names were used where it could be demonstrated that stratigraphy correlates clearly with named successions in nearby jurisdictions, or with the Irish onshore. In the case of offshore Ireland, the UK offshore area is contiguous to the north (Rockall Basin), southeast and east (Western Approaches Basin, South Celtic Sea Basin, Cardigan Bay Basin) and north east (East Irish Sea Basin). Consideration has also been given to the lithostratigraphic nomenclature utilised in onshore Ireland (Republic of Ireland and Northern Ireland) and onshore UK (England, Wales and Scotland). Detailed literature reviews of areas adjacent to offshore Ireland were conducted (for example, British Geological Survey schemes, such as those of Stoker *et al*., 2007, 2011 and Jackson & Johnson, 1997). The overall patterns of stratigraphic development were evaluated including the assessment of major basin changes and unconformity development, in adjacent areas, and correlated these to offshore Ireland. It was concluded that in many instances it was appropriate to continue the usage of an existing offshore UK name into offshore Ireland, while there remained many instances where a new name was required.

UK names have been applied in the following stratigraphic intervals, either wholly or in part: -

- *Quaternary to Cenozoic*: UK offshore Rockall Basin and UK Cardigan Bay-Celtic Sea nomenclature.
- *Upper Cretaceous*: UK offshore and onshore nomenclature at group level.

- *Lower Cretaceous*: Some UK offshore and onshore nomenclature for marine intervals west of Ireland and non marine intervals east of Ireland.
- *Lower Jurassic*: Existing south of England, Bristol Channel nomenclature applied, in part, to Fastnet and Celtic Sea basins. For west of Ireland basins, some nomenclature from west of Scotland basins has been applied.
- *Triassic*: Existing south of England/Bristol Channel nomenclature for Celtic Sea (part); existing East Irish Sea nomenclature for Central Irish Sea and Kish Bank basins.
- *Permian*: UK nomenclature applied to most offshore occurrences.
- *Carboniferous*: UK onshore nomenclature at group level, for south and east of Ireland basins. Southern onshore Ireland (South Munster Basin) nomenclature applied in Fastnet-North Celtic Sea Basin.

In the proposed lithostratigraphic scheme, rock units are named when they can be represented in most cases by a minimum of two wells. Where a rock unit has only been penetrated in one well or borehole, it was generally referred to informally (for example, the "26/28-1 Sandstone"). In some cases units penetrated by single wells have been named where the unit in question is considered to be of significant interest.

Regarding the naming of igneous rocks, Murphy & Salvador (1999) state that; "Stratified volcanic rocks and bodies of metamorphic rocks that can be recognized as of sedimentary and/or extrusive volcanic origin can be treated as sedimentary lithostratigraphic units." In this report, therefore, extrusive igneous rocks are described as members, where they can be seen to have been extruded into marine settings and are therefore interbedded within sedimentary formations. Where an interfingering relationship of an extrusive igneous rock with sediments is not apparent, this rock unit is recognised at formational level, for example the Eocene aged Druid Formation. Intrusive igneous bodies, in contrast, have not been named in the new scheme.

The following naming themes have been used for the naming of new rock units for specific stratigraphic intervals in the Ireland offshore area (Shannon *et al*., 2019):-

- Neogene: Irish artefacts and jewellery
- Paleogene: Irish bays
- Upper Cretaceous: Native fish in Irish waters
- Lower Cretaceous: Native fish in Irish waters – fresh water fish for Celtic Sea, salt water fish for west of Ireland
- Upper Jurassic: Irish peninsulas, headlands and points (west and south coast as appropriate to basins)
- Middle Jurassic: Irish birds.
- Lower Jurassic: Irish lakes.
- Triassic: Irish archaeological features, boats and musical instruments.
- Pennsylvanian: Native Irish plants
- Mississippian: Sea shells
- Devonian: Irish colours.
- Igneous rocks: Celtic folklore

PROJECT INFORMATION

GEOLOGICAL TIMESCALE

The geochronological time scale used in the project is that of Ogg *et al*. (2016), which represents an update to the earlier schemes of Gradstein *et al*. (2004, 2012). The chronostratigraphical subdivisions set out in these publications (into Eras, Periods, Series/Epochs, Stages and Substages) have for the most part been followed.

The definition of the Cretaceous/Jurassic boundary is based on current recommendations from the International Commission on Stratigraphy, Berriasian working group (Wimbledon, 2017). Precise definition of the base of the Cretaceous (Berriasian stage), with the selection of a global stratotype and point (GSSP) has yet to be made and therefore a pragmatic placement of this boundary has had to be made in the current project.

There is a particular question with regard to the definition of the Jurassic/Triassic boundary in offshore Ireland, as also in the UK onshore and offshore area. This boundary is discussed in Chapter D.5.

SOFTWARE UTILISED

The *IHSMarkit Kingdom*™ Suite (herein referred to as Kingdom) was used to house the complete seismic database and to carry out all seismic interpretation.

The *Esri® ArcGIS*™ (herein referred to as ArcGIS) project was established incorporating shapefiles available on the PAD website such as well locations, 2D and 3D offshore seismic coverage, fields and discoveries, tectonic/geological and structural elements (revised in this study). New interpretations were input into the project including palaeofacies and lithostratigraphic unit distribution maps. The database is in *Microsoft Access* (2016) allowing map displays of the numerical data.

The *LR IC*™ software (herein referred to as IC) has been used to collate all well data and produce the final report displays. Data includes, where applicable, well engineering information, MWD/wireline logs, seismic horizons, biostratigraphic markers, lithostratigraphic information, geochemical data, core data. All well log displays in this atlas have been generated from IC.

The *Stratadata StrataBugs*™ software has been utilised to hold all detailed stratigraphic data, including legacy biostratigraphic data (i.e. taxa occurrences and numerical counts by sample) and data from new sample analyses carried out for this study.

The *IGI p:IGI-3* software, a specialized software designed to hold and interpret geochemical data, has been used to compile and quality control a fully integrated geochemical database of all available geochemical data, as part of a previous PIP project IS 16/01. In the current project, *p:IGI-3* built-in tools were used to apply the updated stratigraphy names and ages to all geochemical samples in the database, carry out the source rock interpretation work, and produce the final graphs and outputs for this atlas.

CO-ORDINATE REFERENCE SYSTEM

The coordinate reference system (CRS) for the whole project is ED50 UTM Zone 29N as requested by the PAD, the details of which are given below.

CRS ED 1950 UTM Zone 29N	
EPSG WKID	23029
Projection	Transverse Mercator
False Easting	50000.0
False Northing	0
Central Meridian	-9.0
Scale factor	0.9996
Latitude of origin	0
Linear Unit	metre

Table A.4. ***Details of the co-ordinate reference system used in the project.***

DATABASE & METHODOLOGY

The project database comprises seismic and well databases, previous PIP-sponsored project reports, shallow borehole reports, theses and data from the public domain.

WELL & BOREHOLES DATABASE

The complete database of subsurface penetrations within the IS16/04 project area comprises 264 wells and boreholes; this includes 219 oil and gas wells, 31 DSDP/ODP/IODP boreholes and 14 shallow/mining boreholes from offshore Ireland (**Figure A.2**). 198 of these released wells and boreholes contain legacy or newly generated biostratigraphy data and comprise the interpreted database for this project (**Figure A.3**). A listing of available legacy stratigraphic reports that were reviewed for this study is provided as a spreadsheet in the Digital Addenda accompanying this Atlas (IS16_04_Ire_LegacyBioRpts_listing.xlsm).

In addition, a small number of UK wells that are close to the median line with Ireland, have been tied to the evaluations, and are 93/2-1 (South Celtic Sea Basin), 103/2-1 (St George's Channel Basin), 103/1-1 (North Celtic Sea Basin), 106/24-1 (Cardigan Bay Basin) and 132/15-1 (Rockall Basin). 103/2-1 has been chosen as the type well for one of the new Ireland lithostratigraphic units (the Lower Jurassic Gill Formation).

OIL AND GAS WELLS

A total of 217 released oil and gas wells had been drilled offshore Ireland at the time of project initiation (2016). In this total, re-entries and side-tracks are categorised as individual wells.

One unreleased well, 44/23-1, was provided to the project by ENI; data provided included wireline log data, the final well report and biostratigraphic report. ENI also allowed access to the existing biostratigraphical slides created by RPS; several of these slides were relogged and new microfossil taxa identified in this project. This well was released in mid-2018. At the time of report preparation (late 2018), two wells remain unreleased, 49/11-3 and 53/6-1, and these are not included in the project for this reason.

All released oil and gas well data held by the PAD was provided at the beginning of the project, from exploration, appraisal and development wells. Supplied well data comprises full data suites, which includes wireline log data in LAS format, composite logs and field prints of MWD/wireline logs and a range of scanned well reports. A range of individual well reports was made available, including routine biostratigraphic reports (with or without distribution charts), geochemistry reports and sedimentology reports. In addition, a number of multi well studies, some proprietary and others speculative, were made available. The PAD provided Drill Stem Test data from 52 wells that has been imported into the IC database and is plotted on the well summary logs (Appendix C). Sidewall core sample points were provided by PAD (from 123 wells) and are shown on the summary logs. Cored intervals (from 144 wells and boreholes) were collated by the consortium team and have been entered into the database, and are shown on the summary logs.

SHALLOW BOREHOLES & SEA BED SAMPLES

Data from 14 shallow boreholes were incorporated in to the study to assist the regional interpretation of the stratigraphy in under explored areas, for example at sites in the Macdara Basin and North and South Bróna basins. These shallow boreholes are very valuable data points in being located well away from commercial wells. They provide good sources of biostratigraphic data and, in being cored, provide important information on the geological successions and lithological developments at those locations. Of the 14 shallow/mining boreholes, 10 contain biostratigraphy data and are analysed within the project.

Five shallow boreholes, 11/20-sb01, 16/28-sb01, 83/20-sb01, 83/24-sb01, 83/24-sb02, were drilled as part of a PIP Rockall Study, all on the Eastern Flank of the Rockall Basin (Stoker, 1999; Jacovides, 1999; Harrington *et al*., 2000), further data from which was published by Haughton *et al*. (2005). Three shallow boreholes, 19/13-sb02 (BH1A), 27/24/sb01 (BH2), 27/24-sb02 (BH2A), were drilled by Statoil in the Slyne Basin (Fugro, 1994) and two were drilled in the Kish Bank Basin by VP Power Ltd (McArdle & Keary, 1986). One of the sea bed sampling sites (referred to here as "Dobson-2568", from data in Dobson & Whittington, 1979), provides an important sea bed penetration of Lower Jurassic sediments in the Kish Bank Basin.

Data from one UK offshore British Geological Survey borehole 89/10 was accessed via the BGS Geoindex Offshore online database (http://mapapps2.bgs.ac.uk/geoindex_offshore/home.html).

Some of the shallow boreholes have penetrated significant igneous bodies, two of which were sampled for radiometric dating as part of this study (see **Appendix D** for further information).

DSDP/ODP/IODP BOREHOLES

31 boreholes have been drilled within and near the project area as part of the Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP). Drill sites are located in the Rockall Basin, the eastern margin of the Porcupine Basin and the Goban Spur area (see **Figure A.2** for borehole locations).

The lithostratigraphic, biostratigraphic and wireline log data from the 31 DSDP/IODP/ODP boreholes were included in the project based on reports from the shipboard scientific parties. All data were accessed from the public domain, primarily the ODP website.

The DSDP holes are significant in that they provide stratigraphic information on many geologically young intervals that are otherwise typically not sampled by conventionally drilled wells. For this reason, some of the DSDP holes are reference sections for Neogene lithostratigraphic units.

BIOSTRATIGRAPHIC DATABASE & INTERPRETATION

Biostratigraphic data have been used extensively in this study primarily to provide a biozonal and interpreted chronostratigraphic framework for all the subsurface evaluations. This framework has been utilised in the following ways:-

- to calibrate and support seismic correlations, and related well-based sequence stratigraphic interpretations.
- as a basis for the stratigraphic well to well correlations that have demonstrated those lateral facies and geological relationships that are the basis of the understanding of the regional development of the offshore area.
- to provide the basis for the recognition of unconformities (by the absence of missing biozones) which have aided the definition of stratigraphic sequences.
- to age date these breaks, which will aid in the recognition of the timing of major tectonic changes across the region.

The micropalaeontological and palynological content of key stratigraphic intervals have been used to aid the interpretations of palaeoenvironments, allowing the recognition of a range of depositional settings of key sedimentary successions. Shifts, whether gradual or sharp, in biofacies are indicative of palaeoenvironmental changes and can be used to recognise relative deepening and shallowing trends that aid the definition of stratigraphic sequences.

The biostratigraphic database for this study comprises legacy data from various sources, which has been supplemented in the project by new data generated from either new sample study or re-examination of existing palaeontological slides. The project incorporated all released biostratigraphic reports that are held by the PAD, PhD theses, published literature and published reports on the DSDP/IODP/ODP sites. From many of the wells, several separate reports contained biostratigraphic data, bringing the total number of individual wellbore data sets to 591. These are listed in **Appendix B**.

A limited amount of new data was generated by RPS as part of the BeicipFranlab (2017) project, on the 26/22-1A, 35/30-1 and 43/13-1 wells and raw data (DEX files) were provided to the current project and incorporated into the interpretations.

Legacy biostratigraphic data was incorporated into a *Stratabugs* database newly created for this project. The locations of wells and boreholes included in the project are shown in **Figure A**.2 and, of these, those with existing legacy biostratigraphic data are shown in **Figure A**.3. Within the legacy database, the extent of the coverage with respect to the age interval (Period) covered by the data has been assessed. This is shown in the listing of available legacy stratigraphic reports in the Digital Addenda accompanying this Atlas (IS16_04_Ire_LegacyBioRpts_listing.xlsm). The Period covered by the legacy biostratigraphic data available from each well is shown also in map form in **Appendix B**.

Biostratigraphic reinterpretations were carried out on the legacy biostratigraphic database and well intervals where improved stratigraphic understanding was required were identified. To address poor data quality or data gaps, a substantial programme of new sampling and biostratigraphic analysis was carried out on over 3000 samples from 106 wells (see **Figure A**.4 and **Appendix B**) which were incorporated into the biostratigraphic database. (Note that this approach to the new sample analysis replaced the original request, in the Invitation to Tender document, to carry out "*top to bottom analysis of 10 key wells*". This decision was based on a discussion between the project team, PAD and the project Steering Committee).

The new biostratigraphic analysis and legacy data included data from all micropalaeontological disciplines, i.e. microfauna (foraminifera, ostracoda, radiolaria), palynoflora (spores, pollen, dinocysts) and calcareous nannoplankton. These interpretations were carried out by a number of biostratigraphers within the project team who have particular expertise in one or more of these microfossil groups (see **Table A**.3 for details). Details of wells and intervals newly sampled for biostratigraphic analysis in this project, and the rationale for the sample selection, are discussed in **Appendix B**.

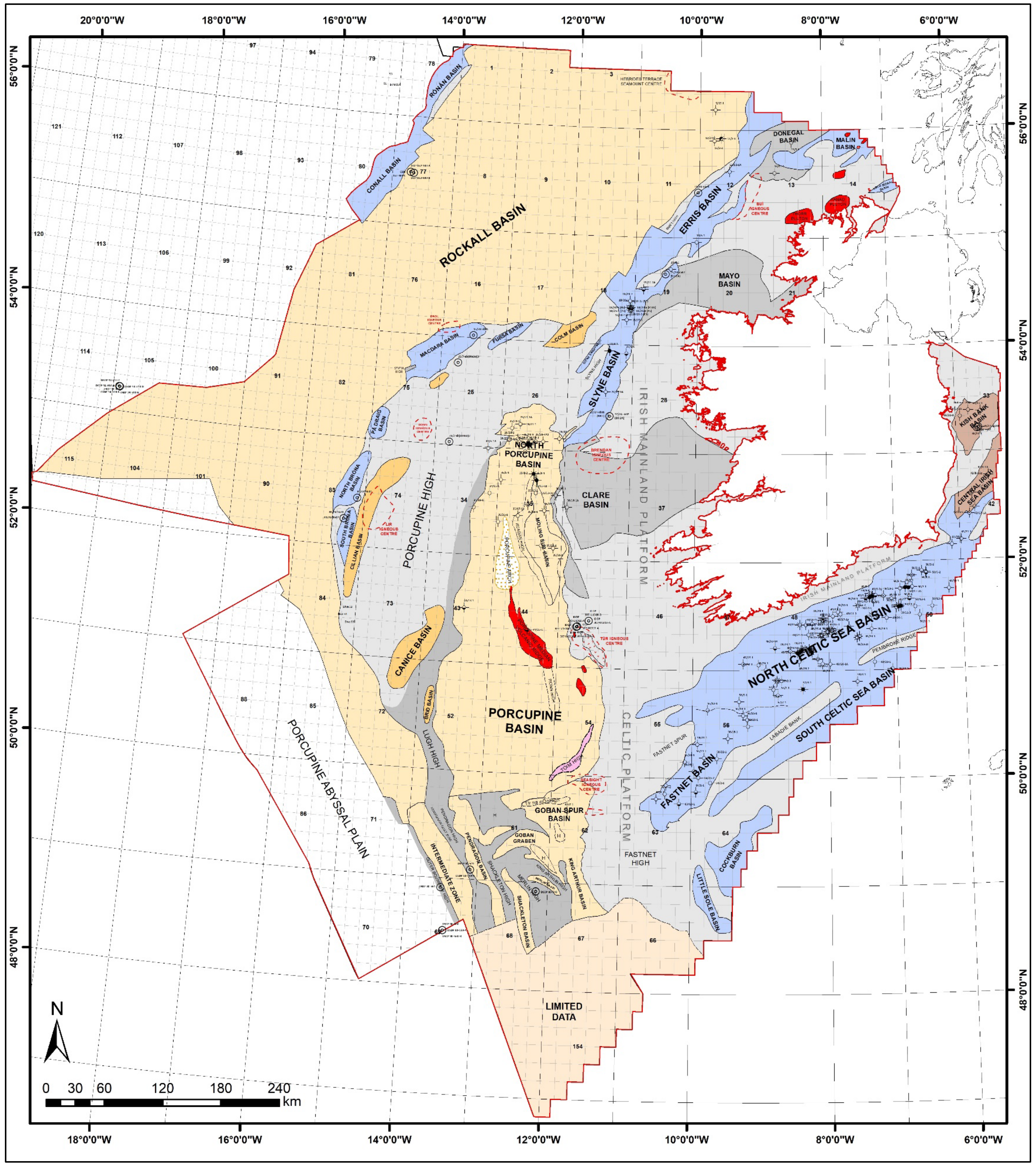


Figure A.2. *Map showing location of all wells and boreholes in the project.*

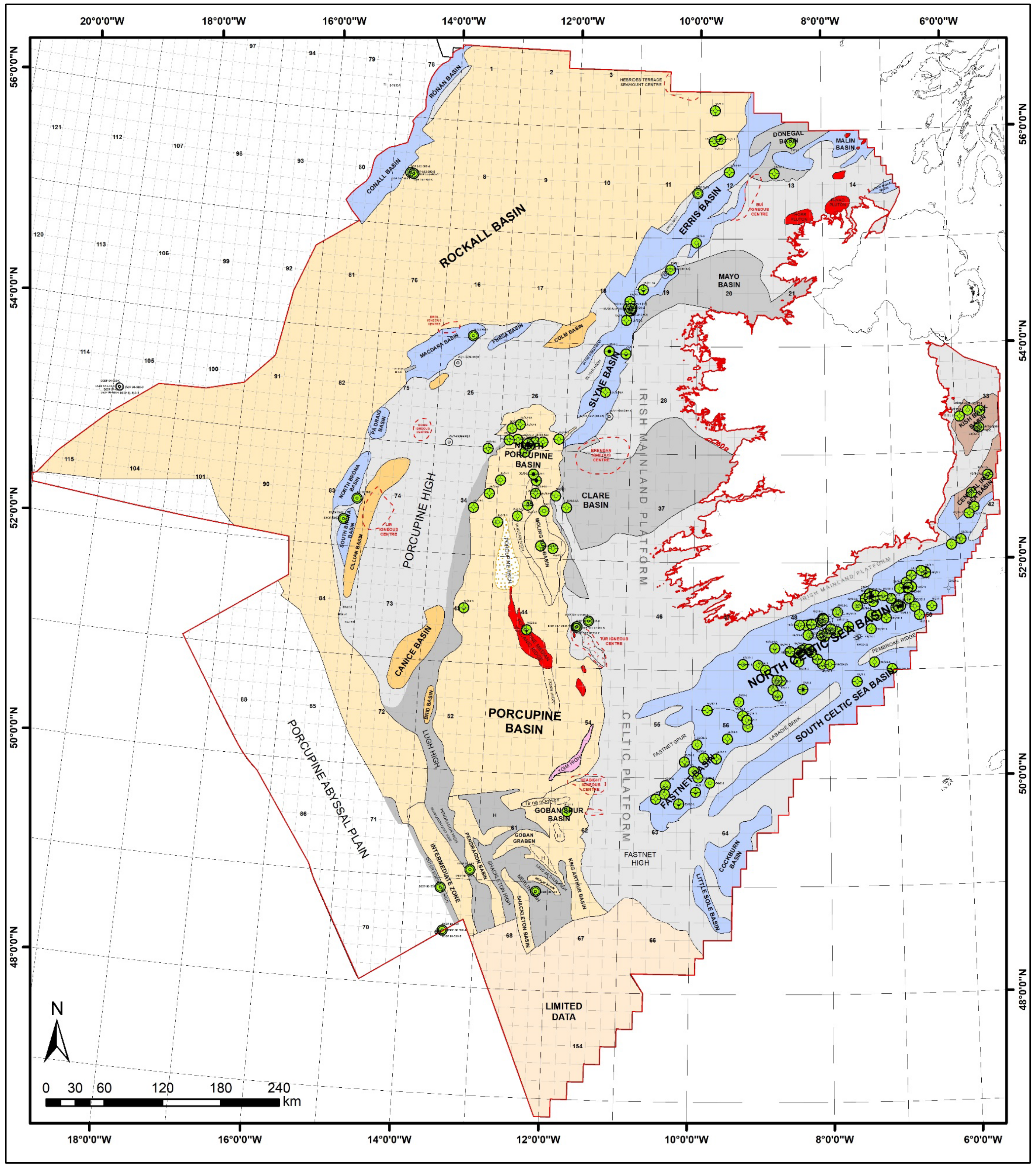


Figure A.3. *Map showing location of wells with legacy biostratigraphic data (green circles).*

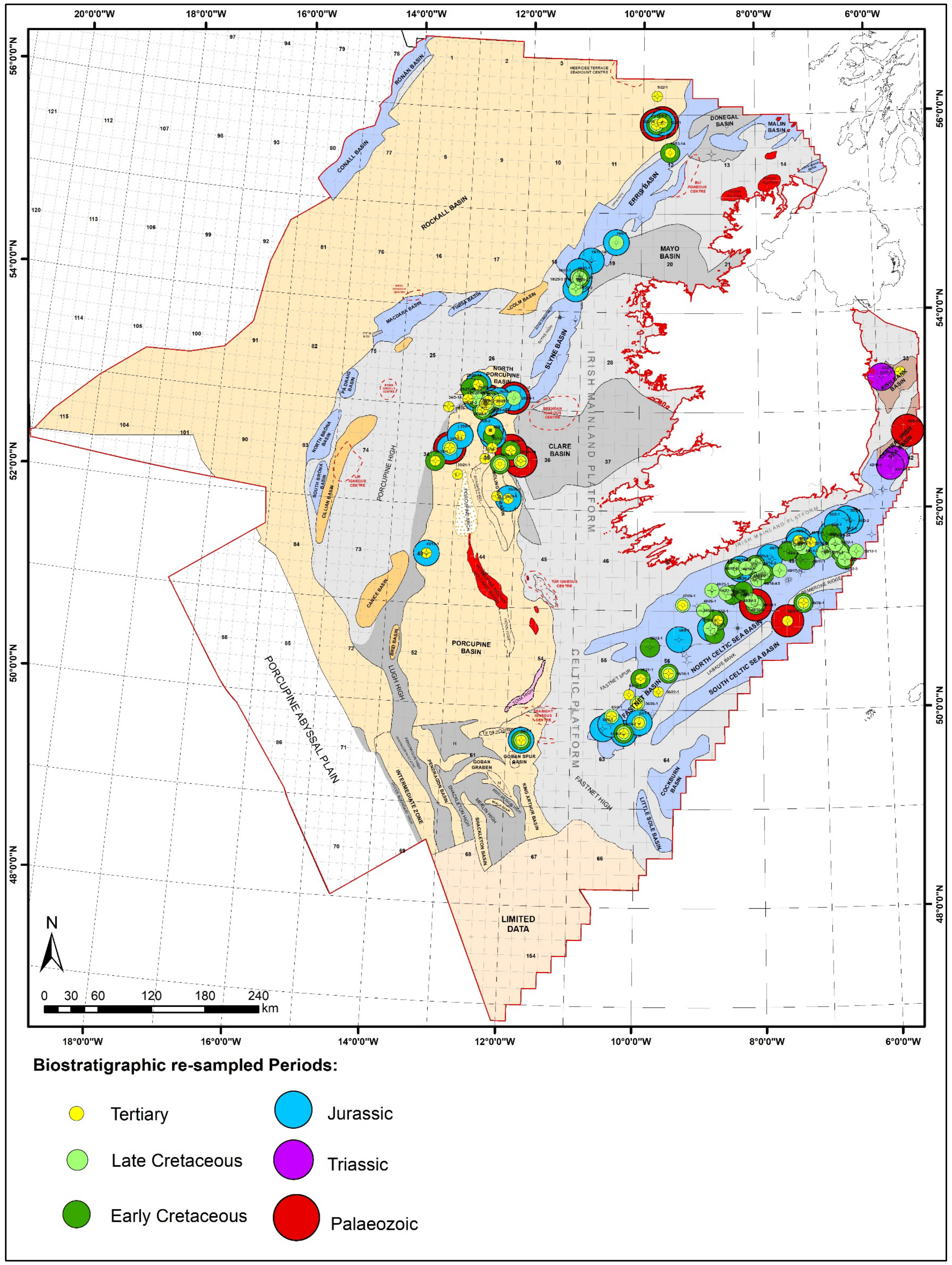


Figure A.4. ***Map showing location of wells sampled for new biostratigraphic analysis. Bubble colour indicates age of intervals sampled in this study.***

IGNEOUS ROCKS AND RADIOMETRIC DATING DATABASE

Volcanic rocks occur throughout the offshore Ireland area, at many stratigraphic levels, some of which have been described in several publications and well reports (for example, Caston *et al*., 1981; Tate & Dobson, 1988; Naylor & Shannon, 2005). These include rocks of both intrusive (plutonic rocks, sills and dykes) and extrusive (lava flows, including pillow lavas and tuffs) origin. These recorded occurrences have been reviewed as part of this study, and a listing is shown in **Table A.4**. The locations of igneous occurrences are shown in **Figure A.5**.

Those extrusive igneous rock units that can be proven to be extensive (i.e. penetrated in more than one well or borehole) or where single well penetrations, are considered to be significant, are named and described in the detailed lithostratigraphic discussions below. Extrusive igneous rocks are described as members where they can be seen to have been extruded into marine settings and are therefore interbedded within sedimentary formations. Intrusive igneous bodies, in contrast, have not been named in the new scheme.

Well/Borehole Name	***Igneous type***	***Rock Type***	***Extrusive Geological Age/Stratigraphical Occurrence/Host Formation (intrusive)***	***Radiometric Date and source***	***Lithostratigraphic Name***
11/20-sb01	Extrusive	Lapilli Tuffs & Pyroclastic Sediments	Eocene, Lutetian		?Druid Formation
12/2-1Z	Extrusive	Basalt	?Early Triassic	250 Ma Early Triassic, Induan (Shell, 2014) Older c.187 Ma Early Jurassic, Early Pliensbachian or older (This study)	Merrow Member (Cot Formation)
13/3-1	Intrusive	Olivine-pyroxene gabbro	Intruded into Carboniferous, Pennsylvanian, Blackthorn Group		
16/28-sb01	Extrusive	Basalt	?Late Jurassic, ?Tithonian	150.5 ± 1.2 Ma Late Jurassic, Tithonian (This study). (A second sample produced no reliable date)	Selkie Member (Dursey Formation)
18/20-1	Extrusive	Basalt	Eocene, Lutetian	40 – 43 Ma Eocene, Bartonian – Lutetian (Corcoran & Mecklenburgh, 2005)	Druid Formation
18/20-2	Extrusive	Interbedded basalts &	Eocene, Lutetian		Druid Formation

		pyroclastic sediments (tuff)			
18/20-3 (P3)	Extrusive	Basalt overlain by pyroclastic sediment (tuff)	Eocene, Lutetian		Druid Formation
18/20-4 (P4)	Extrusive	Interbedded basalts & pyroclastic sediments (tuffs)	Eocene, Lutetian		Druid Formation
	Intrusive	Mafic igneous sills	Intruded into Lower Toarcian Whitby Mudstone Formation		
18/20-7	Extrusive	Basalt	Eocene, Lutetian		Druid Formation
18/25-1 (P2)	Extrusive	Basalt	Eocene, Lutetian		Druid Formation
	Intrusive	Mafic igneous sills	Intruded into Lower Bajocian-Aalenian Kestrel and Harrier formations		
18/25-2	Intrusive	Mafic igneous sills	Intruded into Lower Toarcian Whitby Mudstone Formation		
18/25-3 (P5)	Extrusive	Basalt	Eocene, Lutetian		Druid Formation
19/11-1A	Extrusive	Basalts & Pyroclastic sediments (tuff)	Eocene, Lutetian		Druid Formation
	Intrusive	Dolerites	Intruded into Kimmeridgian Dawros Formation; Oxfordian Sybil Formation; Lower Toarcian Whitby Mudstone Formation		
19/13-sb02 (BH1A)	Extrusive	Basalt	Eocene, Lutetian	54.3 ±1.2 Ma Eocene, Ypresian (Corcoran & Mecklenburgh, 2005) No reliable age from new radiometric analysis (This study)	Druid Formation
19/8-1	Extrusive	Basalts & Pyroclastic	Eocene, Lutetian		Druid Formation

		sediments (tuff)			
26/29-1	Extrusive	Basalt	Paleocene, Danian		Changeling Member (Mangach Formation)
26/30-1	Basement	Granite	Pre-Carboniferous	No reliable age from new radiometric analysis (This study)	Unnamed
27/13-1A	Intrusive	Basic	Intruded into Lower Jurassic Pabay Shale Formation		
27/5-1	Intrusive	Dolerite	Intruded into Carboniferous, Pennsylvanian, Blackthorn Group		
35/13-1	Intrusive	Olivine-Pyroxene Gabbro	Intruded into Lower to Middle Albian Bradán Formation	25.8 ± 2.6 Ma Late Oligocene, Chattian (Tate and Dobson, 1988 and Irish Shell Petroleum Development Company Teoranta, 1978). No reliable age from new radiometric analysis (This study)	
35/15-1	Extrusive	Picritic Basalt	Paleocene, Danian	58.2 ± 1.8 Ma Paleocene, Thanetian (Robertson, 1981)	Changeling Member (Mangach Formation)
	Intrusive	Basic dolerite/gabbro	Intruded into Albian Bradán Formation and Paleocene, Danian, Mangach Formation. Sills of Cretaceous (post Albian, pre-Late Maastrichtian) age (cf. Tate & Dobson, 1988)		
	Intrusive	Basalt	Intruded into Carboniferous Mussel-Ruacan Formation		
	Extrusive	Pyroclastic sediments (tuff)	?Mississippian		Single occurrence (35/15-1 Tuff), within Ruacan Formation
35/19-1	Extrusive		Paleocene, Danian		Changeling Member

					(Mangach Formation)
35/2-1	Extrusive	Altered Volcanic Deposit (Basalt)	Paleocene, Danian		Changeling Member (Mangach Formation)
	Intrusive	Weathered dolerite	Intruded into Upper Jurassic, Oxfordian Minard Fm		
35/8-1	Extrusive	Pyroclastic sediments (pumice)	Early Cretaceous, Middle Albian	No reliable age from new radiometric analysis (This study)	Sheerie Member (Bradán Formation)
	Intrusive	Dolerite	Intruded into Albian Bradán Formation	18.0 ± 6.0 Ma Early Miocene, Burdigalian (Robertson, 1978) 60.6 ± 4.4 Ma Middle Paleocene, Selandian (Tate and Dobson, 1988)	
42/8-1Az	Intrusive	Igneous	Intruded into Carboniferous Pennine Coal Measures / Warwickshire Group		
43/13-1	Extrusive	Basalt	Eocene, Ypresian	No reliable age from new radiometric analysis (This study, 2019)	Péist Member (Gweedore Formation)
5/22-1	Extrusive	Pyroclastic sediments (tuff)	Eocene, Ypresian		Single occurrence (5/22-1 tuff). Unnamed separately, within Killeany Formation
55/30-1	Extrusive	Pyroclastic sediments (tuff)	Late Devonian		Single occurrence (55/30-1 tuff). Unnamed separately, within Darrig Formation
56/18-1	Intrusive	Alkali-olivine Dolerite	Intruded into Lower Jurassic Glenbeg Formation	113.0 ± 5.0 Ma Cretaceous, Albian-Aptian 125.0 ± 4.0 Ma Cretaceous, Aptian	

				127.0 ± 4.0 Ma Cretaceous, Barremian (Robertson, 1984)	
56/26-1	Intrusive	Gabbro	Intruded into Lower Jurassic Glenbeg Formation	170.0 ± 4.0 Ma Middle Jurassic, Bajocian - Aalenian (Caston *et al.*, 1981) No reliable age from new radiometric analysis (This study)	
56/26-2	Intrusive	Olivine Dolerite	Intruded into Lower Jurassic Glenbeg Formation		
56/9-1	Intrusive	Dolerite	Intruded into Upper Cretaceous Chalk Group, Leith Formation	46.6 ± 3.7 Ma Middle Eocene, Lutetian (Robertson, 1979)	
62/7-1	Extrusive	Porphyritic Basalt with trachytic texture	Late Jurassic	133.5 Ma Early Cretaceous, Hauterivian (Tate and Dobson, 1988) 93.8 Ma Late Cretaceous, Turonian (Mark et al, 2009) Middle Jurassic, Bathonian radiometric date (Colin *et al.*, 1992) 154.4 Ma Late Jurassic, Early Kimmeridgian (This study)	Púca Member (?Galley Formation)
64/1-1	Intrusive	Olivine Dolerite	Intruded into Middle Jurassic Sparrowhawk Formation		
64/2-1	Intrusive	Dolerite	Intruded into Hettangian, Leane Formation		
DSDP 80-549	Extrusive	Pyroclastic sediments (tuff)	Late Eocene Clew Bay Formation and Paleocene Cashla Formation		

DSDP 80-550-B	Extrusive	Basalt (with interbedded volcanic breccia)	Late Albian		Oakshee Member (Rødby Formation)
DSDP 80-551	Extrusive	Basalt (pillow lava)	Late Albian		Oakshee Member (Rødby Formation)

Table A.5. ***Wells and boreholes penetrating igneous rocks offshore Ireland.***

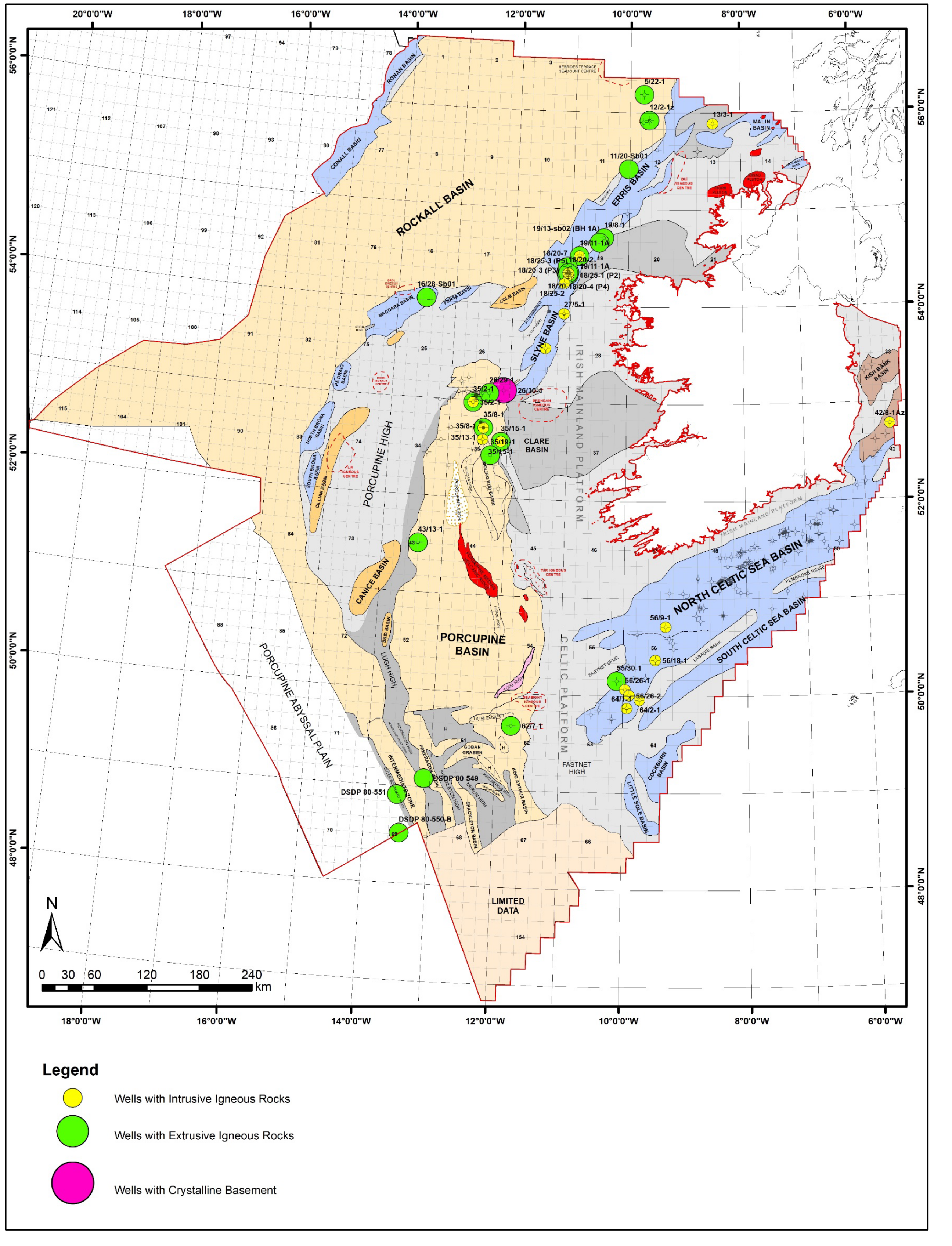


Figure A.5. ***Map showing wells and boreholes that penetrated igneous rocks, offshore Ireland.***

To assist the evaluation of the age of these igneous rock units, 10 new radiometric dating (Ar-Ar) analyses were carried out within this project. The wells and igneous rocks selected for this new analysis were chosen in cases where no previous dating had been carried out and it was considered important to date the rock in question, or to obtain a check on a previously carried out radiometric dating (whether K-Ar or Ar-Ar). The focus was on obtaining samples from cores. The wells and boreholes chosen for radiometric dating are shown in **Figure A.6.**

The wells and boreholes were sampled at the PAD Dublin sample store. Most of the samples are cores, however, cuttings samples were taken for two of the wells. All samples taken were described and studied in thin section by Dr Carl Stevenson (University of Birmingham, UK), as described by Stevenson (2017). This study made recommendations for new radiometric dating, types of minerals to be analysed and potential risks that could affect the generation of an accurate radiometric dating, such as degree of mineral alteration. Ar-Ar dating was contracted out to ActLabs, Ontario, Canada. Results from the analyses were incorporated into the individual rock unit sections. The ActLabs radiometric dating results are provided in **Appendix D**. The Stevenson (2017) and ActLabs (2017) reports are provided as part of the Digital Addenda of this project. **Appendix D** discusses the new radiometric dating carried out and summarises the results of each dating analysis. The results of these analyses are also discussed, in those instances where the analysed rock units are described, in **Section D; Stratigraphic Intervals**.

PUBLIC DOMAIN DATA

In excess of 800 scientific publications have been provided for use within the project, supplemented by additional articles, publications and research theses accessed by the project team. In addition, several released PIP reports, available via download from the PIP website, have been utilised.

GIS DATABASES

Several ArcGIS projects produced by previous PIP sponsored projects were provided to Merlin at the beginning of the project. These databases have aided the development of the project GIS database and key data from these have been imported into the project database.

Various shapefiles are available from the PAD website. These include the well locations (accompanied by well headers), 2D and 3D offshore seismic coverage, fields and discoveries, tectonic/geological and structural elements, and the current licence authorisations.

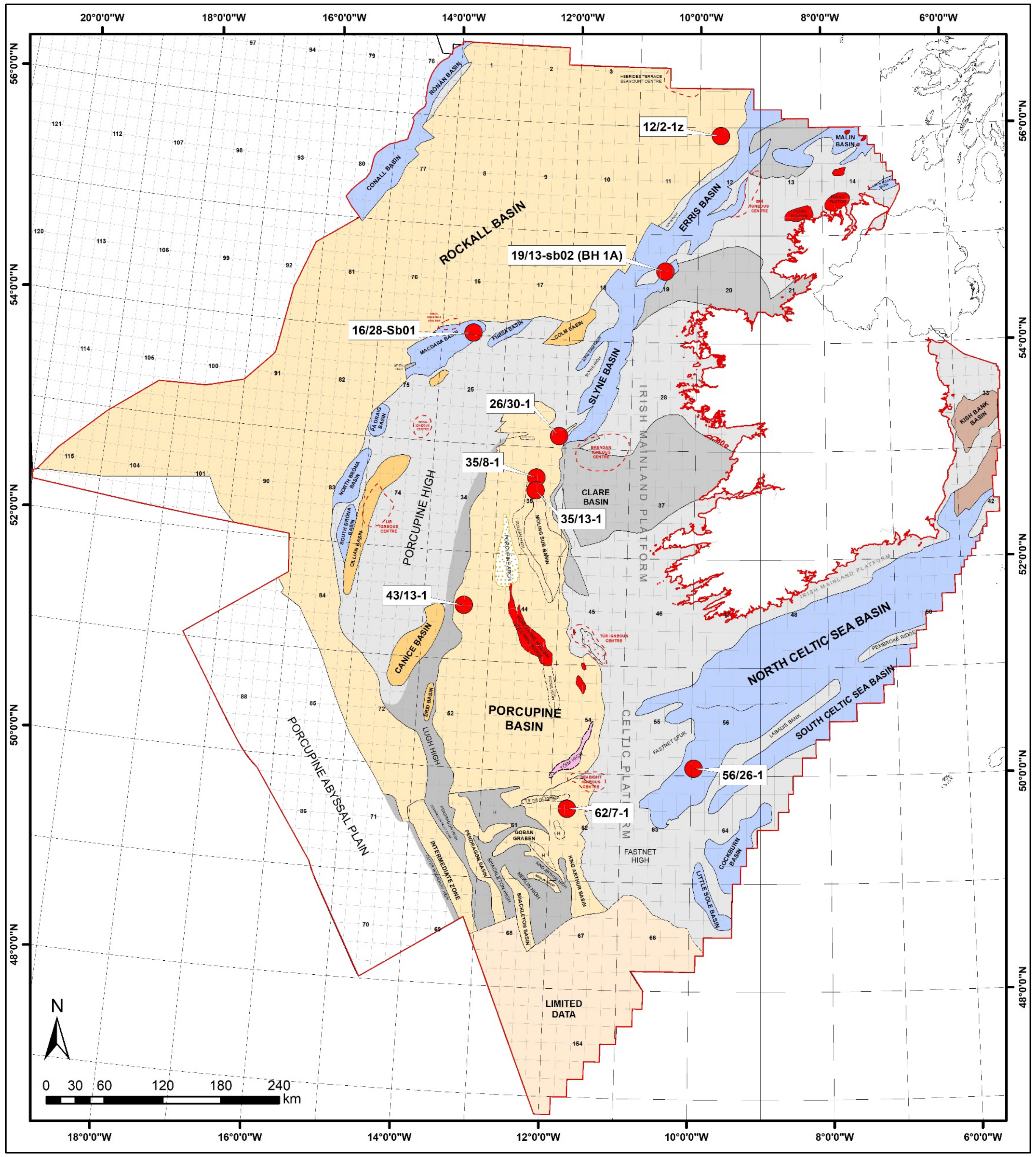


Figure A.6. ***Wells and boreholes selected for new radiometric dating (red circles).***

STANDARD LEGEND

The legend used throughout this atlas is a modified version of the Shell (2016) standard legend for the lithologies and depositional environments. This has been applied to all well displays, maps (particularly palaeofacies maps) and stratigraphic summary diagrams (see **Figure A.7**). The legend used for the structural elements maps is also shown in this figure, as are the symbols used for well statuses as used on well headers and on maps.

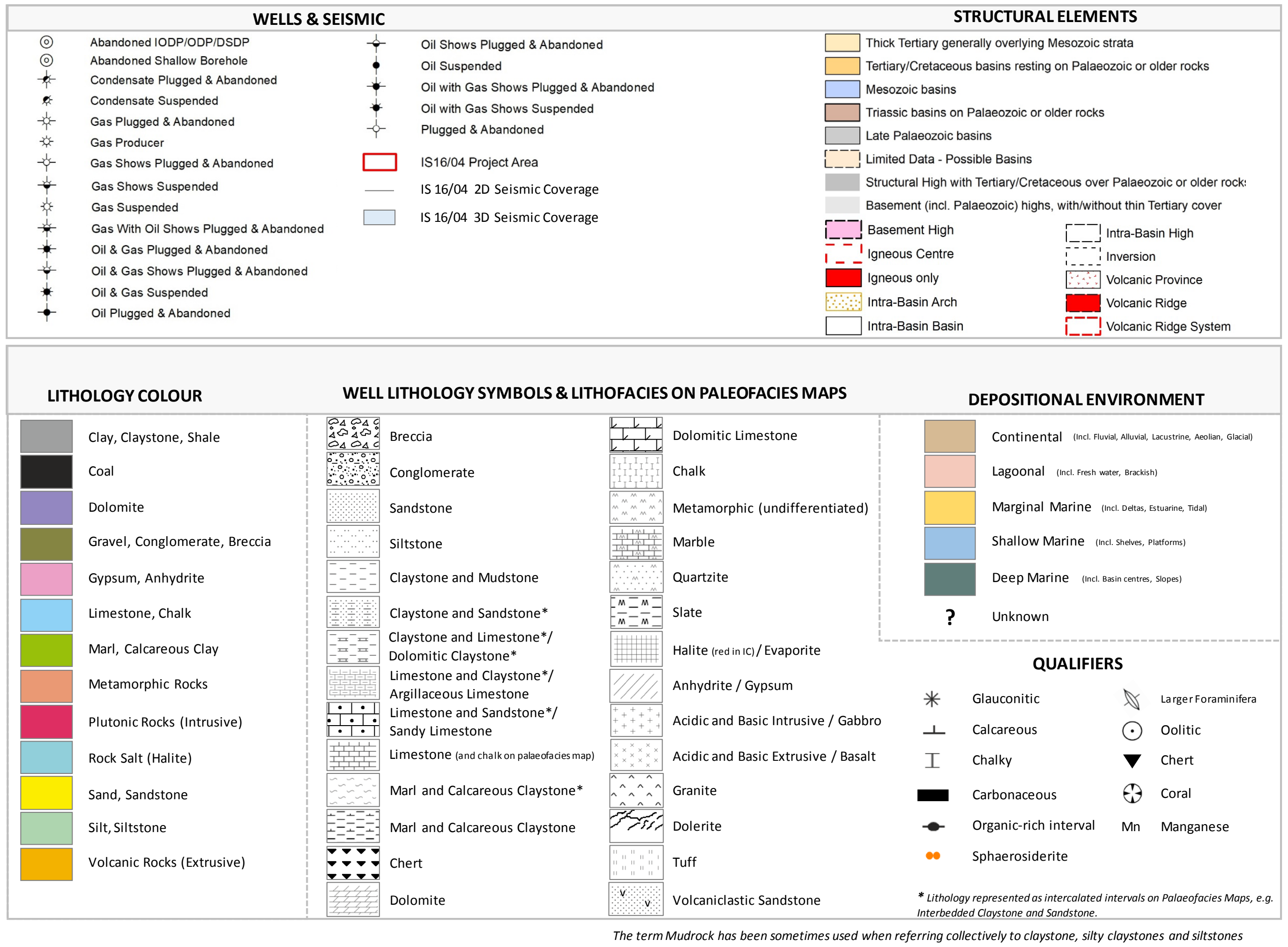


Figure A.7. ***Legend utilised in well displays, maps and stratigraphic summary diagrams throughout the Atlas.***

SEISMIC DATABASE & INTERPRETATION

SEISMIC DATABASE

The seismic database included 19 released 3D surveys of 1985-2011 vintage and 4,351 released 2D lines of 1970-2014 vintage provided by the PAD. The distribution of the data is shown in **Figure A.8**, and in **Figure A.9**, the data is colour coded by acquisition vintage. A total of 182,136 line km of 2D and 13,127 km2 of 3D data were available to the project. This, however, includes the Dragon (176.14 km^2) and the Druid (144.30 km^2) 3D surveys which straddle the UK-Ireland offshore boundary. Two further released UK seismic lines have also been referenced in the current study.

Seismic acquisition offshore Ireland has been historically driven by the availability of exploration acreage, dependent on the timing and location of the various licence rounds held. Seismic acquisition largely focused in the south, south-east and east of Ireland, with additional surveys in the west between 1980 and 1985. Focus shifted to the west of Ireland and a substantial amount of data were acquired mainly between 1994 and 1999. The PAD 2D long offset regional lines further supplemented the 2D database in 2014. Of the 3D data provided, the first survey was acquired during 1985 over the Helvick Field. The subsequent 3D surveys provided to the project are located mainly north-west of Ireland and were acquired between 1994 and 2011. A significant number of 3D surveys have been acquired since 2011. These were located mainly within the Southern Porcupine area and were not released at the time of the writing therefore were not available to this project.

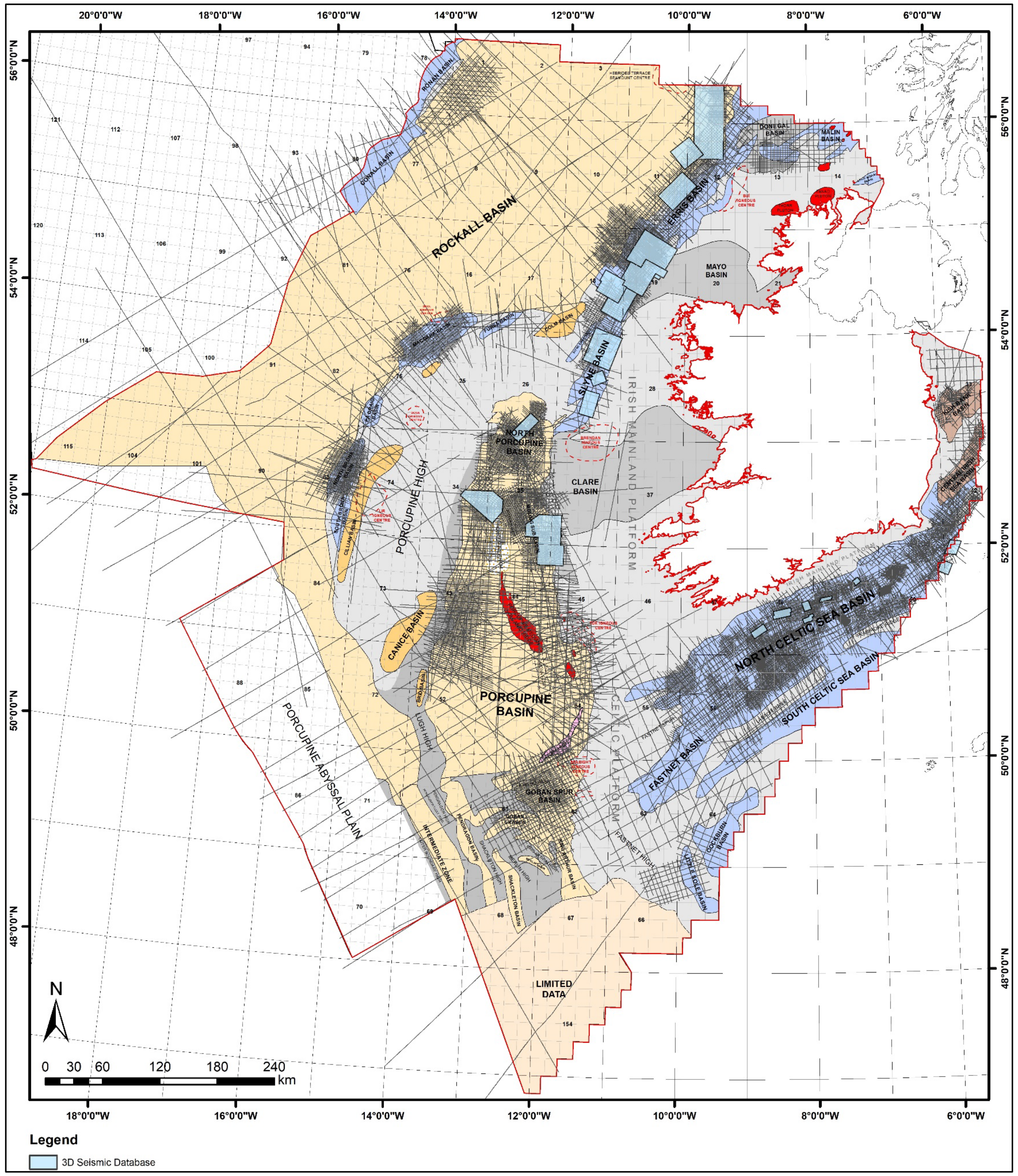


Figure A.8. ***Released seismic database provided for the project, 2D and 3D.***

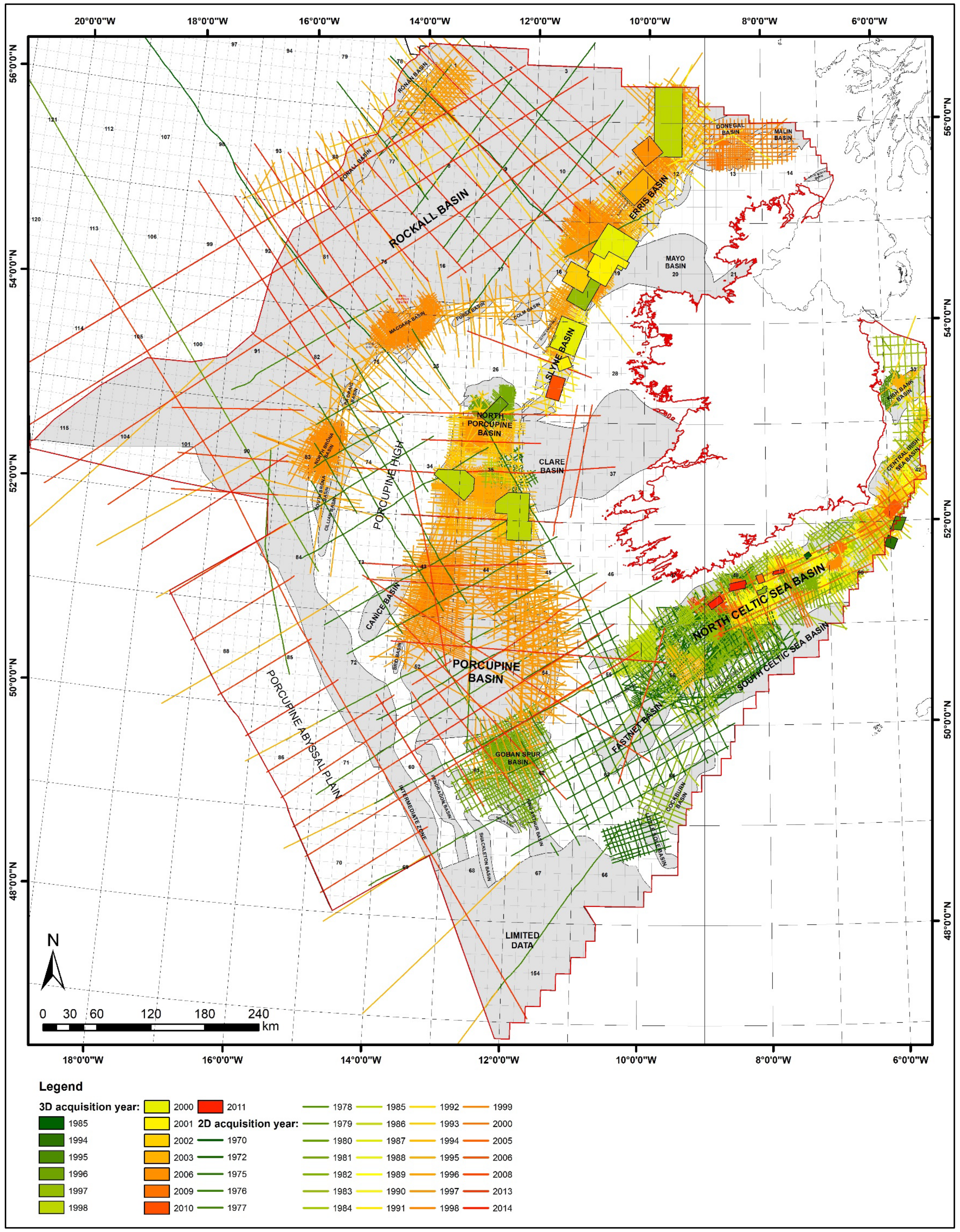


Figure A.9. ***Released seismic data coverage, 2D and 3D across the project area. Surveys coloured by year of acquisition.***

SEISMIC INTERPRETATION

The priority objectives for incorporation of the seismic data were to tie the newly defined stratigraphic well tops and ages to the seismic lines and to correlate stratigraphic boundaries with both local and basin wide seismic reflection horizons. Consequently, a limited selection of the seismic lines was interpreted for this purpose as a detailed interpretation of the large seismic dataset provided lies outside the defined scope of this project. Selected illustrated seismic lines that are figured in the atlas are shown in **Figure A.11**.

Within this Atlas, wherever possible, a standard European polarity display convention has been adopted (**Figure A.10**). Unless stated otherwise, an increase in acoustic impedance encountered at a soft to hard transition (for example, Seabed or Top Chalk) results in a negative amplitude value (rarefaction) which is coloured red in the seismic displays. A soft (compressive) event is coloured black with a positive amplitude value (for example, Base Chalk). As a result of the extensive nature of the database and wide variety of vintage processing sequences applied, some lines can be characterised as zero phase, minimum phase or indeterminate phase with phase rotations within individual sections. In such cases, a "best match at seabed" approach has been adopted. Amplitudes values are "relative" with lines being subject to unknown processing sequences which may, in some circumstances, have included amplitude gain corrections (AGC). This convention has been applied to seismic lines displayed from west of Ireland basins where the seismic data quality is generally good.

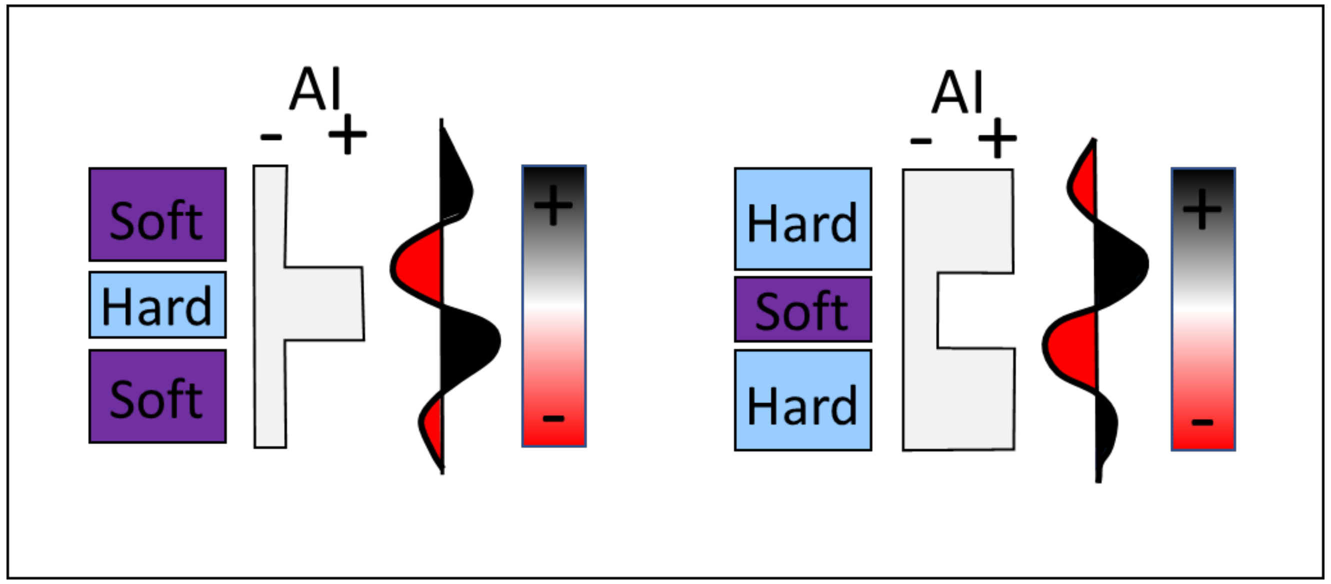


Figure A.10. ***Definition of seismic polarity convention adopted in the Atlas.***

Within the project, consistent sets of seismic horizons were interpreted within regions of tectonic compartmentalisation and include; the Rockall Basin, the Porcupine – Slyne – Erris basins, Fastnet – North and South Celtic Sea basins, Central Irish Sea Basin and Kish Basin. On completion of the stratigraphic interpretations for the project, it was possible to more clearly date the seismic horizons, and to determine their regional and local extent. All surveys that have been interpreted, in part, are listed in the spreadsheet **IS16_04_Ire_Interpreted_Seismic_Listing.xlsx** provided in the Digital Addenda to this Atlas. It should be noted that no survey has been interpreted in its entirety and few of the lines listed have been interpreted across their whole length at all geological horizons.

Basins across which seismic data have been interpreted include; the Conall Basin, Rónán Basin, Rockall Basin, the Porcupine – Slyne – Erris basins, Fastnet – North and South Celtic Sea basins, Central Irish Sea Basin and Kish Bank Basin. Some of the horizons are quite localised (or have only been interpreted in a small area due to data constraints), others are restricted to particular basins, while a significant number are regional in extent, extending across two or more basins. Some of the regional horizons can be interpreted across much of the offshore area.

A total of 60 significant seismic horizons were interpreted in the offshore areas of Ireland in this project (**Table A.5**). The seismic horizons are defined and named in this project by a combination of age and lithostratigraphic unit association. The lithostratigraphic unit names applied are those arising from the new lithostratigraphic nomenclature defined in this project. It becomes difficult to apply this scheme where a regional seismic horizon is present across more than one basin, over which lithostratigraphic names change; examples are the Oligocene and Eocene horizons, which are present in deep marine and shallow marine (carbonate and clastic dominated) settings, that carry different lithostratigraphic unit nomenclature from area to area. In these cases, these horizons are named on the basis of their chronostratigraphic age (for example, Oligocene).

All the horizons are considered to be significant and represent key levels and surfaces across which significant geological changes have taken place. The vast majority are seismic sequence boundaries, in that in some areas, in some cases most areas, the horizon in question is an unconformity. In all cases these horizons are dated where they tie to the most complete stratigraphic successions, or to more than one section that together show the age and identity of the youngest sediment below the surface and the oldest sediment above it. This is sometimes in basin centre locations, but not always, as in some of the Cenozoic horizons where display major downcutting erosional form in basinal settings, for example the Oligocene horizon and the several intra Eocene horizons, the Priabonian (C30), Lutetian (Intra Trawbreaga) and Ypresian (Base Blacksod Sandstone).

Some of the recognised horizons have been documented by previous workers in the area, or in nearby areas. Good examples of this are the C10, C20, Near Base Neogene and C30 unconformities of Stoker *et al.* (2001, 2005), which have been the focus of significant ongoing research in the west of Ireland area and UK offshore area (Rockall Basin). These surfaces have also been used by Stoker *et al.* (2007, 2011) to define major lithostratigraphic boundaries, an approach which has been followed in this project. These familiar names are therefore retained in Irish framework, preceded by the currently interpreted age of that horizon (for example, Priabonian (C30)) based on the extensive well/borehole-seismic ties carried out in this project.

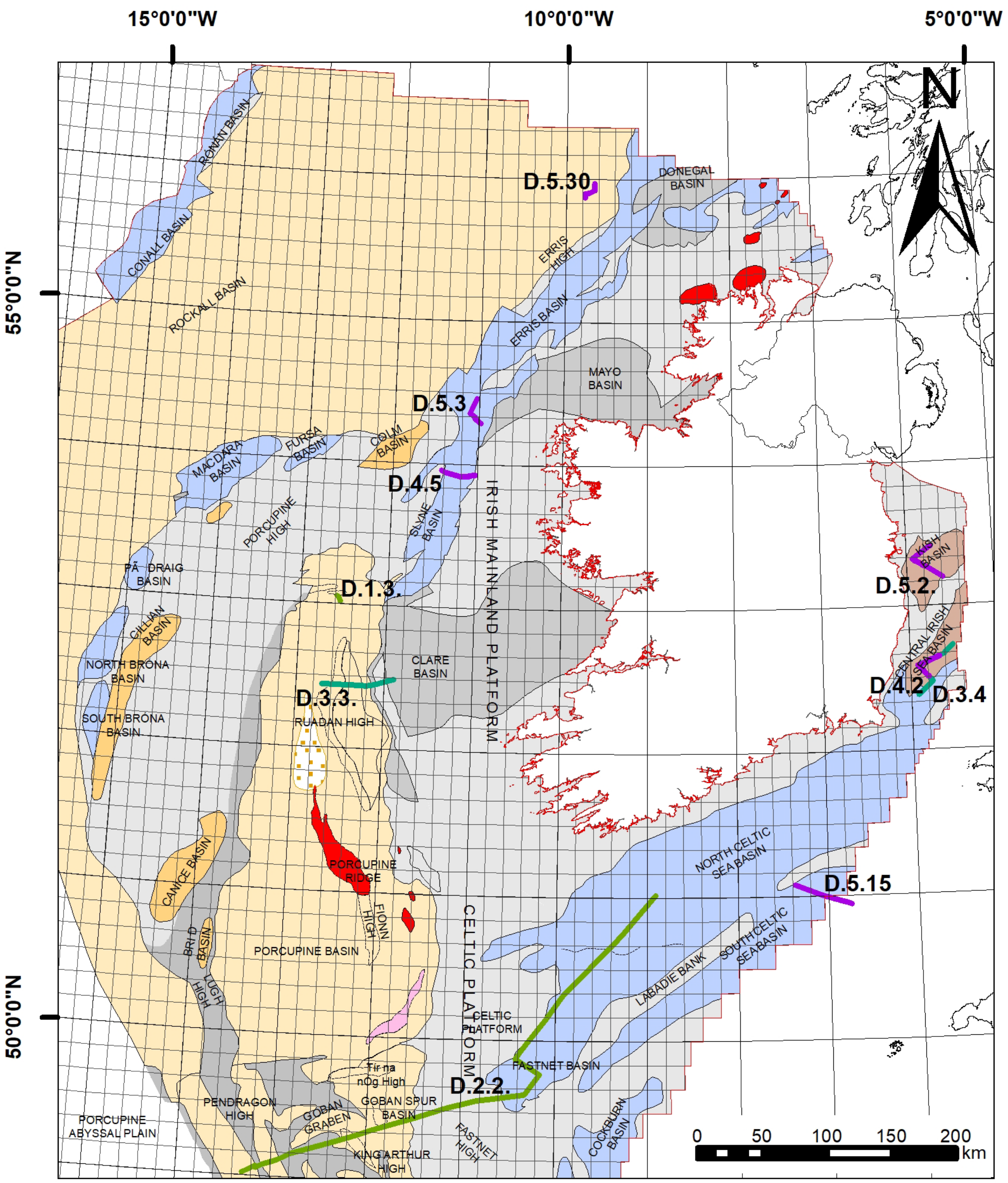
The so-called Base Cretaceous Unconformity has been studied in this project; it is prominent in the Porcupine Basin and a similarly named horizon, termed the "Base Cretaceous (Cimmerian Unconformity)" by Naylor *et al*. (1981) is present in the Fastnet, South Celtic Sea and North Celtic Sea basins (herein named the "Berriasian (Intra Perch)" horizon). The current assessment of the ages of these horizons, however, indicates that they are not coeval. The surface in the Porcupine Basin is at the Tithonian/Berriasian boundary as defined by biostratigraphy, whereas that in the Fastnet-Celtic Sea basins appears to be of Late Berriasian age (albeit with the age uncertainties inherent given the non-marine facies in which this surface falls within the Purbeck Group). The Base Cretaceous seismic horizon in the Porcupine is older than the horizon of the same name in the North Sea basin, which is approximately the same age as the surface in the Fastnet-Celtic Sea basins. These horizons are discussed further in **Chapter D**, Lower Cretaceous.

Seismic Horizon (in stratigraphic order)	***Area/Basin recognised***
Seabed	All areas
Pleistocene	Rockall, Donegal
Pliocene (C10)	Rockall, Conall, Rónán
Middle Miocene	Fastnet, North Celtic Sea, Central Irish Sea, Kish Bank, Celtic Platform
Lower Miocene (C20)	Conall, Rónán, Porcupine, Fastnet
Oligocene	Conall, Rónán, Macdara, North Bróna, Porcupine, Rockall, Fastnet, North Celtic Sea, Central Irish Sea
Priabonian (C30)	Porcupine, Rockall
Lutetian (Intra Trawbreaga)	Rockall, Macdara, Porcupine
Ypresian (Base C50)	Conall, Rónán, Macdara, Porcupine, Rockall
Ypresian (Base C60)	Porcupine
Ypresian (Base C70)	Porcupine
Ypresian (Top Péist)	Porcupine
Thanetian (Intra Gweedore)	Conall, Rónán, Macdara, Porcupine, Goban Spur
Thanetian (Top Ballyheige)	Porcupine
Near Base Thanetian (Top Gweebarra)	Porcupine
Danian (Top Chalk/Shetland)	Conall, Rónán, Rockall, Macdara, Slyne, Erris, Porcupine, Fastnet, North Celtic Sea, South Celtic Sea
Santonian (Top Leith)	Fastnet, Rockall
Turonian (Top Scadán)	Porcupine
Cenomanian (Top Cadóg)	Fastnet, North Celtic Sea, South Celtic Sea
Base Cenomanian (Base Chalk)	Rockall, Slyne, Erris, Porcupine, Fastnet, North Celtic Sea, South Celtic Sea
Mid Albian (Near base Daba Sandstone)	Porcupine
Albian (Top Agone Sandstone)	North Celtic Sea
Albian (Base Gault)	North Celtic Sea, South Celtic Sea
Aptian (Near base Bradán)	Porcupine
Hauterivian (Intra Rainbow)	North Celtic Sea
Hauterivian (Top Leathóg/Doingean Limestone)	Porcupine
Valanginian (Intra Pike)	North Celtic Sea
Berriasian (Intra Perch)	North Celtic Sea, Fastnet, South Celtic Sea
Base Cretaceous (Base Cromer Knoll)	Conall, Rónán, Rockall, Macdara, North Bróna, Slyne, Erris, Porcupine, Goban Spur
Tithonian (Top Knockadoon)	North Celtic Sea

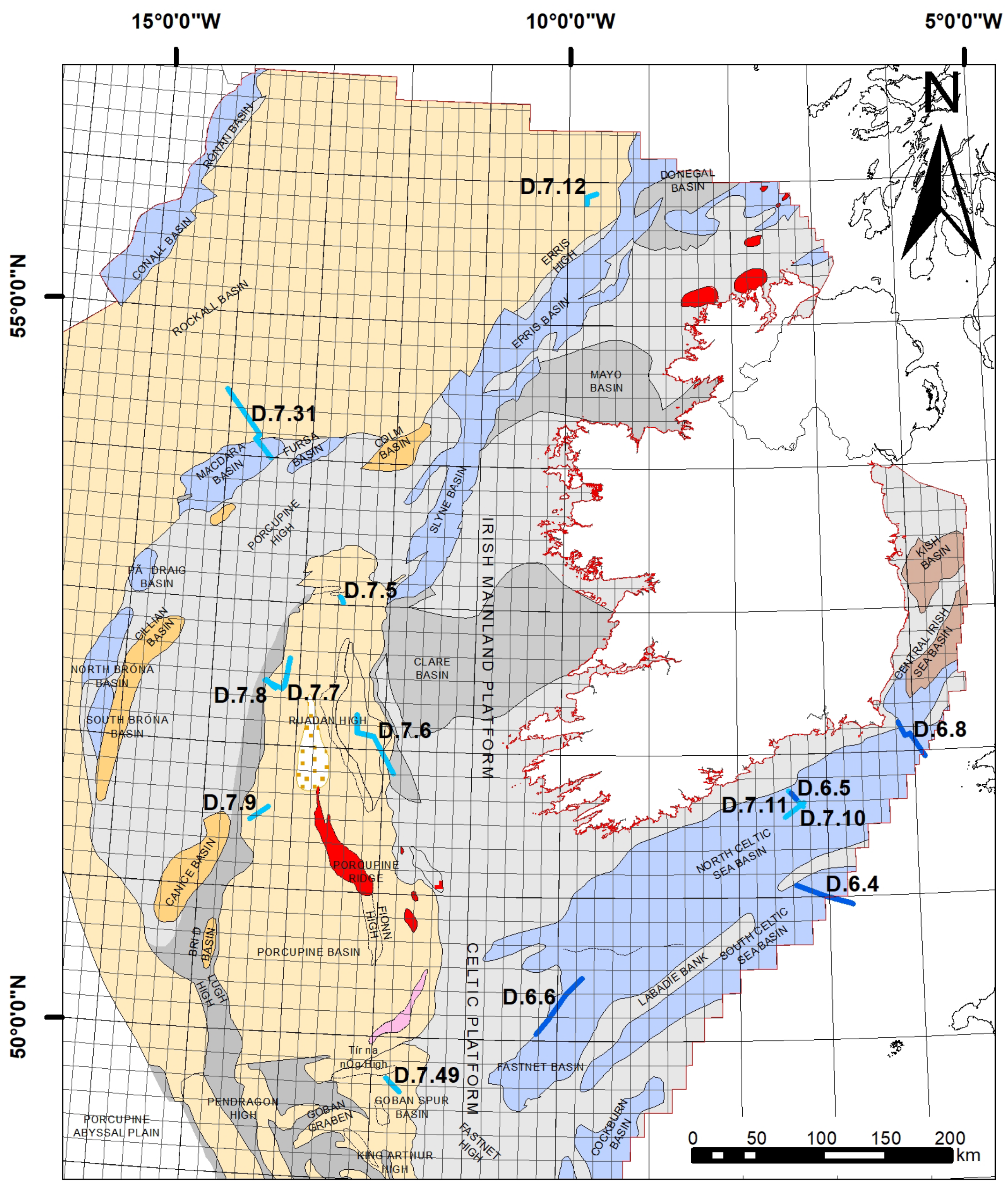
Near Base Tithonian	Conall, Rónán, Porcupine
Kimmeridgian (Top Baginbun)	North Celtic Sea
Kimmeridgian (Intra Bolus)	?Conall, ?Rónán, ?Rockall, Porcupine
Oxfordian (Top Dunbrattin)	North Celtic Sea
Oxfordian (Top Minard)	Porcupine, Slyne
Oxfordian (Intra Minard)	Porcupine
Base Minard	Slyne
Lower Bajocian	Slyne, Erris, Goban Spur
Bathonian (Top Peregrine)	North Celtic Sea
Aalenian (Top Lias)	North Celtic Sea
Toarcian (Whitby Mudstone)	North Celtic Sea Basin
Top Pliensbachian (Top Pabay)	Slyne, Erris, Fastnet, North Celtic Sea, South Celtic Sea
Pliensbachian (Intra Pabay)	South Celtic Sea
Top Sinemurian (Top Glenbeg)	South Celtic Sea, Fastnet
Upper Sinemurian (Top Meelagh)	Conall, Rónán, Slyne, Erris, Porcupine
Lower Sinemurian (Top Currane)	North Celtic Sea, Fastnet
Hettangian (Top Leane)	North Celtic Sea, Fastnet
Triassic (Top Penarth)	Erris, Slyne, Porcupine, Fastnet, North Celtic Sea
Triassic (Top Mercia Mudstone)	Erris, Slyne, Porcupine, Fastnet, North Celtic Sea
Triassic (Top Feadóg Halite)	North Celtic Sea, South Celtic Sea
Triassic (Intra Mercia)	Central Irish Sea
Triassic (Top Fylde Halite)	Central Irish Sea, Kish Bank
Triassic (Top Sherwood Sandstone)	Erris, Slyne, Porcupine, Fastnet, North Celtic Sea, Central Irish Sea, Kish Bank
Triassic (Top Calder Sandstone)	Central Irish Sea, Kish Bank
Triassic (Rottington Sandstone)	Central Irish Sea, Kish Bank
Top Permian (Zechstein/Cumbrian Coast)	Slyne, Central Irish Sea, Kish Bank
Permian (Top Collyhurst Sandstone)	Central Irish Sea, Kish Bank
Top Carboniferous	Donegal, Slyne, Porcupine, Fastnet, Central Irish Sea, Kish Bank (in some areas may merge with Top Bairneach)
Carboniferous (Intra Blackthorn/Pennine Coal Measures)	Porcupine, Central Irish Sea
Carboniferous (Top Bairneach)	Fastnet Basin, Central Irish Sea, Kish Bank
Top Devonian	?Macdara, Fastnet, Goban Spur
Top 26/28 basal conglomerate	Porcupine
?Cambrian (Top ?Bray)	Kish Bank

Table A.6. ***Seismic horizons interpreted in this study and their corresponding new nomenclature.***

This atlas contains a considerable number of illustrated seismic lines. The locations of those lines that are figured in the Stratigraphic Intervals Section D of the atlas are shown in **Figure A.11** and **Figure A.12**. In addition, ten regional seismic lines are illustrated in Section E Regional Seismic Lines, as shown in **Figure A.13**. Some of the latter lines are duplicates of lines also illustrated in the Stratigraphic Intervals Section D.

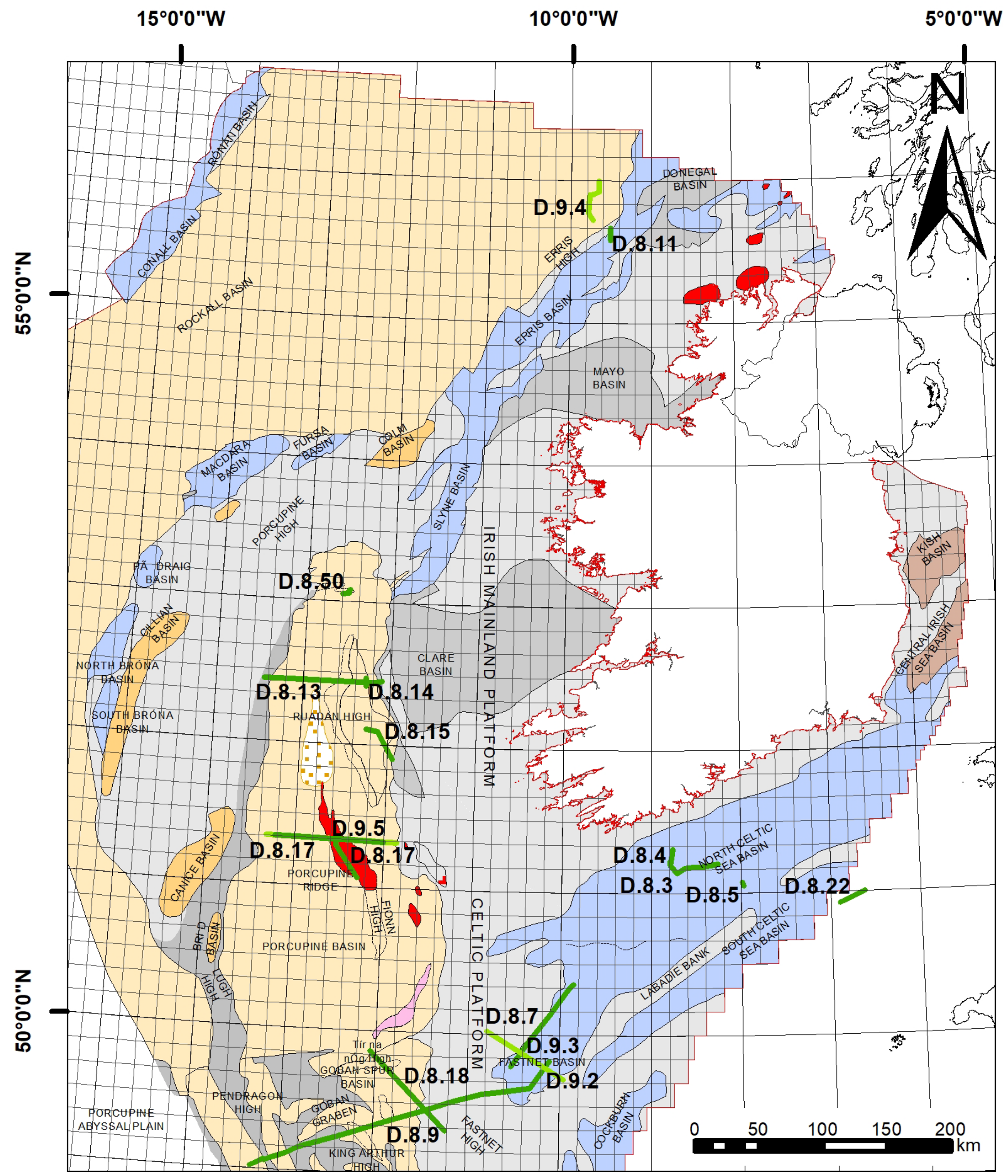


Illustrated seismic lines showing development of PreCambrian, Devonian, Carboniferous, Permian and Triassic in offshore Ireland (sections D.1, D.2, D3, D4, D5 of the Atlas)

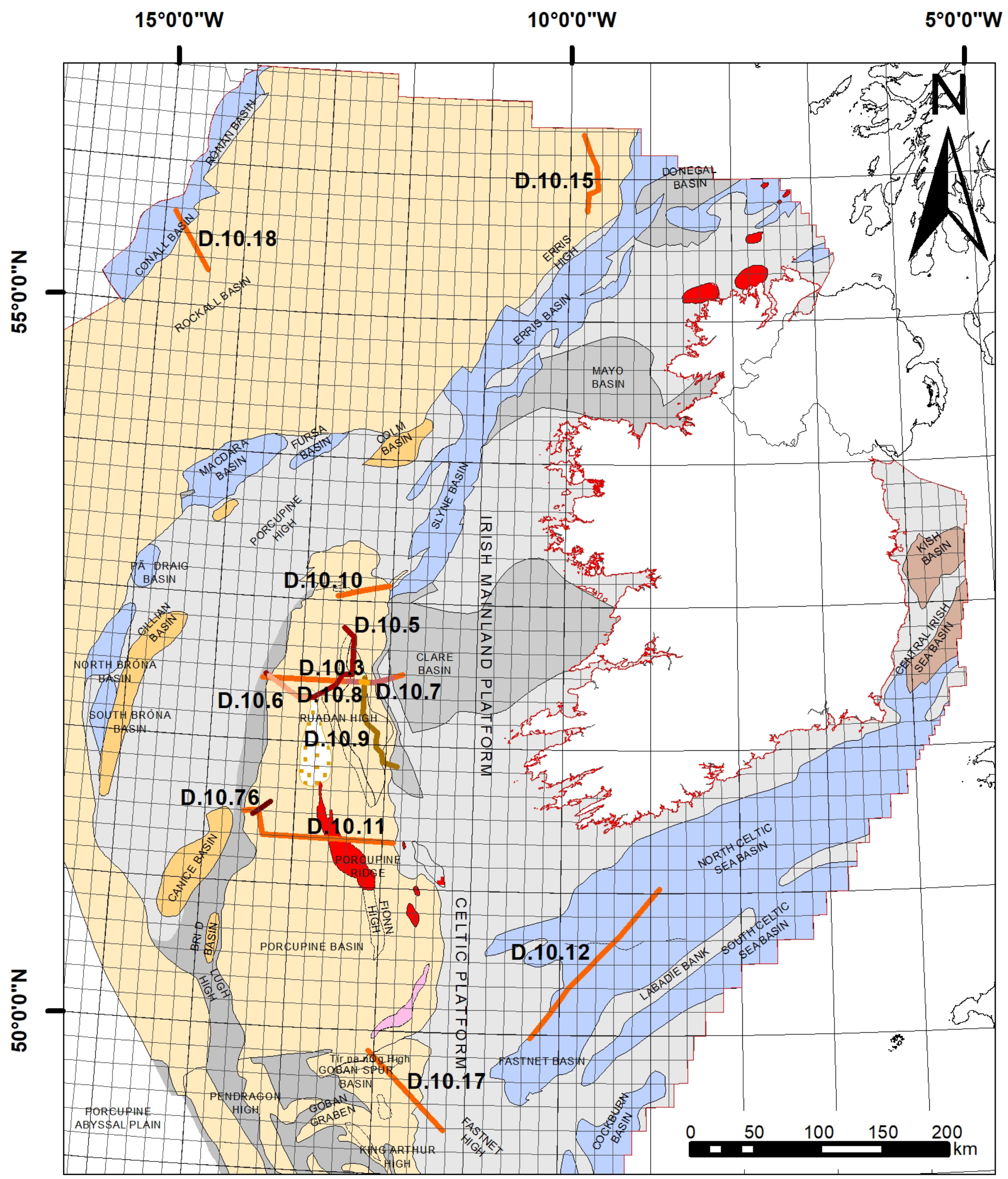


Illustrated seismic lines showing development of Jurassic in offshore Ireland (sections D.6, D.7 of the Atlas)

Figure A.11. ***Maps showing locations of seismic lines figured in the atlas (Palaeozoic to Triassic intervals, Sections D1-D7).***



Illustrated seismic lines showing development of Cretaceous in offshore Ireland (sections D.8 and D.9 of the Atlas)



Illustrated seismic lines showing development of Cenozoic in offshore Ireland (sections D.10 of the Atlas)

Figure A.12. ***Maps showing locations of seismic lines figured in the atlas (Jurassic to Cenozoic intervals, Sections D8-D10).***

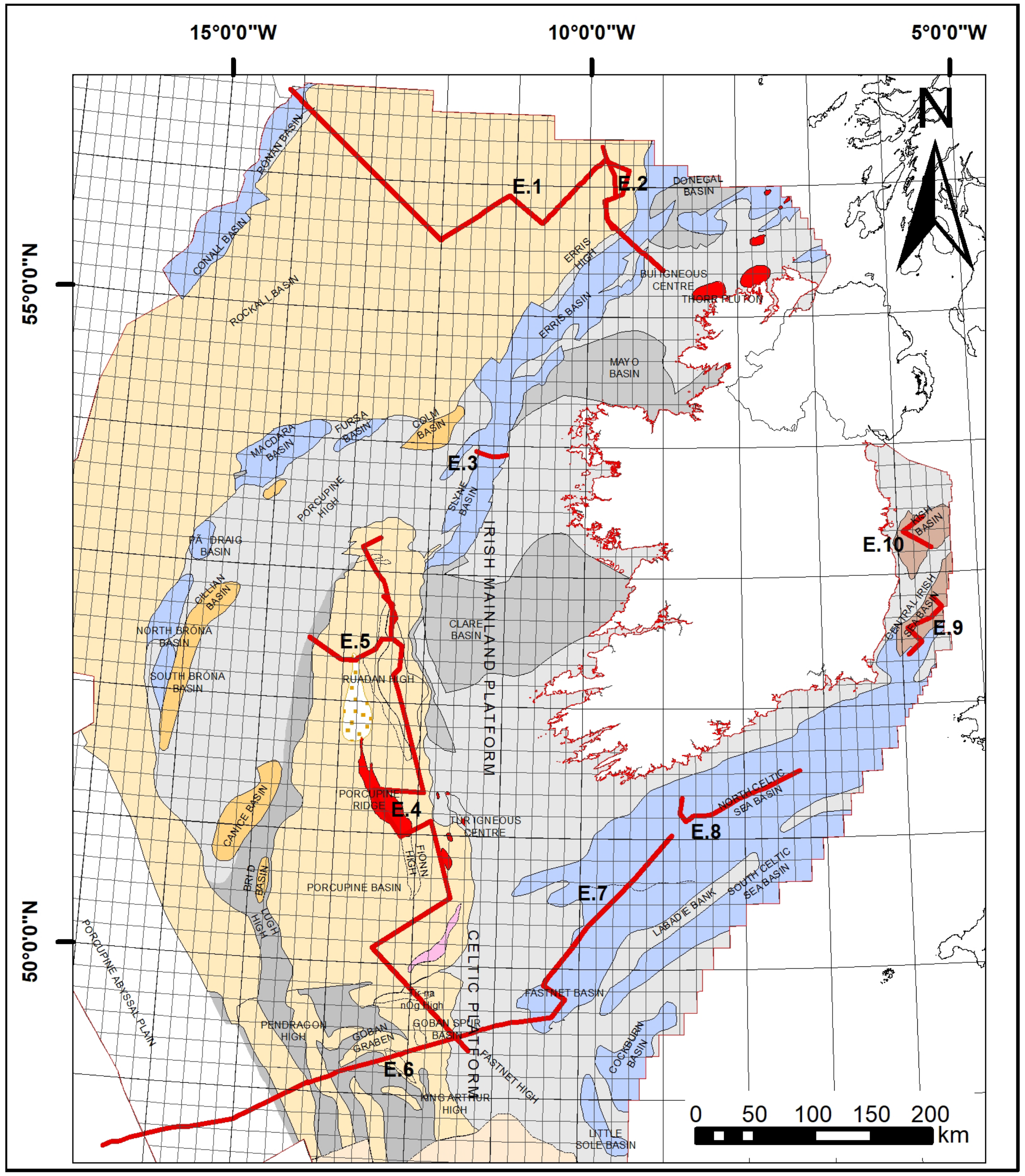


Figure A.13. *Map showing locations of regional seismic lines figured in the atlas, Section E Regional Seismic Lines.*

SYNTHETIC SEISMOGRAMS

Example synthetic seismogram well ties are presented in this Atlas for two wells located within different parts of the North Celtic Sea Basin. The primary aim of this work was to help define the ties between the seismic data and wells over the Wealden-Purbeck interval, in particular to aid identification of the seismic horizons that are recognisable over that interval, namely the Valanginian (Intra Pike) and Berriasian (Intra Perch) horizons.

Two wells that displayed reasonable seismic data quality over the Wealden – Purbeck interval were selected, 48/22-1A and 49/26-1A. In the western part of the North Celtic Sea Basin, 48/22-1A (**Figure D.8.4**) was located approximately 20kms west of the Barryroe discovery. Towards the southern edge of the basin, 49/26-1A (**Figure D.8.5**) was drilled approximately 30kms south of the Kinsale Head Field.

The synthetic seismograms have been produced by convolving the acoustic impedance, generated from the well sonic and density logs, with a Ricker wavelet of either 25 or 35Hz dominant frequency. Except for well 49/26-1A, the phase of the Ricker wavelet is at, or near to, zero phase. Displays are shown with a polarity such that a reduction in acoustic impedance is displayed as a black seismic peak. The generated synthetics are compared to 2D data derived from seismic lines intersecting the well locations. As discussed elsewhere, one of the difficulties within the North Celtic Sea Basin is the generally unknown phase and polarity of the vintage 2D seismic data. Nevertheless, reasonable seismic matches have been produced for the two example wells evaluated.

SEQUENCE STRATIGRAPHY INTRODUCTION

Stratigraphic sequences have been recognised and defined in this study both from interpretations of well data (by the recognition of unconformities, transgressions and regressions) and on seismic data (seismic sequences defined by reflector terminations, truncations, onlaps, toplaps etc.). These data sets have been interpreted on the basis of first principles to derive a set of sequences based on the project database. Once the sequences have been recognised, comparisons were made with previously published schemes in the area and in neighbouring regions (for example, the North Sea). In some instances, it is evident that previously published sequences from the UK onshore and North Sea areas are applicable to the offshore Ireland area. Such schemes include those defined for the Jurassic of the North Sea and UK onshore (J sequences of Partington, Mitchener *et al*., 1993; Partington, Copestake *et al*., 1993) and for the Lower Cretaceous of the North Sea (K sequences of Copestake *et al*., 2003; Copestake, 2003). For other intervals, for example the Upper Jurassic and Cenozoic, a set of stratigraphic sequences has been defined that are recognisable across the whole offshore Ireland region. Some of these can be correlated with the North Sea sequences, however, most of these intervals are developed in different facies to the North Sea basin and hence new sequences have been defined for these intervals in offshore Ireland.

For offshore Newfoundland (Flemish Pass Basin, Jeanne d'Arc Basin, Labrador Shelf) no sequence stratigraphic schemes have been documented with public domain access, preventing either usage of or detailed comparison with the sequence stratigraphy schemes of these areas and offshore Ireland. Within the published data sets of these offshore Canada areas, however, unconformities have been documented, and these may be compared with those identified in offshore Ireland in this project.

In this project, stratigraphic sequences have been recognised and defined in sufficient wells, over a given area in order to demonstrate the validity of the sequence in question across a region, ideally spanning more than one basin. In total, sequences have been interpreted in 117 wells and boreholes in the project. Sequences have not been interpreted in all wells in the project, or over the whole penetrated well sections in those wells that have been interpreted, however. Therefore on the well and borehole stratigraphic summary logs (Appendix C), there are sometimes gaps in the interpreted sequence column; this is intentional. The sequences recognised on the basis of well data and well correlations have been tied to those interpreted seismic horizons that reflect sequence boundaries. These are horizons at which unconformities (reflected in seismically expressed reflector terminations; onlaps, downlaps and toplaps) can be seen on seismic data. The sequences recognised and described in this atlas utilise both well based and seismic based criteria in their definitions.

The variation in seismic data quality available to the study has affected the effectiveness of seismic sequence boundary recognition across the offshore Ireland region. The best seismic data quality is available from west of Ireland on the whole, within which the long offset PAD 2014 lines offer the best resolution. On these lines, a clear set of regionally developed seismic sequences are recognisable from the Jurassic to Cenozoic intervals. In the Fastnet – North Celtic Sea – Central Irish Sea basins, seismic data quality (of the data available to this study) is generally significantly poorer. Nevertheless, it has been possible to recognise a consistent set of regionally developed seismic sequence boundaries (horizons) in the latter area. The main seismic sequence boundaries (horizons) interpreted in the offshore areas of Ireland are tabulated in **Table A.5.**

The sequences defined are described in Section D and are illustrated on numerous figures and illustrative displays in this atlas.

SEQUENCE STRATIGRAPHIC APPROACH AND METHODOLOGY

A range of sequence stratigraphic approaches are currently used among practitioners and several definitions of concepts exist in the literature, which can potentially cause confusion when trying to carry out a sequence stratigraphic evaluation of an area such as offshore Ireland. A useful definition of sequence stratigraphy has been provided by Embry (2009), as follows; "*sequence stratigraphy consists of: 1. the recognition and correlation of stratigraphic surfaces which represent changes in depositional trends in the rock record, and, 2. the description and interpretation of resulting, genetic stratigraphic units bound by those surfaces*". This is the approach that has been applied in this project. There is a prime requirement to correlate any recognised surfaces both locally and regionally, thus it was essential to obtain a high resolution chronostratigraphic scheme as the framework to calibrate the key stratigraphic surfaces. There are several types of data that were used to provide a chronostratigraphic framework, from biostratigraphy to chemostratigraphy, magnetostratigraphy and carbon isotope stratigraphy. In addition to providing a chronostratigraphic framework for sequence stratigraphy, biostratigraphy can be used to aid the recognition of sequences by providing distinctive palaeontological characterisation of these units.

One of the fundamental aspects of sequence stratigraphy is the identification of stratigraphic surfaces that are used to subdivide geological successions into stratigraphic sequences and their component sub-units ("systems tracts"). These bounding surfaces can be recognised in outcrops and well sections. The three main key surfaces are the *correlative conformity* (or *depositional sequence boundary*), *transgressive surface* and *maximum flooding surface* and form the basis of the recognised sequence methodology and terminology accepted by the International Subcommission on Stratigraphic Classification (see Catuneanu *et al*., 2011; Abreu *et el*., 2014). In most cases, the maximum flooding surface is the most readily recognisable of these key surfaces, however, there are frequent instances where the transgressive surface can be defined. Recognition of the depositional sequence boundary is more problematic and is often highly interpretive and conceptual, though there are instances of sharp basinward shifts of facies (and associated unconformities) that have provided the clearest evidence for depositional sequence boundaries in this project. For reasons of difficulty of recognition, and the lack of clear, objective criteria on which to define this type of surface (see discussions in Embry, 2009), we have not used the term "*correlative conformity*".

In general, the sequences have been interpreted by the integration of wireline logs, biostratigraphy, lithostratigraphy, seismic and sedimentology (particularly facies analysis). Characteristic well log profiles of sequences and parasequences, in clastic depositional settings, have been published by Rioult *et al.* (1991), Vail & Wornardt (1991), Van Wagoner *et al.* (1990), Emery & Myers (1996) and Posamentier & Allen (2000). It is possible to recognise many of these typical log profiles in the Jurassic, Lower Cretaceous and Cenozoic of offshore Ireland, including those of progradational, shallow marine settings, retrogradational, shallow marine settings and aggradational profiles in both shallow and deep marine settings.

One typical wireline log profile is the symmetrical (or "bow trend" of Emery & Myers, 1996, or "gamma–sonic bow"), which is characteristic of shelf to basinal claystone argillaceous (and in some cases carbonate) sediments. Such a profile is common in argillaceous and occasionally carbonate successions in offshore Ireland, of various ages. Several examples of this profile can be seen on the various well correlation lines and individual well displays in this Atlas.

Other characteristic wireline log patterns reflecting particular parts of sequences are the coarsening upwards (funnel shaped) and fining upwards (bell shaped) log profiles, representing progradational (shallowing) and retrogradational (deepening) trends respectively. The bases and tops of these trends typically fall at major changes in depositional style, usually interpreted as regional maximum flooding surfaces (within major condensed units). The bases and tops of these trends, where seismic data quality allows, match the downlap surfaces onto which prograding seismic clinoform units build. There are many examples of this from the current project, as illustrated in the seismic figures in this Atlas. Where apparent, seismic reflection terminations are highlighted on many of the illustrated seismic lines.

Critical steps in the definition of sequences, in well (and seismic) data, are the recognition of unconformities and major palaeoenvironmental changes. The latter includes levels of significant deepening (to reflect transgressions or peak flooding) or shallowing (sudden shallowing reflects basinward shifts of facies); these types of changes can be recognised on the basis of changes in microfauna or palynoflora and are thus recognisable from palaeontological/biostratigraphic data. At the detailed level, the recognition of unconformities can be based on subtle changes in biostratigraphic data sets, for instance, by the determination of levels where biozones may be absent. In some cases, of course, missing section may be due to fault intersection of well bores; in such instances the likelihood of the presence of faults has been assessed from the available seismic data at the well location.

The recognition of a set of regionally developed seismic horizons in this project supports the definition of a set of well based stratigraphic sequences, with boundaries defined at particular horizons and their correlative levels in well data. In this project, we have integrated sequences that are apparent in both well and seismic data sets and, depending on the sequence defined, it may be the seismic data or the well data or both that drives the definition of a particular sequence. Examples of seismic data driving the sequence definition are:-

- the Base Cretaceous (Base Cromer Knoll) horizon in the Porcupine, Slyne and Erris basins comprising the base of the K10 Sequence (which is not strongly expressed on wireline log data).
- The Berriasian (Intra Perch) horizon in the Fastnet, North Celtic Sea and South Celtic Sea basins defining the top of the UJ50 Sequence (which is not apparently consistently expressed on wireline log data).
- The Aptian (Near base Bradán) horizon in the Porcupine Basin, which is tied in relatively few wells and which is not well characterised on wireline log data. This is a very prominent seismic horizon.
- The Lutetian (Intra Trawbreaga), Priabonian (C30) and Oligocene horizons which are major downcutting events on seismic data but which have rather indistinct character on wireline logs.

Examples of major stratigraphic sequence boundaries that are defined mainly on well data, with little apparent expression on seismic data (available to this project) include:-

- Base UJ20 sequence surface, which is a level of major change regionally, but which is often poorly expressed seismically (Top Minard horizon in Porcupine Basin, Top Dunbrattin in the North Celtic Sea Basin).
- Base K55b surface, ties to intermittently recognised Albian (Base Gault) seismic horizon in Fastnet, North Celtic Sea and South Celtic Sea basins. This is a major regional unconformity that onlaps above and truncates much older section beneath.
- Base K55d MFS that terminated deposition of the Agone Sandstone Member in the North Celtic Sea Basin. On seismic this is one of several "reflectors" and does not appear to show any distinctive seismic character.

SEQUENCE NOMENCLATURE

Procedures for naming and numbering of stratigraphic sequences do not appear in any stratigraphic codes or guides. As a consequence, there are several different approaches to sequence naming in the literature. The approach taken in this project has been to define sequences for offshore Ireland based on first principles and direct observation from the data, that is by the identification of levels of unconformities, flooding surfaces and transgressive surfaces from well data (wireline logs), seismic and biostratigraphy. Once this was completed, the succession of sequences was compared to other published schemes. This includes schemes defined for Europe (including the North Sea, for example, Partington, Mitchener *et al*., 1993, Copestake, 2003 and onshore Europe, for example, Hardenbol *et al*., 1998) as well as Eastern Canada. For the latter area, some initial sequence stratigraphic surfaces have been proposed for some parts of this region, such as the Terra Nova area (see Sinclair *et al*., 2014).

The sequence naming/numbering system applied in this project generally adopts even numbers (for example, 2, 4, 6, or 20, 30, 40) to allow the insertion of additional sequences as more wells are drilled in the future (for example, 1, 3, within the 10 sequence, or 22, 23, 24 etc within the 20 sequence). In the North Sea basin this method has successfully been applied with the J sequences, where the second order sequences are J10, J20 etc, and third order sequences, J02, 04, 06, 12, 14, 16, J22, J24, J26 when initially defined (Partington, Mitchener *et al.*, 1993; Partington, Copestake *et al*., 1993). Subsequent work has allowed the insertion of additional sequences, for example, J17, J15. A similar approach has been used for the North Sea Lower Cretaceous sequences (Copestake *et al*., 2003) and the Phanerozoic sequences of the Arabian Plate (Sharland *et al*., 2001).

In the current study it is possible to recognise some previously defined sequences in offshore Ireland for certain intervals, for example in the Lower-Middle Jurassic, the North Sea and onshore British J sequences are clearly recognisable, as are most of the North Sea K sequences in the Lower Cretaceous of offshore Ireland. For other intervals, however, it is necessary to define new sequences for Ireland, for example where depositional conditions differ from those areas in which sequences were originally defined (for example, over the Oxfordian to Tithonian and Cenozoic of Ireland, compared to the North Sea) or where biostratigraphic data are not sufficiently detailed to allow a detailed correlation with the North Sea. Even in these latter cases, though it is frequently possible to correlate the offshore Ireland sequences with those of the North Sea, suggesting that some of the controls on sequence development and expression are common to both regions.

Within this project, the following numbers of stratigraphic sequences (or subsequences) have been recognised:-

- Triassic; 3
- Lower Jurassic; 10
- Middle Jurassic; 6
- Upper Jurassic; 5
- Lower Cretaceous; 10
- Upper Cretaceous; 4
- Cenozoic; 15

Existing sequence stratigraphic schemes have been applied for the following intervals:-

- J1-J34 sequences for the Lower and Middle Jurassic (all areas).
- K20-K55 sequences for the Lower Cretaceous (all areas).

New sequences are defined for the Triassic, Upper Jurassic, Upper Cretaceous and Cenozoic. These alphanumeric schemes allow for the future recognition of additional sequences as knowledge and data availability advances.

PALAEOFACIES MAPS INTRODUCTION

Palaeofacies maps were constructed at specific geological age intervals to best represent palaeogeographic variations through geological time, which coincide with changes in lithological facies and depositional extent. While palaeogeographic and gross depositional environments maps were mentioned in the Invitation to Tender document, it was decided, by consultation with the project Steering Committee, that palaeofacies maps would be produced instead. Similarly, while play fairway maps were required in the Invitation to Tender document, it was agreed, at a meeting with the project Steering Committee, that, due to the lack of sufficient budgeted time for detailed seismic mapping in the project, that it would not be feasible to carry out play fairway mapping within this project.

Palaeofacies interpretations were constrained to the known present-day structural extents of the basins and palaeo-shorelines or palaeo-faulting were not defined.

A total of thirty palaeofacies maps have been constructed, including; 1 Carboniferous, 1 Permian, 3 Triassic, 10 Jurassic, 7 Cretaceous and 8 Cenozoic maps. The palaeofacies maps have been created using ArcGIS software. Depositional environments are represented by colour, whilst carbonate or clastic facies are distinctly separate using gradations of blues and browns respectively.

Interpretation was guided by available penetrative well data and was not reliant on seismic. Lines and palaeofacies extents drawn on the maps are interpretative and do not definitively define boundaries between depositional environments. Palaeofacies were drawn to fit areas of proven occurrence, and only extrapolated to areas where their presence is confidently expected. The use of question marks communicates areas of uncertainty. Depositional environments represent the broader regional approach (for example, marine shelf) rather than localized variations (for example, inner marine shelf). The lithofacies plotted represents the dominant sedimentation within a geological interval, whilst not necessarily representing all variations of lithofacies present.

The lithological legend used on the palaeofacies maps is based on the Shell (2016) standard legend (see **Figure A.7**).

GEOCHEMISTRY INTRODUCTION

A geochemical characterisation of all source rock intervals based on the new stratigraphy and revised ages was carried out and the occurrence of each identified source interval throughout the different offshore basins have been highlighted. The main source rock conclusions of the project are presented in Section B.

Analysis of the geochemistry data for this project was carried out in *p:IGI-3* software. Data relevant for the source rock identification and characterisation presented in this study include total organic carbon contents (TOC), as well as data derived from Rock-Eval pyrolysis. These data were available for a total of 116 wells offshore Ireland. The map in **Figure A.14** shows all wells with geochemical data that were included in the database, highlighting those that were considered for source rock characterisation. Listings of source rock data that were compiled by BeicipFranlab (2017, PIP Project IS16/01), together with a tabulation of all identified source rock intervals (of intervals by well) have been provided. These data were imported into the IC stratigraphic database for the current project and displayed against the new stratigraphic interpretations (lithostratigraphy, chronostratigraphy, biostratigraphy, sequence stratigraphy). A number of key wells and intervals, illustrating the source rock data, and the comparison with the BeicipFranlab (2017) soruce rock intervals, are provided as figures in this Atlas. It is on the basis of these displays that it has been possible to compare the source rock intervals identified in the current project to those recognised by BeicipFranlab (2017).

To effectively assign the updated stratigraphy to all samples and carry out the interpretation work, a fully integrated geochemical database containing all available data of the petroleum exploration wells offshore Ireland has been compiled. The data were provided by PIP and the PAD in multiple separate Excel files for individual wells, these having been extracted and quality controlled from the original source reports within project IS16/01, that were then compiled into one integrated geochemical database as part of this study to be used in the *p:IGI-3* software. The data provided by PIP and the PAD consisted of all released Irish geochemical data from historic reports together with additional data from the previous ISPSG IS16/01 (BeicipFranlab, 2017).

Considering the varying quality of the original source reports that were produced by several laboratories and date back to the early 1970s, the data may contain errors introduced during the extraction. Quality control of the final database has been completed and obvious errors have been corrected, but no data have been recaptured or added from the original source reports for this study and all information were included as given in the Excel files provided to this project. After formatting and exporting all relevant data from these files, the data were imported into *p:IGI-3* on a well-by-well basis and merged together based on a set of key parameters to generate a single, comprehensive database.

Note that raw geochemical data that exist in DSDP/IODP/ODP holes were not provided for integration into the geochemical database and therefore have not been analysed in the current study.

A source rock characterisation was conducted on all wells with appropriate data to evaluate their organic content, hydrocarbon yield, and kerogen type, but only results for those intervals that are considered to demonstrate significant hydrocarbon source potential are described in this atlas. Organic richness, kerogen type, and hydrocarbon generation potential were used as parameters to identify the source rock intervals. The organic richness is identified based on the Total Organic Carbon (TOC) content and data were available for over 12,700 samples. The quantity of TOC alone however is not a definitive measure of the source rock generative potential and various parameters derived from Rock-Eval pyrolysis provide characteristics on the kerogen type and hydrocarbon potential. These parameters are displayed for each selected interval to demonstrate its source rock potential using TOC vs S2 cross plots, pseudo-van Krevelen diagrams and Hydrogen Index vs Tmax plots. A total of 21 formations with source potential were identified based on the project stratigraphy, with another 10 formations including a few samples showing some source potential.

To highlight the regional distribution of each identified source rock interval, as well as potential similarities or variations between different basins, separate bubble maps showing average TOC and HI values have been produced for each. The values shown on these maps represent averages calculated from all available data for the specific source interval at each well location.

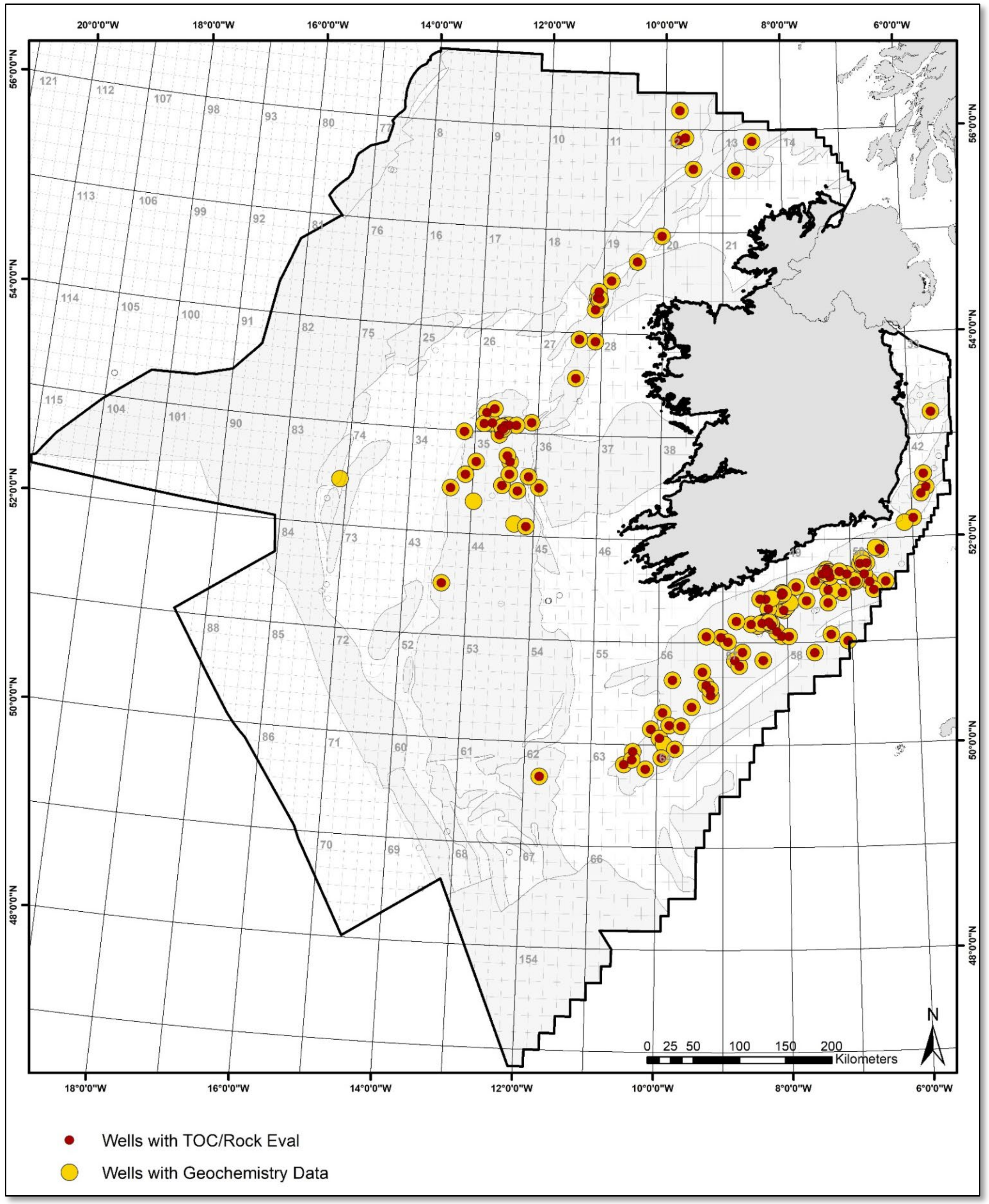


Figure A.14. ***Map showing all wells and boreholes offshore Ireland for which geochemical data were available.***

Highlighted are the ones with TOC and Rock-Eval data that were considered for the source rock characterisation**.**