British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Devonian and Carboniferous stratigraphical correlation and interpretation in the Orcadian area, Central North Sea, Quadrants 7 - 22

Energy and Marine Geoscience Programme

Commissioned Report CR/16/032

BRITISH GEOLOGICAL SURVEY

ENERGY AND MARINE GEOSCIENCE PROGRAMME

COMMERCIAL REPORT CR/16/032

Devonian and Carboniferous stratigraphical correlation and interpretation in the Orcadian area, Central North Sea, Quadrants 7 - 22

K. Whitbread and T. Kearsey

Contributor

N. Smith

Keywords

Report; Stratigraphy, Carboniferous, Devonian, Central North Sea.

Bibliographical reference

WHITBREAD, K AND KEARSEY, T 2016. Devonian and Carboniferous stratigraphical correlation and interpretation in the Orcadian area, Central North Sea, Quadrants 7 - 22. *British Geological Survey Commissioned Report*, CR/16/032. 74pp.

Keyworth, Nottingham British Geological Survey 2016

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276

email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488

email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683

email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270

Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

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

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

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

Tel 01793 411500 Fax 01793 411501

www.nerc.ac.uk

Website www.bgs.ac.uk

Shop online at www.geologyshop.com

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

Foreword

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

Acknowledgements

A large number of individuals involved with the 21CXRM project have contributed to this study. We would particularly like to thank Mark Fellgett and Sandy Henderson for well data gathering and preparation. We acknowledge LR Senergy for use of ODM™ under license. CGG are thanked for the provision of LAS files for selected wireline logs. We thank Tony Hewett (Eon/Premier Oil) and Rosie Kelly (LR Senergy) for technical review of this report.

Contents

FIGURES

Summary

This report details the stratigraphy and palaeogeography of Devonian and Carboniferous rocks of the northern sector of the UK Central North Sea (the 'Orcadian Area') for the 21CXRM Palaeozoic project. The work integrates the lithostratigraphic framework for the Middle Devonian to Late Carboniferous succession in the region of the Mid North Sea High developed in the first phase of the 21CXRM Palaeozoic project (Kearsey et al., 2015), with the Early Devonian to Early Carboniferous succession present in the north Central North Sea.

This report describes the stratigraphical correlation of Devonian and Carboniferous strata of the Orcadian Basin and the northern extension of the Forth Approaches into the Witch Ground Graben (Quadrants 7 – 22). A lithostratigraphic framework for the region is presented, building on the work of Cameron (1993) and Marshall and Hewett (2003).

For the Devonian strata, the lithostratigraphic framework developed by Marshall and Hewett (2003) is followed. Their study presented a substantial revision of the previous Devonian stratigraphy for the region, particularly related to (1) reassessment of the Devonian - Permian contact and (2) the identification of the Eday Group offshore in the Inner Moray Firth Basin. In this study, onshore outcrops, well data and seismic interpretation (cf. Arsenikos et al., 2016) verify the key elements of the framework of Marshall and Hewett (2003). In addition, well interpretations further define the extent of the stratigraphical units and form the basis of potential source and reservoir horizon palaeogeographic reconstructions for four time intervals within the Devonian succession. For example, the potential source rock of the Orcadia Formation has been interpreted to the north of the Halibut Horst and into the East Orkney Basin, significantly increasing the extent of this unit outside the Inner Moray Firth.

A revised lithostratigraphic framework for the Carboniferous strata of Quadrants 14, 15, 20 and 21 is presented. This framework links the Carboniferous succession of the Orcadian Area with equivalent age strata in areas on and surrounding the Mid North Sea High (Kearsey et al., 2015). Well and seismic interpretations have been integrated to better define the extent of Carboniferous units. Regional facies variations for key time intervals in the Early Carboniferous are presented which highlight relationships between the Carboniferous basins of the Witch Ground Graben and Forth Approaches, and those of the Mid North Sea High and adjacent regions to the south. For example, fluvial channel systems have been interpreted within late Visean age coal-bearing, fluvial and lacustrine deposits of the Firth Coal Formation, that are potential feeder systems for Yoredale Formation fluvio-deltaic to marine deposits farther south.

This report forms one of a series of outputs from the 21CXRM Palaeozoic project (Orcadian Area) and provides explanatory information for the associated digital datasets (spreadsheet). The Orcadian Area study follows previous work undertaken in the Mid North Sea High area of the Central North Sea (CNS area; Figure 1). Key elements of the regional petroleum geology of the Orcadian area are summarised in an accompanying synthesis report (Monaghan et al., 2016).

1 Introduction

The aim of the 21CXRM Palaeozoic Project is to stimulate exploration of the Devonian and Carboniferous plays of the Central North Sea – Mid North Sea High, Moray Firth – East Orkney Basin and in the Irish Sea area. The objectives of the project include regional analysis of the plays, building consistent digital datasets, and working collaboratively with the OGA, Oil and Gas UK, and industry.

This report describes the stratigraphy and palaeogeography of the Devonian and Carboniferous strata in Quadrants 7 – 22 of the Inner Moray Firth and adjacent areas, informally termed the 'Orcadian Area' (Figure 1), and the associated onshore strata around the margins of the Moray Firth, Caithness and Orkney (Figure 2). Sedimentary strata of Devonian age are widespread throughout the northern sector of the Central North Sea and adjacent onshore areas of Scotland, where they occur in the Midland Valley, around the margins of the Moray Firth, and across Caithness, Orkney and Shetland (Figures 1 and 2). The Orcadian area is distinguished from the Devonian-Carboniferous basins of the Midland Valley and south Central North Sea by the presence of a thick sequence of lacustrine strata of Middle Devonian age. The lacustrine succession is well exposed onshore in Caithness and Orkney and has been penetrated by a number of wells offshore.

Six correlation panels were constructed across the region, tying in selected key wells in order to erect a framework for the Devonian and Carboniferous strata and to provide regional-scale seismic ties (Figure 3).

The onshore geology of the Devonian of the Moray Firth area, Caithness and Orkney has been studied extensively. Summaries of the lithostratigraphy, palaeogeography and tectonic evolution are provided by Mykura (1976), Trewin and Hurst (2009) and Trewin and Thirlwall (2002). A regional onshore lithostratigraphic framework for the Devonian successions of the Midland Valley of Scotland was presented by Browne et al. (2002), but the complex lithostratigraphic nomenclature of the Devonian succession of the of northeast Scotland (i.e. the Orcadian strata) has yet to be formally summarised.

The geology of the Devonian strata of the North Sea has previously been reviewed by Downie (1998). The main elements of the lithostratigraphy of the Devonian strata of the offshore Orcadian area were originally described by Cameron (1993). This lithostratigraphic framework for the region was later revised by Marshall and Hewett (2003) on the basis of new palynological data and correlations between onshore and offshore successions (Figure 4). The most significant change arising from this revision was the reassignment of substantial portions of strata originally assigned by operators to the Permian Rotliegend Group to the Middle and Late Devonian. During this reassignment, Marshall and Hewett (2003) recognised extensive occurrence of the Late Devonian Buchan Formation within the Inner Moray Firth area, where it was previously deemed to be absent (cf. Andrews et al., 1990; Cameron, 1993), and described a distinct set of strata of Middle Devonian age – the Eday Group – comparable to successions found onshore in Orkney.

Strata of Carboniferous age are less widespread in the Orcadian area, only occurring offshore in the east of the region, in Quadrants 14, 15, 20 and 21 (Figure 1). In onshore areas, Carboniferous rocks are widespread throughout the Midland Valley of Scotland, but are not found to the north of the Highland Boundary Fault. The lithostratigraphy of the Carboniferous strata of the Orcadian area is based on the work of Cameron (1993). A regional assessment of Carboniferous strata, based on analysis of wells in Quadrants 14 and 15, was undertaken by Leeder and Boldy (1990). The outcomes of this study include a revised lithostratigraphic framework for the Early Carboniferous strata of the Orcadian area (Figure 4), and reassessment of the relationship with Carboniferous successions of the Mid North Sea High area (Figure 5).

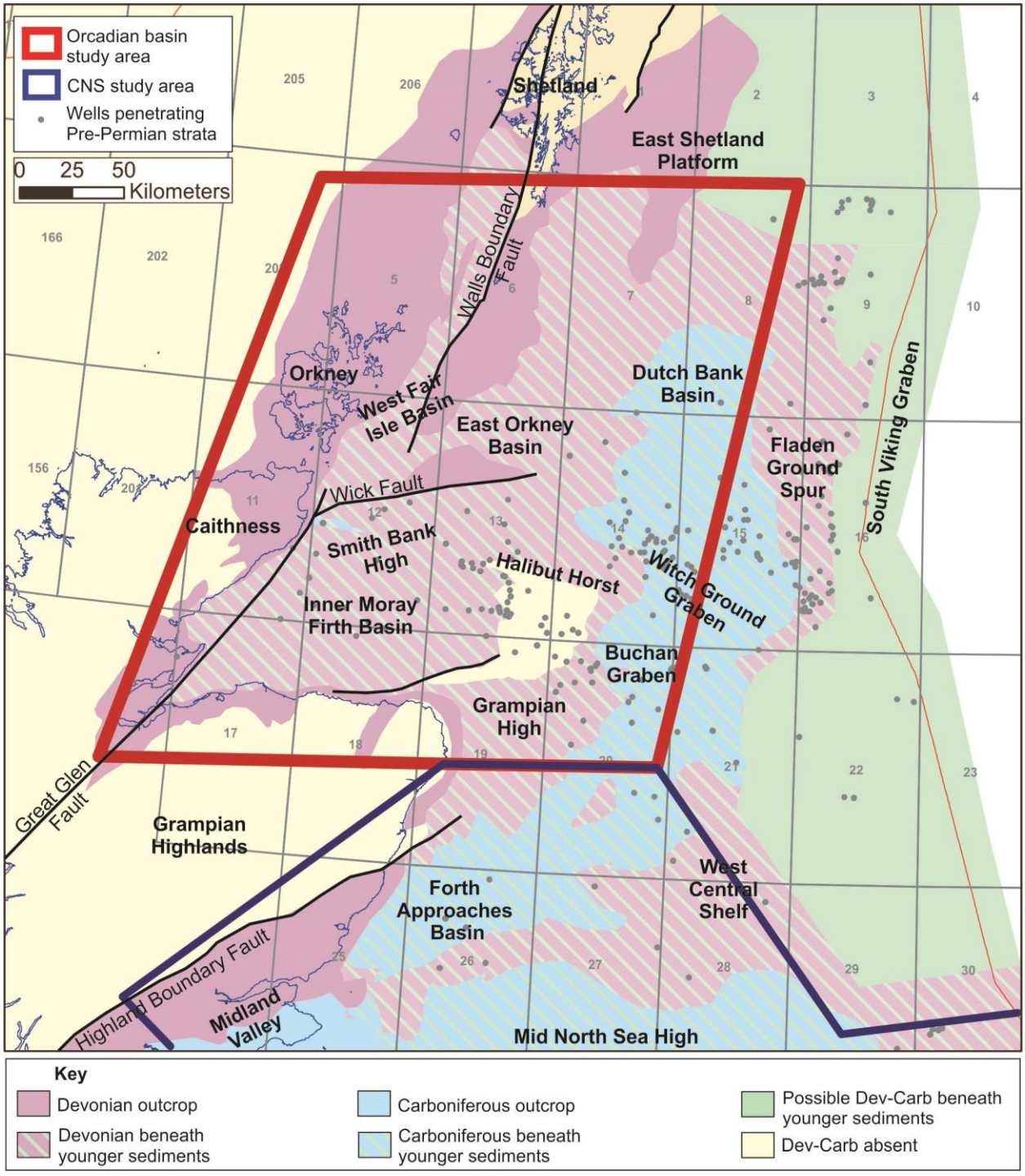


Figure 1 – The Orcadian study area (in red) and the distribution of Pre-Permian strata.

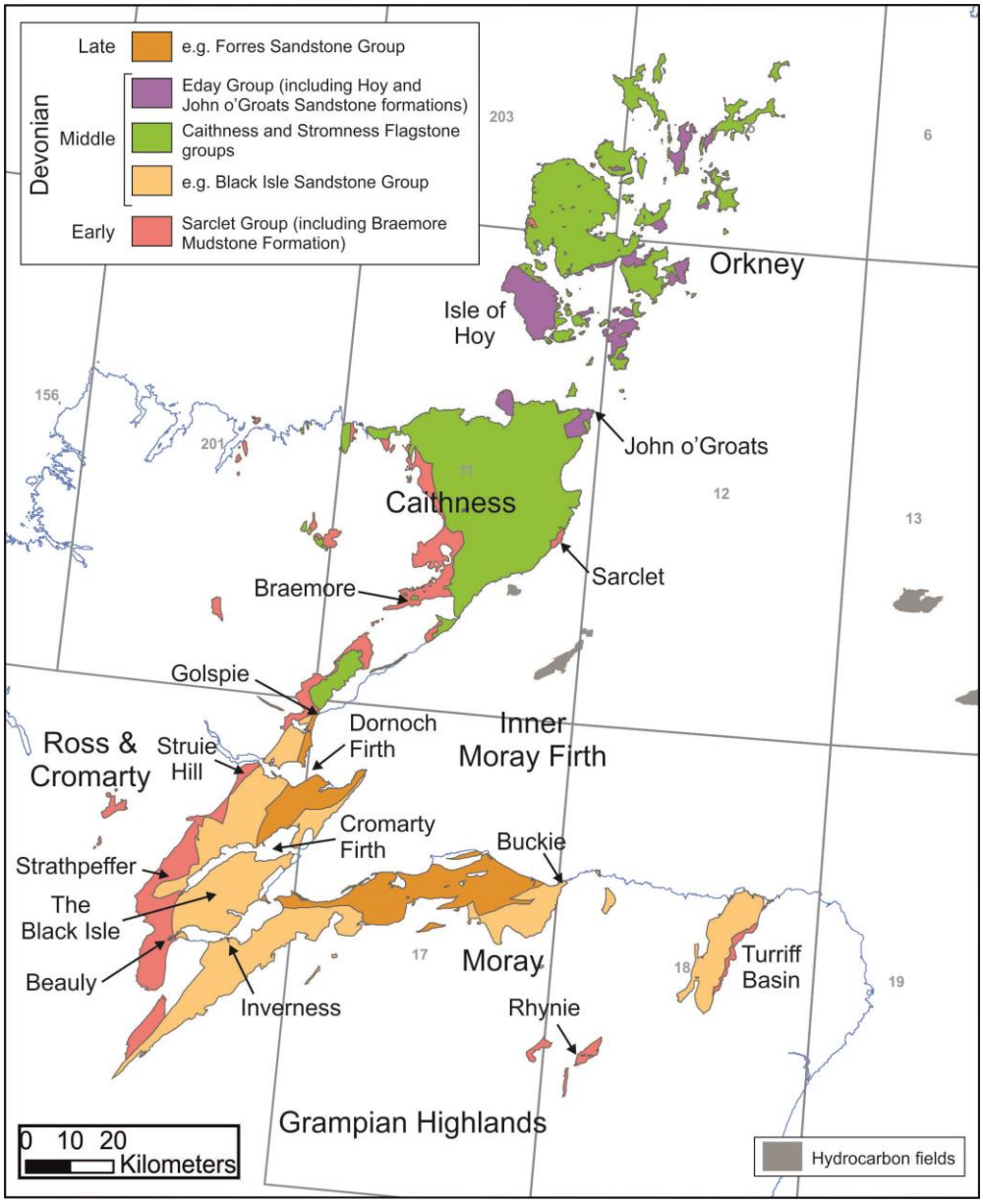


Figure 2 – Summary map of onshore Devonian strata in the Moray Firth region and Orkney showing locations of onshore sites mentioned in the text.

1.1 DATA AND WORKFLOW

More than 320 wells have penetrated Devonian and Carboniferous rocks in Quadrants 7 – 22 (Figure 3). The distribution of wells is uneven, with very few located in the northern part of the study area, and a very sparse distribution in Quadrants 21 – 23 and in the southern half of Quadrant 20.

Only four wells, all located within the Inner Moray Firth Basin (Quadrants 12 and 13), penetrate a full thickness of Devonian strata to basement (12/23- 1, 11/30a- 10, 12/29- 2 and 13/19- 2). Elsewhere variable lengths of Devonian-Carboniferous successions have been proved, and penetrations in Quadrants 14 – 15 and 20 – 22 are typically less than 600 m.

Previous interpretations of the Devonian successions provided in completion reports typically assign the strata to broad chronostratigraphic epochs (Lower, Middle or Upper Devonian) on the basis of regional correlations, and palynological constraints where available. In this study, these assignments were reassessed in light of the stratigraphic framework, available biostratigraphical

reports held in BGS records, published papers, and through consideration of the regional seismic interpretations undertaken in this project (Arsenikos et al., 2016).

For 92 selected wells, revised stratigraphic picks for formation top and bases were compiled. The target wells were selected on the basis of the length of the succession, the quality of the wireline and biostratigraphical data, significance for seismic ties, and importance with regard to regional stratigraphic relationships. The revision of the stratigraphic assignments was based on assessment of composite logs, wireline geophysical logs (mainly gamma, calliper, sonic, neutron porosity and density), biostratigraphical and petrographical reports, and core photographs. Full suites of wireline logs and biostratigraphy were unavailable for some wells.

Six correlation panels were constructed using 43 of the reassigned wells to illustrate the regional stratigraphic relationships, and highlight key ties with seismic data (Figure 3). These panels are presented in figures 19 to 24.

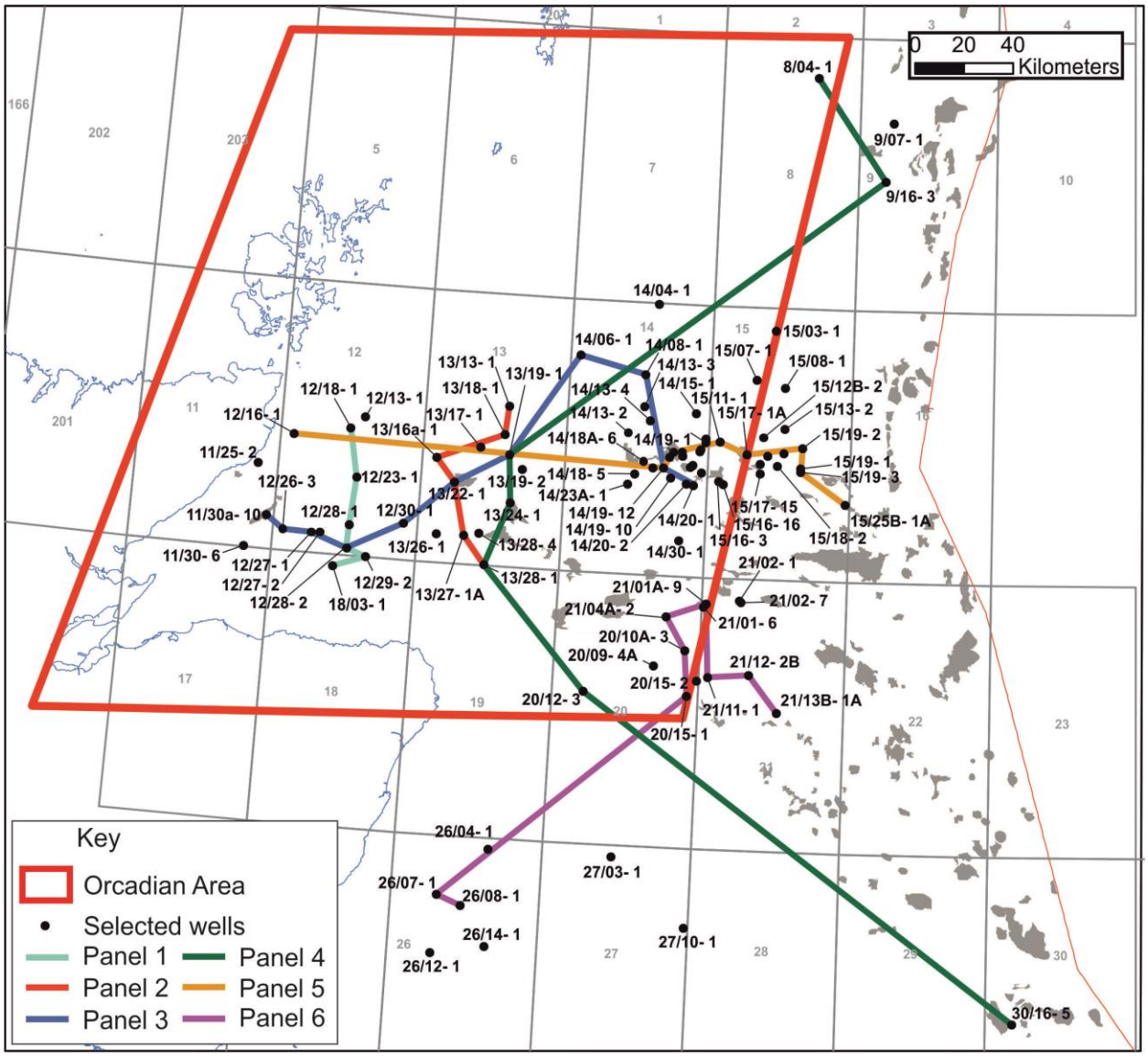


Figure 3 – Selected wells and correlation panel lines within the Orcadian Basin study area and extension to the south into the Central North Sea area.

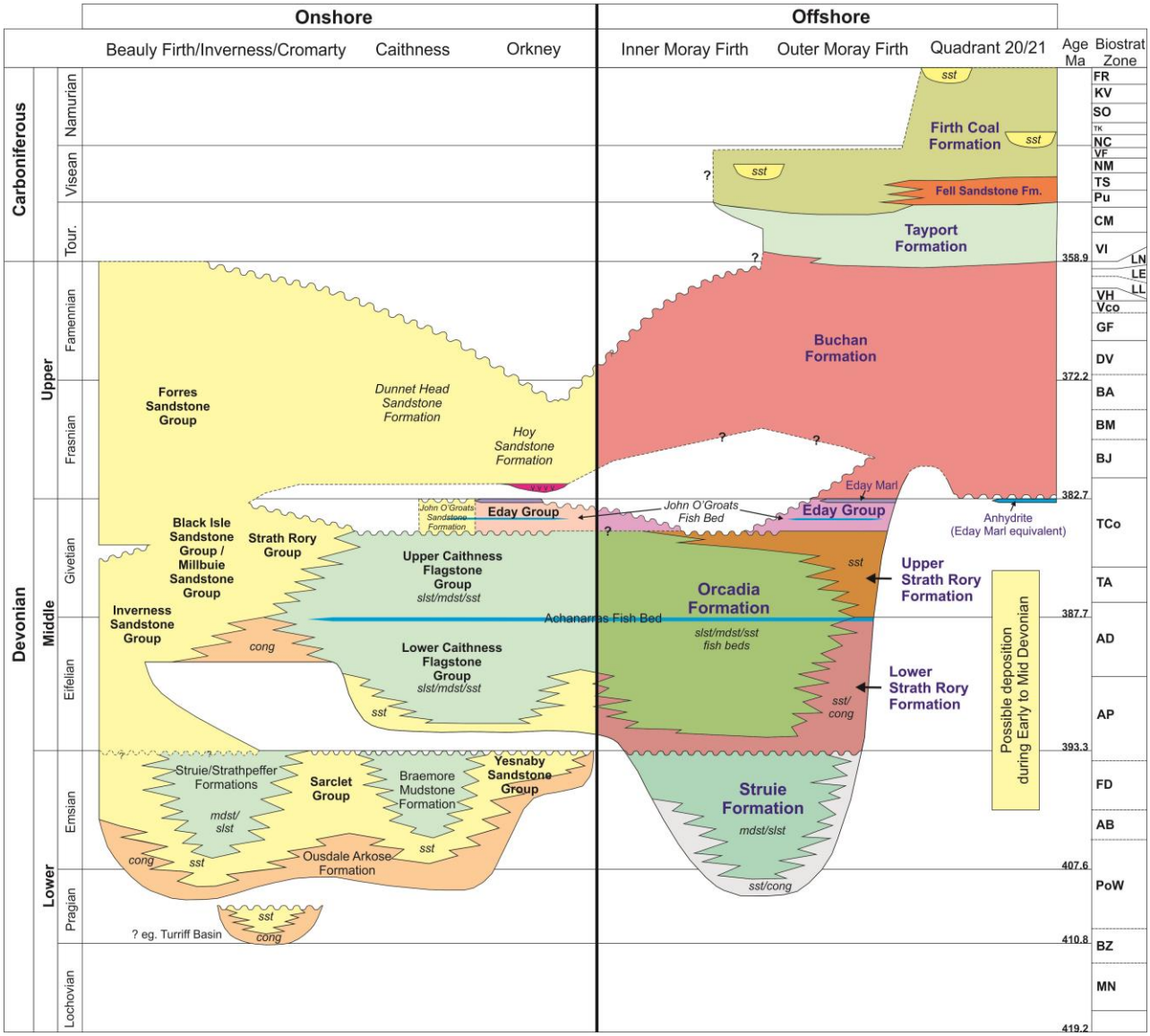


Figure 4 – Stratigraphic relationships of Devonian and Carboniferous strata in the onshore and offshore regions of the Orcadian area. The main elements of the stratigraphy of the offshore Devonian strata are as defined by Marshall and Hewett (2003).

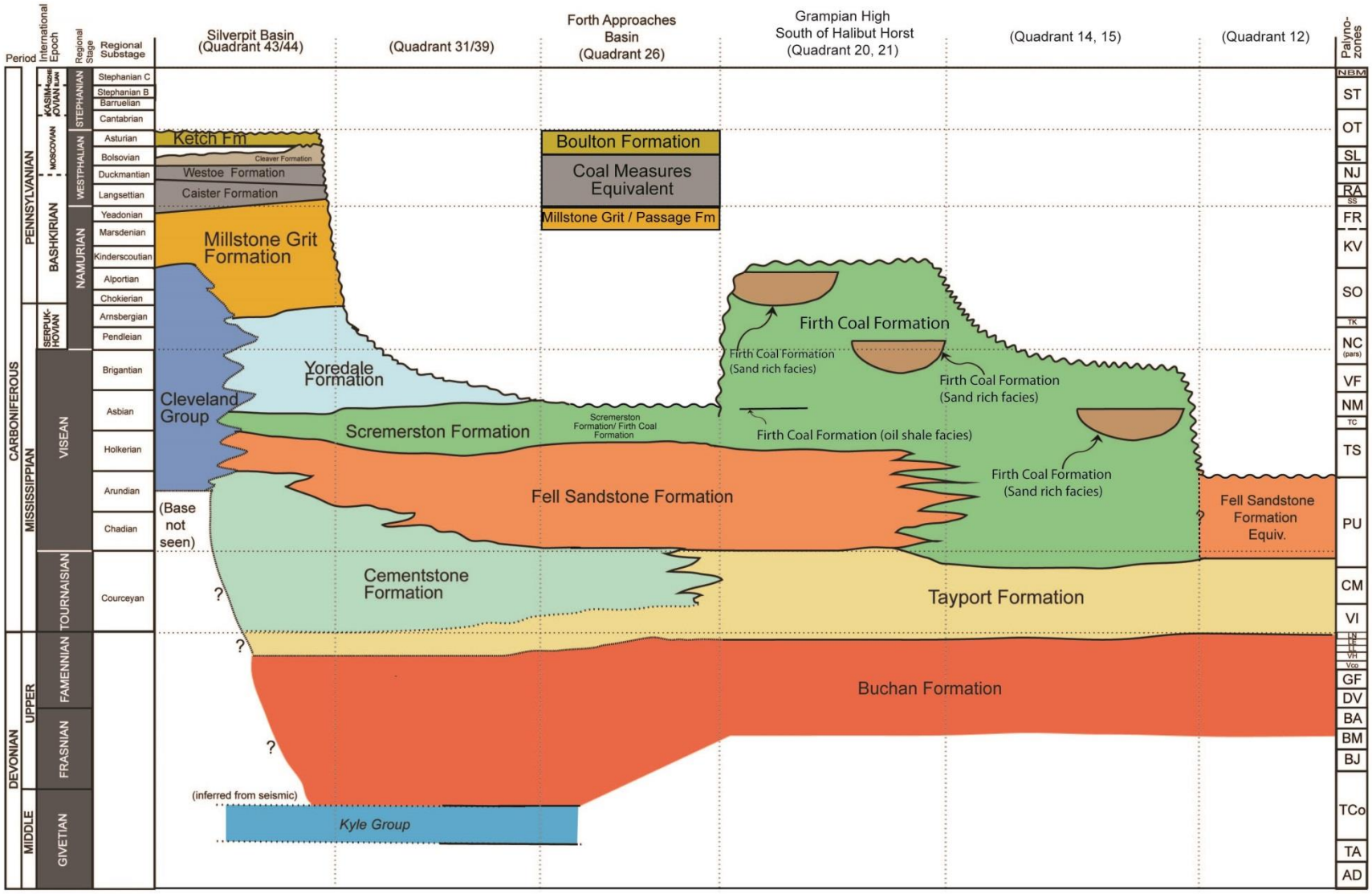


Figure 5 – Stratigraphic relationship of Late Devonian to Early Carboniferous strata between the Orcadian area and the Central North Sea.

1.2 CHRONOSTRATIGRAPHY AND BIOSTRATIGRAPHY

The most recent global chronostratigraphic framework for the Devonian is provided by Becker et al. (2012). Regional correlation of the onshore Devonian successions of the Orcadian area is largely based on fish fossil assemblages (e.g. Trewin and Thirlwall, 2002). Regionally important stratigraphic horizons include the Achanarras Fish Bed of Eifelian to early Givetian age, which is equivalent to the Sandwick Fish Bed of Orkney (cf. Marshall et al., 2007), and the John o'Groats Fish Bed of mid to late Givetian age, which is correlated with the Eday Flagstone Formation of Orkney (Figure 4).

The offshore chronostratigraphy of the Devonian strata has been established using palynomorph zonations, following the schemes of Richardson and McGregor (1986), Streel et al. (1987) and Streel (2009). Substantial parts of the Devonian succession comprise coarse clastic sediments deposited in arid terrestrial environments and consequently have limited palynological age constraint. The lacustrine sediments of Lower to Middle Devonian age are typically better constrained by biostratigraphic data. The main fish bed horizons are associated with characteristic palynomorph assemblages (e.g. Marshall et al., 1996; Marshall and Fletcher, 2002) and these horizons provide important regional stratigraphic constraints (Marshall and Hewett, 2003).

The biostratigraphic zonation for the Carboniferous strata of the Orcadian area is summarised in Waters et al. (2011), and is consistent with that used for the adjacent Central North Sea area (Kearsey et al., 2015). Palynomorph assemblages are commonly reported for the coal bearing strata of the Firth Coal Formation and are also associated with fine-grained facies of the Fell Sandstone and Tayport Formations.

Several volcanic horizons occurring within the Palaeozoic strata of the Orcadian area have been dated using ^{40}Ar-^{39}Ar and K-Ar radiometric dating techniques (e.g. Halliday et al., 1977) but a wide range of numerical ages have been obtained. Therefore palynological constraints combined with stratigraphic considerations have been favoured (cf. Andrews et al., 1990; Marshall and Hewett, 2003).

The biostratigraphical reports available for wells assessed in this study vary in the date of completion, the amount and quality of the data, and the interpretation that they contain, resulting in uncertainty in the precise biostratigraphical age of parts of the sequence.

1.3 ACCOMPANYING DATA SETS

Along with the descriptions of the units in Section 2, the key wells are shown in a set of correlation panels (Section 3); these are also available as A0 PDFs. The lithostratigraphic picks described in this report are also available as an Excel™ spreadsheet.

2 Stratigraphic succession of the Orcadian Area

2.1 EARLY DEVONIAN

2.1.1 Struie Formation

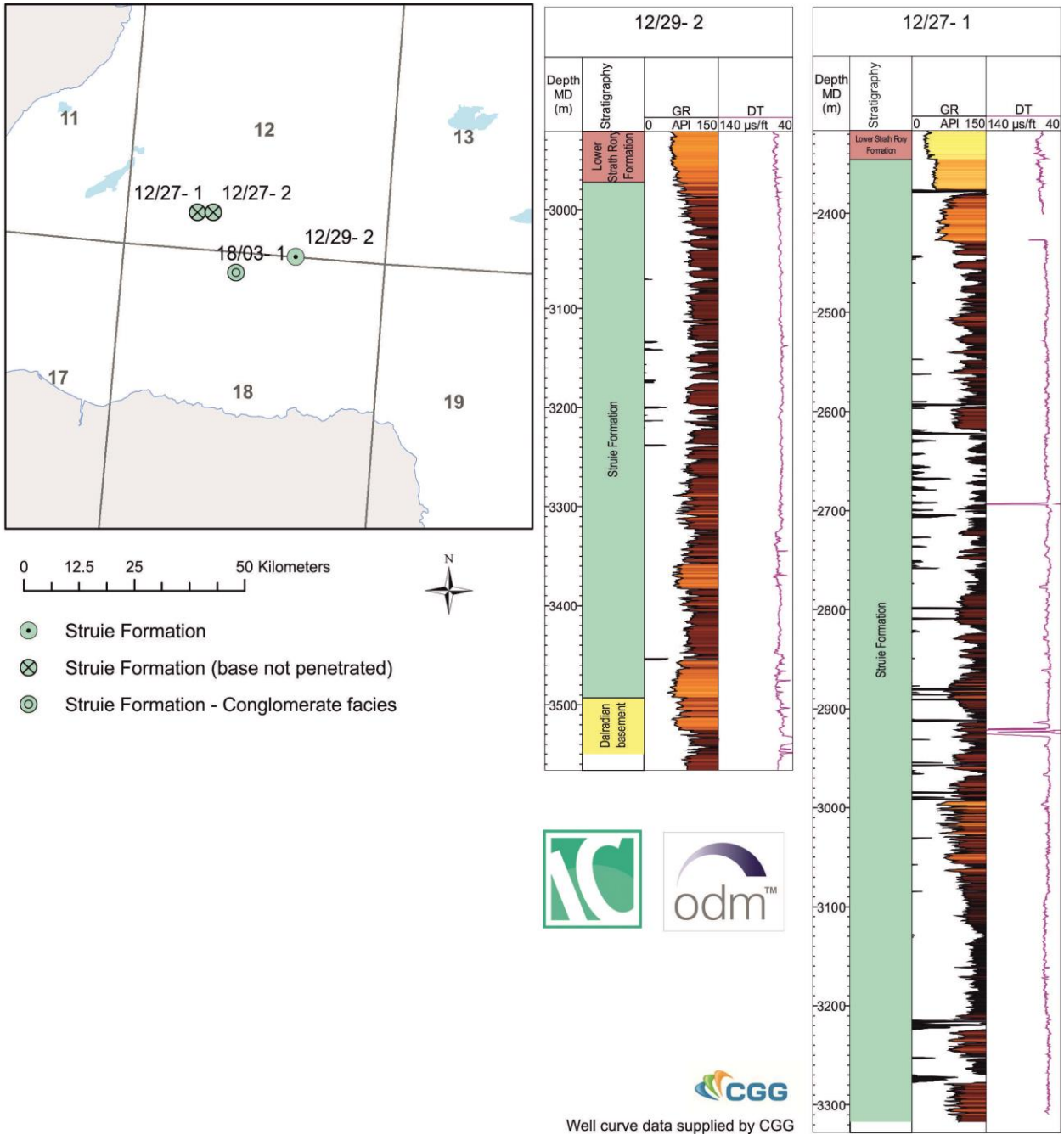


Figure 6 – Map showing the location of wells in which the Struie Formation has been interpreted and the key well profiles that illustrate the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Struie Formation was adopted by Cameron (1993) for lacustrine and alluvial strata of Early Devonian age in the central and northern North Sea.

Geographical extent

Lacustrine and alluvial rocks of the Struie Formation occur onshore in the Strathpeffer area of Ross and Cromarty, and have been proved in a small number of wells in the Inner Moray Forth Basin where it reaches approximately 970 m in thickness (Richards, 1985a; Marshall and Hewett, 2003).

The Struie Formation is absent over the Smith Bank High and wells in this area prove strata of Middle Devonian age directly overlying metamorphic or granitic basement (e.g. wells 11/30a- 10 and 12/23- 1). Elsewhere in the Orcadian area, wells terminate in younger strata and the Struie Formation has not been proved.

Previous assignments of strata in wells 12/28- 2 and 13/19-1 to the Struie Formation (Andrews et al., 1990; Cameron, 1993) were subsequently reassigned by Marshall and Hewett (2003) to Middle Devonian formations on the basis of palynological constraints.

Lithology

Where encountered in wells, the Struie Formation predominantly comprises dark grey, reddish brown, and occasionally black, micaceous siltstone and claystone. The strata are locally intercalated with thin dolostone and limestone beds, and sparse, fine-grained, calcareous sandstones (Richards, 1985a; Andrews et al., 1990; Marshall and Hewett, 2003). Coarse-grained facies including sandstone and conglomerate are present within the base of the Struie Formation (well 12/29- 2) and near the basin margins (well 18/3- 1).

Ripple laminae and minor slump structures have been observed in the siltstones (Richards, 1985a), indicating deposition of the strata on distal outwash plains and playa with shallow, ephemeral lakes (e.g. Trewin and Thirlwall, 2002; Marshall and Hewett, 2003). A tendency for increasing sandstone content in the top 40 – 80 m of the Struie Formation is indicative of more widespread fluvial activity developing in the latter part of the Early Devonian.

Approximately 400 m of organic rich claystones and siltstones are present within the onshore equivalent of the Struie Formation, the Braemore Mudstone Formation, in the vicinity of Beauly and Strathpeffer (Trewin and Thirlwall, 2002). Along the onshore basin margins west of Beauly, Golspie and northwards into Caithness, Lower Devonian strata are typically dominated by sandstone and conglomerate of the Ousdale Arkose Formation (Figures 2 and 4).

Key Wells

The top and base of the Struie Formation are seen in well 12/29- 2, where 520 m of lacustrine strata overly basement and are overlain by fluvial sandstones of Middle Devonian age (Figure 6). A thick section of Struie Formation (over 976 m) is also seen in well 12/27- 1 but the base of the unit is not proved in this well (Figure 6).

Lower boundary

The Struie Formation overlies metamorphic or granitic basement in well 12/29- 2. Onshore equivalent units may be directly underlain by metamorphic basement rocks, or by sandstone or conglomerate of Early Devonian age (the Ousdale Arkose Formation).

Upper boundary

The Struie Formation is overlain by sandstone and conglomerate of the Lower Strath Rory Formation.

Age

The Struie Formation has been palynologically dated as Pragian to Emsian in age (Marshall and Hewett, 2003). The age of the unit is proved biostratigraphically in wells 12/27- 1 (Richards, 1985a) and 12/29- 2 (Braham et al., 1985)

Correlation with Onshore UK

The Struie Formation is considered to be equivalent to the Braemore Mudstone Formation (Sarclet Group) exposed onshore between Braemore in Caithness in the north, Struie Hill in Cromarty and Strathpeffer to the south (cf. Trewin and Thirlwall, 2002; Clarke and Parnell, 1999). Elsewhere, onshore strata of Early Devonian age are represented by the coarse clastic deposits of the Ousdale Arkose Formation. The Struie Formation in the southern parts of Quadrant 12 may be associated with fluvial sandstones exposed onshore in the Turriff Basin to the south (Richards, 1985a).

Associated correlation panels

Wells showing the Struie Formation and relationship with overlying Middle Devonian strata are shown in the correlation panels in Figures 19 and 21 and the extent/facies shown on Figure 25.

2.2 MIDDLE DEVONIAN – ORCADIAN LAKE AND MARGINAL STRATA

2.2.1 Strath Rory Formation

Name

The term Strath Rory Formation was adopted by Cameron (1993) for sandstone and conglomerate dominated strata associated with alluvial fan deposition along the margins of the Middle Devonian Orcadian lake. Cameron (1993) presents the Strath Rory Formation as the lateral (proximal) equivalent of the lacustrine strata of the Orcadia Formation. However, this interpretation has been modified by Marshall and Hewett (2003) who use informal ‘lower’ and ‘upper’ divisions of the Strath Rory Formation to distinguish sandstone successions occurring both above and below the Orcadia Formation in the Inner Moray Firth area (cf. Figure 4). This model accommodates both lateral and vertical transitions between lacustrine and alluvial deposition that reflect the advance and retreat of alluvial fans and marginal fluvial systems relative to the Orcadian lake margin. Although considered informal by Marshall and Hewett (2003), the upper and lower designations for the Strath Rory Formation provide a more consistent basis for interpreting the wells in the Inner Moray Firth, and have been used in this study.

Geographical extent

Alluvial-fan and fluvial strata of the Strath Rory Formation are widespread in the Inner Moray Firth basin, with onshore equivalent strata occurring along the Moray coast, east of Inverness, on the Black Isle and between the Cromarty and Dornoch Firths. The most easterly occurrence of the unit has been identified in well 13/24- 1 (Andrews et al., 1990; Cameron, 1993).

The Lower Strath Rory Formation is present in the southern half of Quadrant 12 and eastwards into block 13/24. The unit is relatively thin along the basin margin and over the Smith Bank High, where it ranges from c. 100 to 300 m in thickness, but exceeds 1000 m in centre of the Inner Moray Firth Basin.

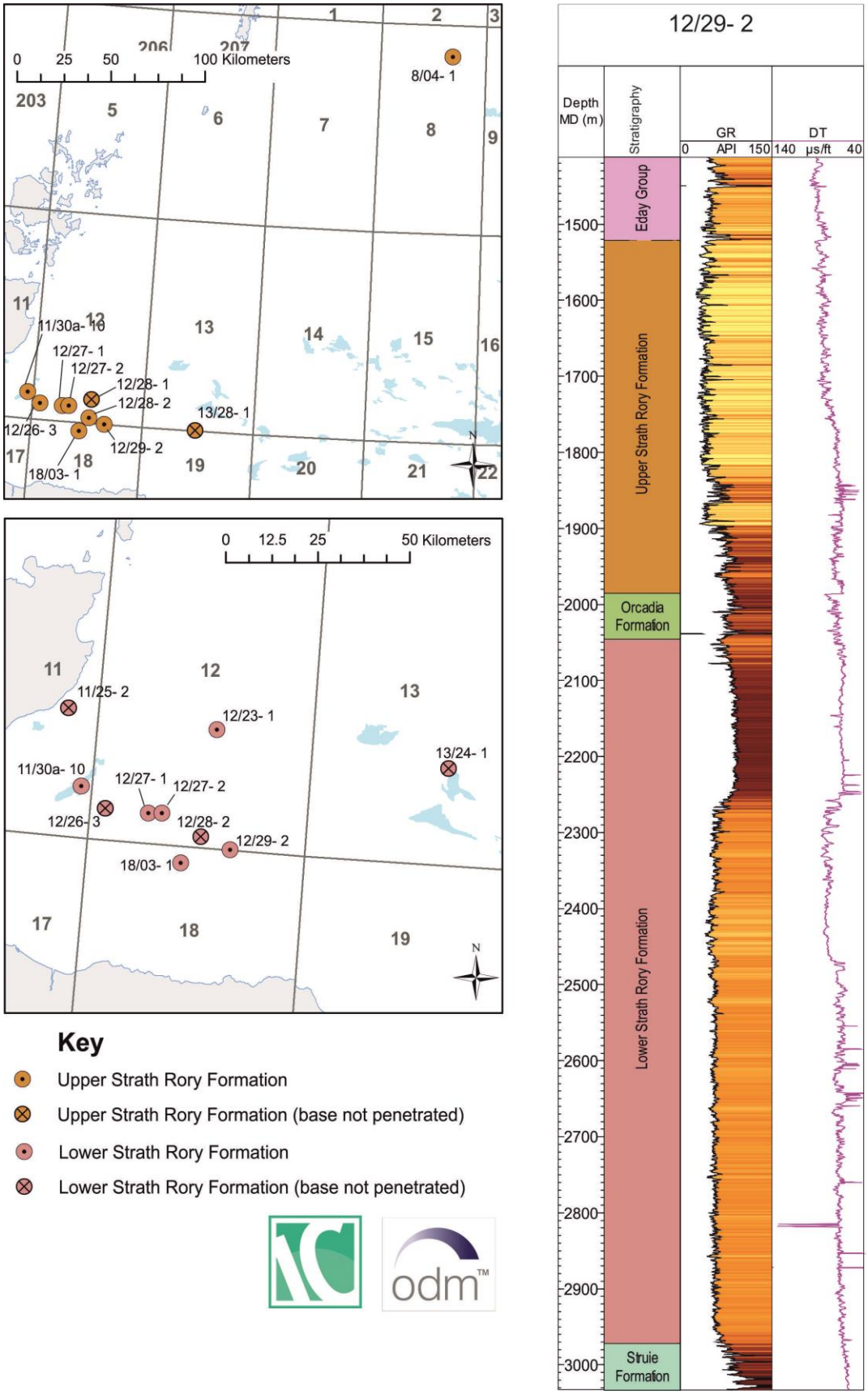


Figure 7 - Map showing the location of wells in which the Strath Rory Formation has been interpreted and the key well profile that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

The Upper Strath Rory Formation is encountered in wells in the very south of Quadrant 12 and eastwards into block 13/28. The unit also thickens into the centre of the Inner Moray Firth Basin, although the degree of thickening is lower than that for the Lower Strath Rory Formation; varying from less than 100 m to c. 460 m. In well 12/23- 1, drilled over the Smith Bank High, the Upper Strath Rory Formation was found to be absent, with the Orcadia Formation unconformably overlain by Permian strata.

Lithology

The Lower Strath Rory Formation comprises conglomerate, or locally breccia, where it has been penetrated in wells along the margins of the Inner Moray Firth Basin or on structural highs. Over the Smith Bank High, c. 150 m of conglomerate containing pebbles of quartz, granite and gneissic rocks, sandstone and sparse thin mudstone beds unconformably overlie metamorphosed basement in Inner Moray Firth wells 11/30a- 10 and 12/23- 1. On the south-east margin of the Inner Moray Firth basin, well 13/24- 1 penetrated c. 350 m of strata attributed to the Lower Strath Rory Formation comprising 100 m of breccia/conglomerate with granitic and gneissose clasts overlain by sandstone with sparse mudstone and siltstone beds (Andrews et al., 1990; Cameron, 1993).

In well 18/03- 1, in the centre of the Inner Moray Firth Basin, approximately 1030 m of conglomerate with some sandstone and pebbly sandstone has been proved. In the southern parts of Quadrant 12 and block 18/3, the largely conglomeratic sequence of the Lower Strath Rory Formation contains a sandstone unit up to 200 m thick, and notable for its high porosity, which can be correlated between wells 12/28- 2, 12/29-2 (around 2300 m on Figure 7) and 18/03- 1 (Marshall and Hewett, 2003)

The Upper Strath Rory Formation typically comprises medium to coarse-grained sandstone, interbedded in places with thin siltstone and claystone beds. The unit may contain sparse beds of pebbly sandstone or conglomerate in places. In well 12/29-2 the basal 50 m of strata assigned to the Upper Strath Rory Formation is composed of sandstone with numerous conglomerate beds containing clasts of quartzite and basic igneous rocks.

Key Wells

A complete section through the Lower and Upper Strath Rory Formation was penetrated in well 12/29- 2 (Figure 7). In this well, the upper and lower units of the Strath Rory Formation are separated by a thin development of the Orcadia Formation and the conformable base overlying the Struie Formation can be seen.

A complete, but somewhat thinner, section through the Strath Rory Formation can be seen in well 11/30a- 10, where the Lower Strath Rory Formation unconformably overlies metamorphic basement.

Lower and upper boundaries of the Lower Strath Rory Formation

The Lower Strath Rory Formation locally overlies strata of the Struie Formation in the centre of the Inner Moray Firth Basin (in wells 12/17- 2, 12/29- 2 and 18/03- 1), and onlaps metamorphosed basement along structural highs at the basin margins (wells 12/23- 1 and 11/30a- 10, located on the Smith Bank High).

The Lower Strath Rory Formation is overlain by lacustrine strata of the Orcadia Formation. In basin marginal areas, the top of the formation is taken at the base of the lowermost siltstone or claystone bed associated with the Achanarras Fish Horizon where this can be recognized within the sandstone dominated succession (e.g. well 12/27- 2; cf. Marshall and Hewett, 2003). In well

12/23- 1, a volcanic horizon occurs between the Lower Strath Rory Formation and the base of the overlying Orcadia Formation (Marshall and Hewett, 2003). In well 13/24- 1, 330 m of conglomerate interpreted as the Lower Strath Rory Formation is unconformably overlain by strata of Early Cretaceous age.

Lower and Upper boundaries of the Upper Strath Rory Formation

Following Marshall and Hewett (2003), the base of the Upper Strath Rory Formation is taken at the top of the cyclic sequence of fine-grained lacustrine strata of the Orcadia Formation. Along the basin margins where the Orcadia Formation is restricted to the thin bed(s) associated Achanarras Fish Horizon, the base of the Upper Strath Rory Formation is taken as the top of the uppermost claystone/siltstone horizon associated with the fish beds (e.g. well 12/27– 2; cf. Marshall and Hewett, 2003).

In the Inner Moray Firth Basin, the Upper Strath Rory Formation is overlain by sandstone-dominated strata assigned to the Eday Group (cf. wells 12/26- 3 and 12/29- 2; Marshall and Hewett, 2003). As both of these units comprise sandstone dominated strata, the contact is difficult to constrain, however the presence of strata of Eday Group age is indicated by a mudstone horizon interpreted as the John o'Groats Fish Bed. The top of the Upper Strath Rory Formation is taken at a minor log break identified by a slight decrease in gamma and decrease in sonic velocity below the gamma ray spike associated with the fish bed (e.g. wells 18/-3- 1 and 12/29- 2).

Elsewhere the upper Strath Rory Formation is unconformably overlain by the Upper Devonian Buchan Formation (wells 12/27- 2 and 11/30A- 10) or by Permian strata (12/27- 1). The contacts are typically defined by a log break, with the higher units distinguished by higher proportions of mudstone and siltstone (e.g. well 11/30A- 10).

Age

The sandstone and conglomerate strata of the Strath Rory Formation are typically barren of palynomorphs and the age is therefore poorly constrained. Marshall and Hewett (2003) indicate a late Emsian to Eifelian age is likely due to the stratigraphic relationship with the Struie Formation and Orcadia Formation. Cameron (1993) suggests a broader age range of Eifelian to Givetian. The association of the Upper and Lower Strath Rory Formations with the Orcadia Formation, which has a Givetian age, is consistent with an age range of late Emsian to Givetian.

Correlation with onshore UK

Onshore equivalents of the Strath Rory Formation occur in the region of Ross and Cromarty. These include the Millbuie Sandstone Group and the Black Isle Sandstone Group, the latter incorporates conglomerate and sandstone units that were formerly known as the Strath Rory Group.

Associated correlation panels

The relationship of the Strath Rory Formation with surrounding strata is shown in the well correlation panels in figures 19 and 21.

2.2.2 Orcadia Formation

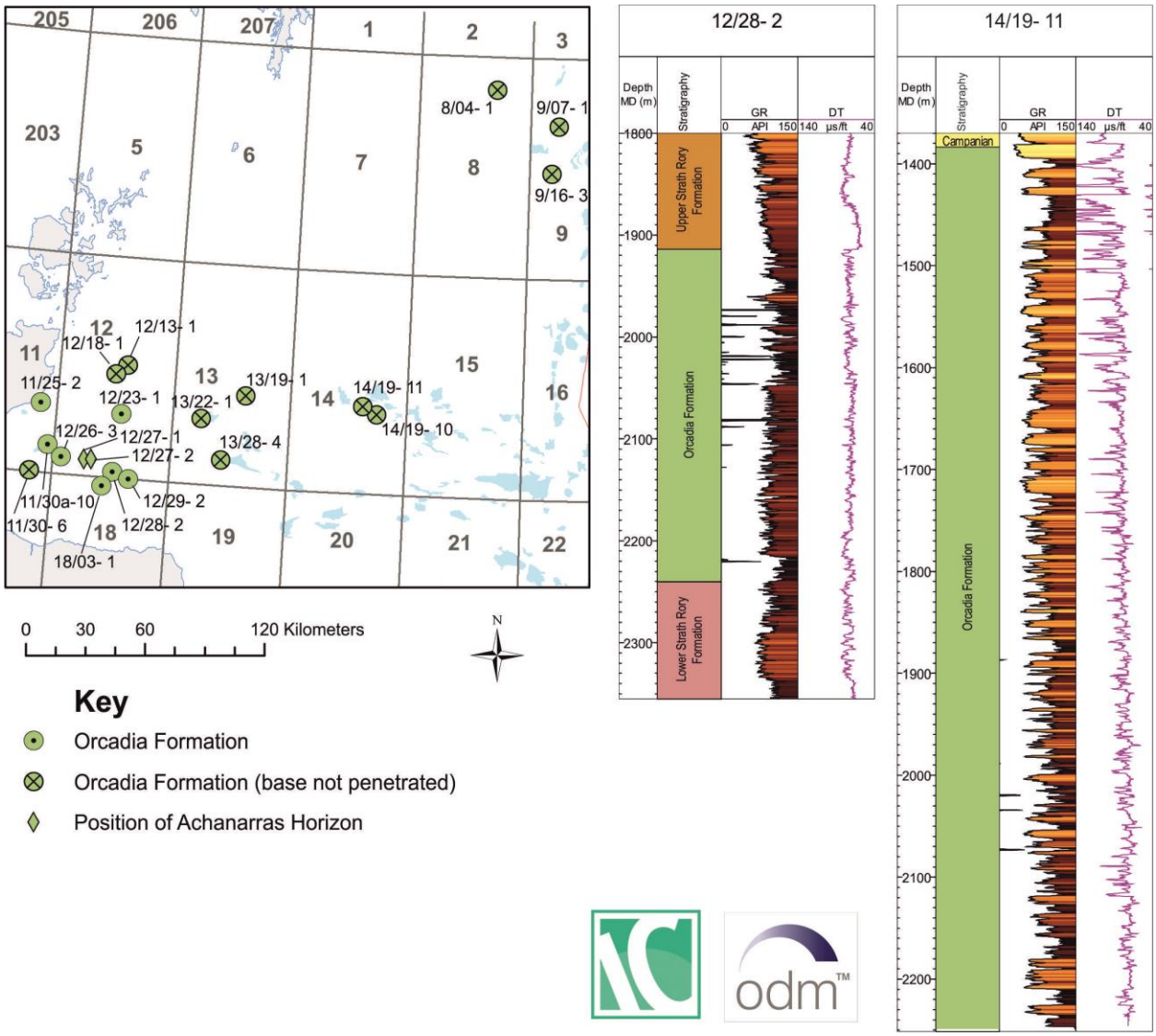


Figure 8 - Map showing the location of wells in which the Orcadia Formation has been interpreted and the key well profiles that illustrate the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The Orcadia Formation was introduced by Cameron (1993) for the lacustrine and fluvial strata of Middle Devonian age, deposited with the Orcadian basin area of the central and northern sectors of the UK North Sea.

Geographical extent

Lacustrine strata of Middle Devonian age assigned to the Orcadia Formation are encountered in wells throughout the Inner Moray Firth Basin, and to the north and south of the Halibut Horst (Quadrant 14; Figure 8, see also Arsenikos et al., 2016). Onshore equivalent strata of the Caithness Flagstone and Stromness Flagstone groups crop out in northern Caithness and on Orkney. The Orcadia Formation has been proved as far east as the East Shetland Platform and the margin of the Central Viking Graben (Quadrants 8 and 9).

The thickness of the Orcadia Formation varies across the region. In the Inner Moray Firth area, the thickest sections of lacustrine strata (300 to over 600 m) are recorded in wells 11/25- 2,

12/18- 1 and 12/23- 1, the latter located on the Smith Bank High. The Orcadia Formation thins southwards towards the southern edge of Quadrant 12. The former lake margin has been interpreted in the region of block 13/23 by Andrews et al., (1990) and Cameron (1993). A cyclic sequence of claystone, siltstone and sandstone at least 870 m thick penetrated in well 14/19- 11 has been palynologically dated as Givetian age and assigned to the Orcadia Formation (Owens, 1986a, cf. Andrews et al., 1990; Figure 8). A lithologically similar but undated sequence also occurs in well 14/19- 10, together these wells indicate that a substantial thickness of lacustrine sediment was deposited during Orcadian lake times in the area now lying just to the north of the Halibut Horst.

Cameron (1993) records a cyclic siltstone – sandstone succession well 14/06- 1 as a type section of the Orcadia Formation, but Marshall et al. (1996) and Marshall and Hewett (2003) revise this assignment to the Buchan Formation (Late Devonian) on the basis of palynological dating yielding a latest Givetian to Frasnian age.

Onshore equivalents of the Orcadia Formation are up to 4000 m thick in Caithness and c. 900 m thick in Orkney (Trewin and Thirlwall, 2002). In the region of Inverness and the Beauly Firth, the Orcadia Formation is represented only by a thin claystone bed containing fish fossils that is regionally correlated with the Achanarras Fish Bed of Caithness. This horizon represents a major lacustrine high-stand that transgressed widely across the basin margin.

Strata referred to the Orcadia Formation also occur in wells 9/07- 1, 8/04- 1 and 9/16- 3 (Cameron, 1993; Duncan and Buxton, 1995; Marshall and Hewett, 2003). In the latter two wells, the Orcadia Formation is overlain by strata assigned to the Eday Group.

Lithology

The Orcadia Formation comprises a cyclic succession of laminated siltstone and claystone interbedded with fine-grained sandstone and sparse limestone or dolostone (Andrews and Hartley, 2015; Astin, 1990; Donovan, 1980; Trewin and Thirlwall, 2002). The laminated siltstones, formed during periods of deep lake development, are commonly dark and organic rich or lighter grey and calcareous. Siltstone and sandstone facies, commonly associated with ripple and current laminations, and desiccation cracks, represent playa and lake marginal environments (e.g. Andrews and Hartley, 2015; Astin, 1990; Donovan, 1980). The proportion of sandstone within the lacustrine succession increases towards the marginal areas of the lake and, in these areas, the sandstone may be locally medium to coarse-grained.

The cyclic lacustrine facies have been interpreted to reflect climatic changes (Donovan, 1980), which have been associated with orbital cyclicity, particularly the precession (~20 ka) and eccentricity (~100 ka) cycles (Andrews et al. 2016; Astin, 1990; Kelly, 1992)

The organic rich, laminated claystone and siltstone horizons associated with the deep lake facies commonly bare characteristic fish fossil assemblages which have been widely correlated in onshore sections. Frequently referred to as fish beds, these horizons are associated with high gamma-ray counts and give rise to spiky gamma-ray logs in offshore wells (Marshall and Hewett, 2003). The most prominent fish bed within the Orcadia Formation and onshore equivalent strata is the Achanarras horizon (or the Sandwick Fish Bed of Orkney).

In addition to its widespread occurrence onshore, the Achanarras horizon has been recognised widely in offshore wells on the basis of palynological associations and log responses (Marshall et al., 2007; Marshall and Hewett, 2003). The Achanarras Fish Bed is associated with a regional transgression of the Orcadian lake and onlap of lacustrine strata over the marginal fluvial succession (e.g. Marshall at al., 2007; Trewin and Thirlwall, 2002). Thus, in marginal areas the Orcadia Formation may be represented only by the presence of the fish-bearing claystone and siltstone bed of the Achanarras horizon within a thick sandstone succession.

Key Wells

The conformable top and base of the Orcadia Formation with the underlying Lower Strath Rory Formation and overlying Upper Strath Rory Formation is proved in well 12/28- 2 (Figure 8). Well 14/19- 11 contains at least 870 m of cyclic siltstone and sandstone strata considered to be Givetian in age (Owens, 1986a) and assigned to the Orcadia Formation. These strata are unconformably overlain by strata of Cretaceous age.

Lower boundary

The Orcadia Formation is conformably underlain by conglomerate and sandstone of the Lower Strath Rory Formation. Along the Orcadian lake margin onshore in Caithness and over local highs within the basin, correlatives of the Orcadia Formation (the Caithness Flagstone and Stromness Flagstone groups) onlap Lower Devonian strata and pre-Devonian basement rocks.

Upper boundary

The Orcadia Formation is overlain by the Upper Strath Rory Formation in the southern parts of the Inner Moray Firth Basin. In the northern parts of Quadrant 12 and into Quadrant 13 the Orcadia Formation is overlain by strata of the Eday Group.

Age

The Orcadia Formation is Eifelian to Givetian in age; the age range is palynologically constrained in wells 12/13- 1, 12/28- 2, 12/29- 2, 14/19- 11 and 13/19- 1 (Braham et al., 1985; Church et al., 1976; Harding et al., 1984; GeoStrat, 1990; Owens, 1986a). The Achanarras Fish Bed has been palynologically constrained in wells 12/29- 2 (cf. Braham et al., 1985; Marshall and Hewett, 2003).

Correlation with onshore UK

The onshore equivalents of the Orcadia Formation are the Stromness Flagstone Group of Orkney and the Caithness Flagstone Group in northern Caithness.

Associated correlation panels

The relationship of the Orcadia Formation with surrounding strata is shown in the well correlation panels in Figures 19 and 21 and the extent shown on Figure 26.

2.3 MIDDLE DEVONIAN – EDAY GROUP

There are spatial variations in the nature of the Eday Group across the region (Figure 9). In eastern Orkney and offshore throughout much of Quadrant 13, the group comprises a series of thin but distinctive formations including (from base to top): Lower Eday Sandstone Formation, the Eday Flagstone Formation, the Middle Eday Sandstone Formation and the Eday Marl Formation (Marshall and Hewett, 2003).

To the west of the exposures on Orkney, a marginal sandstone-dominated facies of the Eday Group is recognised, known onshore in Caithness as the John o'Groats Sandstone Formation (cf. Trewin and Thirlwall, 2002). The John o'Groats Fish Bed occurs within this sandstone unit and has been regionally correlated with the lacustrine succession of the Eday Flagstone Formation (Trewin and Thirlwall, 2002); the fish bed is considered to be associated with a high-stand stage of the 'Eday lake' (Marshall and Hewett, 2003).

The John o'Groats Fish Bed has been recognised in several offshore wells in the Inner Moray Firth Basin, where it occurs as a high gamma spike within sandstone-dominated strata stratigraphically overlying the Orcadia Formation and has similar palynology to the Eday Flagstone Formation (e.g. well 12/29- 2; Marshall and Hewett, 2003). The distinct palynological assemblage of the Eday Flagstone Formation and the John o'Groats Fish Bed indicate that they are associated with a separate period of lake development after the deposition of the earlier Orcadian Lake (Marshall and Hewett, 2003; Trewin and Thirlwall, 2002).

A summary of the stratigraphy of the Eday Group used in this study is given in Figure 9. Where associated with the John o'Groats Fish Bed, the sandstone-dominated strata of mid Givetian to Frasnian age are not accorded a distinct formation name offshore, but are referred to as the "Eday Group" (e.g. well 12/29- 2, Figure 19). In these successions, the top and base of the Eday Group are typically difficult to distinguish from the underlying Strath Rory Formation and overlying Buchan Formation (e.g. well 12/26- 3, Figure 21). The top and base of the unit have been tentatively assigned in relation to minor variations in the characteristics of the gamma-ray and sonic logs.

In wells where the John o'Groats Fish Bed has not been identified within sandstone-dominated strata, the Eday Group has not been assigned. In these wells, the sandstone succession between the Orcadia Formation (or the Achanarras Fish Bed) and the Upper Devonian Buchan Formation or Permian unconformity are tentatively assigned to the Upper Strath Rory Formation (e.g. wells 12/27- 1 and 12/27- 2, cf. Figure 21).

On the Isle of Hoy in Orkney, Eday Group strata are locally absent, having been removed by erosion. In this area volcanic rocks of the Hoy Volcanic Formation, considered to be of Givetian age (Marshall and Hewett, 2003; Trewin and Thirlwall, 2002), are interbedded between the Lower Eday Sandstone and the Hoy Sandstone Formation (Frasnian age), which is an onshore correlative of the Buchan Formation.

The marl facies of the Eday Group, along with the Kyle Limestone of the Central North Sea, and anhydrites considered to be correlatives of these units, are all associated with strong seismic reflectors, providing an important, regional scale, Middle Devonian marker horizon (Arsenikos et al., 2016). Marshall et al. (1996) and Marshall and Hewett (2003) consider these units to represent a range of marginal marine facies formed during a major marine transgression in Late Givetian times.

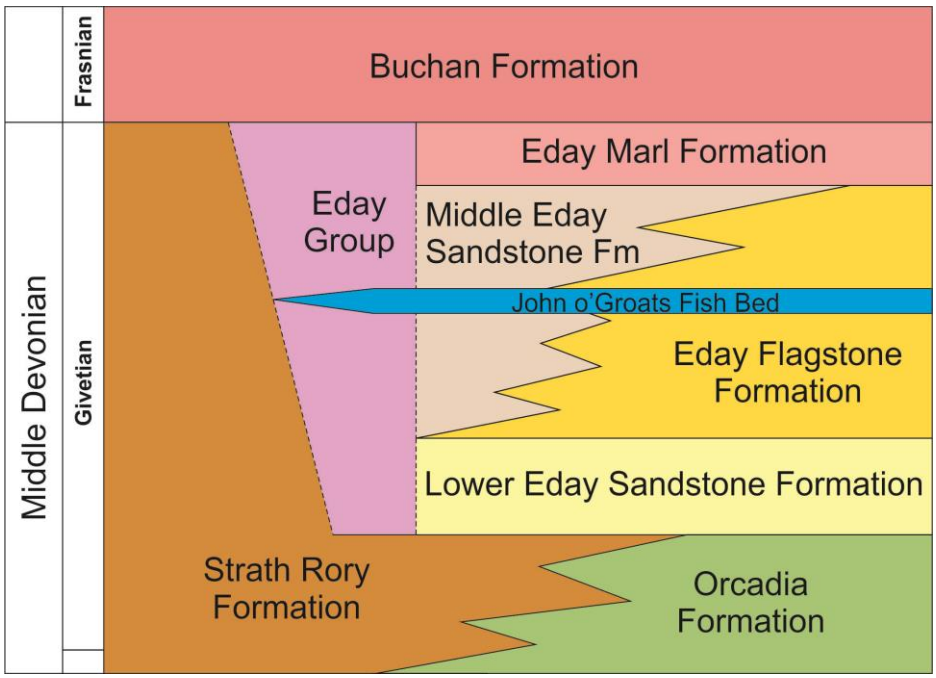


Figure 9 – Stratigraphic summary of the formations within the Eday Group

2.3.1 Lower Eday Sandstone Formation

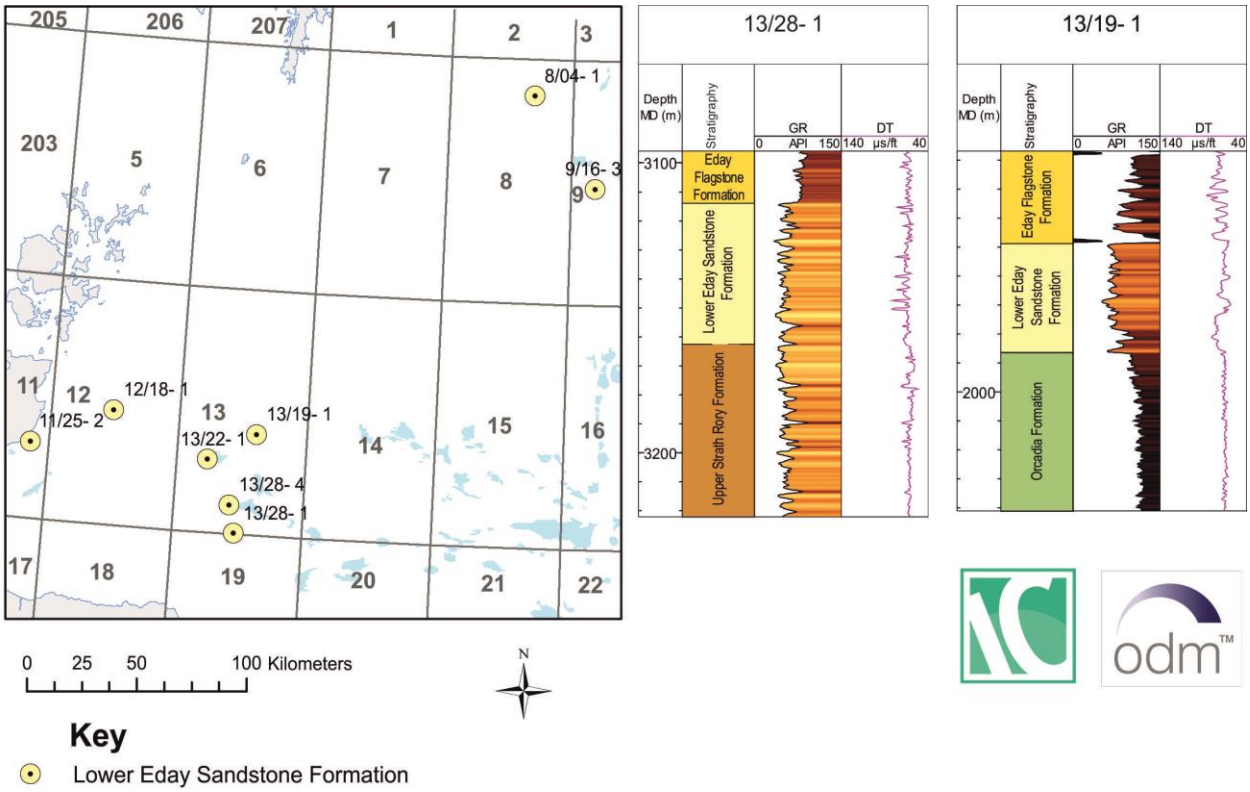


Figure 10 - Map showing the location of wells in which the Lower Eday Sandstone Formation has been interpreted and the key well profiles that illustrate the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Lower Eday Sandstone Formation has been applied onshore to the lowermost sandstone of the Eday Group in Orkney (e.g. Mykura, 1976; Astin, 1985; Trewin and Thirlwall, 2002). The name was used by Marshall and Hewett (2003) to refer to a sandstone unit separating the two intervals of lacustrine sediments that can be distinguished in wells in the north-eastern sector of the of the Inner Moray Firth Basin; the Orcadia Formation (below) and the Eday Flagstone Formation (above).

Geographical extent

The Lower Eday Sandstone Formation is found onshore in Orkney, where its thickness varies from 35 m to 170 m (Astin, 1985). The unit occurs in wells throughout Quadrant 13 and in the northern half of Quadrant 12, where it varies in thickness between 30 and 60 m. Sandstone units assigned to the Lower Eday Sandstone Formation also occur in wells 8/04- 1 and 9/16- 3, the former lies between two units of lacustrine strata, and the latter occurs between an anhydrite bed associated with the Eday Marl Formation and palynologically constrained Orcadia Formation (Marshall and Hewett, 2003).

Lithology

The Lower Eday Sandstone Formation comprises very fine to medium-grained sandstone intercalated with some calcareous claystone and siltstone. Conglomerate or pebbly sandstone may occur locally within the unit. Astin (1985) describes a characteristic colour variation from

brown/green/grey sandstone in the lower part of the unit to white/cream/red sandstones in the upper part which is also observed in some offshore well sections (e.g. well 13/28- 4).

The development of the Lower Eday Sandstone between the lacustrine units of the Orcadian Formation and Eday Flagstone Formation has been associated with a period of shallower, ephemeral lake conditions during which fluvial systems advanced across the Orcadian lake bed and aeolian conditions developed (Astin, 1985; Trewin and Thirlwall, 2002). In the onshore type section on Orkney, the Lower Eday Sandstone Formation represents a transitional unit between the top of the Stromness Flagstone Group and the redevelopment of deeper lacustrine conditions during the deposition of the Eday Flagstone Formation (Astin, 1985).

Key Wells

Complete sections through the Lower Eday Sandstone Formation were penetrated in wells 13/19- 1 (Figure 10) and 13/22- 1; the lower and upper contacts with the Orcadia Formation and Eday Flagstone Formation respectively are seen in both wells. In well 13/28-1, the upper part of a sandstone sequence underlying the Eday Flagstone Formation is tentatively assigned to the Lower Eday Sandstone Formation on the basis of the log response as described below (Figure 10).

Lower boundary

The Lower Eday Sandstone Formation is underlain by the Orcadia Formation (e.g. wells 13/19- 1 and 13/22- 1) or the Upper Strath Rory Formation (e.g. well 13/28- 1). In the latter case, the contact between the two sandstone-dominated units is poorly defined, but has been taken at a minor log break associated with a slight downward increase in sonic velocity and decrease in neutron density in well 13/28- 1 (Figure 10).

Upper boundary

The top of the Lower Eday Sandstone Formation occurs at a lithological transition to the flagstones of the Eday Flagstone Formation.

Age

The Lower Eday Sandstone is mid Givetian age, defined by its stratigraphic relationship to the lacustrine units of the Orcadia Formation and the Eday Flagstone Formation. Palynological dating indicates the former has an Eifelian to early Givetian age, and the latter a mid to late Givetian age (cf. Marshall and Hewett, 2003).

Correlation with onshore UK

The Lower Eday Sandstone Formation crops out on Orkney, and the unit is age equivalent to strata of the John o'Groats Sandstone Formation of northern Caithness (Astin, 1985).

Associated correlation panels

The relationship between the Lower Eday Sandstone Formation and other Eday Group strata is shown in the well correlation panels in Figures 19, 20 and 21 and the extent and facies shown on Figure 27.

2.3.2 Eday Flagstone Formation

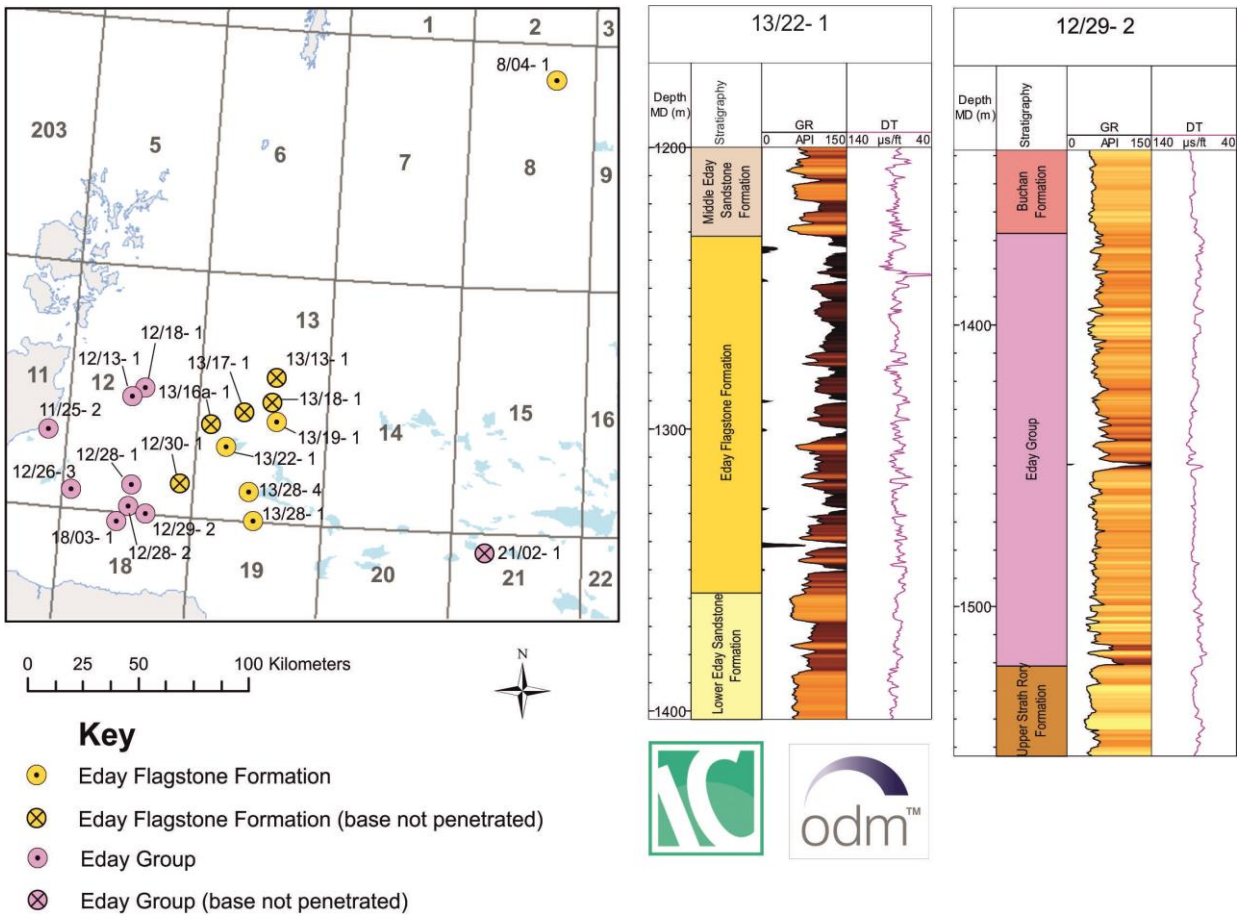


Figure 11 - Map showing the location of wells in which the Eday Flagstone Formation and Eday Group have been interpreted and the key well profiles that illustrate the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit. In well 12/29- 2, the John o'Groats Fish Bed, which is the basin marginal equivalent of the Eday Flagstone Formation, is represented by a high gamma spike at c. 1450 m associated with a thin claystone occurring within a sandstone dominated succession of the Eday Group.

Name

The term Eday Flagstone Formation has been given to a succession of lacustrine strata of Givetian age that occurs within the Eday Group onshore in Orkney (e.g. Astin, 1985; Mykura, 1976; Trewin and Thirlwall, 2002). The application of the name was extended to offshore areas by Marshall and Hewett (2003) to refer to strata of similar age and facies occurring throughout Quadrant 13.

Geographical extent

The Eday Flagstone Formation is found onshore on Orkney where it varies between 10 and 150 m in thickness (Trewin and Thirlwall, 2002). Offshore, the Eday Flagstone Formation occurs in wells throughout Quadrant 13 where it is 50 to 150 m thick. The westernmost offshore occurrence is in well 12/18- 1 and the unit extends eastwards to the East Shetland Platform where it has been proved in well 8/04- 1 (Marshall and Hewett, 2003). Within Quadrant 13, the greatest thickness of the unit is seen in the central part of the Inner Moray Firth Basin.

In marginal areas adjacent to the former Eday lake, the development of lacustrine strata is restricted to the John o'Groats Fish Bed which represents a lacustrine transgression during a relatively short-lived high stand in the lake level.

Lithology

The Eday Flagstone Formation comprises a sequence of red, calcareous claystone and siltstone with traces of limestone intercalated with very fine- to medium-grained sandstone. In onshore sections, the unit is characterised by a distinctive fossil fish fauna that is also found in the John o'Groats Fish Bed of Caithness (Trewin and Thirlwall, 2002). On Orkney, the Eday Flagstone Formation locally contains intercalations of lava and volcaniclastic deposits (Trewin and Thirlwall, 2002).

The Eday Flagstone Formation is associated with a relatively high and spikey gamma-ray count related to the intercalations of claystone, siltstone and sandstone. The John o'Groats Fish Bed gives rise to a strong gamma-ray spike in several wells in the southern half of Quadrant 12, e.g. 12/29-2 (Figure 11, cf. Marshall and Hewett, 2003).

Key Wells

The full thickness of the Eday Flagstone Formation, including contacts with the overlying Middle Eday Sandstone Formation and underlying Lower Eday Sandstone Formation, are seen in wells 13/19- 1 and 13/22- 1 (Figure 11).

Lower boundary

The Eday Flagstone Formation is conformably underlain by the Lower Eday Sandstone Formation.

Upper boundary

The Eday Flagstone Formation is overlain by the Middle Eday Sandstone Formation in Quadrant 13 and onshore in Orkney.

Age

The Eday Flagstone Formation has a distinctive palynological assemblage, containing an abundance of *Geminospora lemurata*, which is indicative of a Givetian age (Marshall and Hewett, 2003). The John o'Groats Fish Bed has been palynologically constrained in well 12/29-2 (Marshall and Hewett, 2003).

Correlation with onshore UK

The Eday Flagstone Formation crops out on Orkney and is correlated with the John o'Groats Fish Bed of northern Caithness (British Geological Survey, 1999; Trewin and Thirlwall, 2002)

Associated correlation panels

The relationship between the Eday Flagstone Formation and other Eday Group strata is shown in the well correlation panels in Figures 20, 21 and 22.

2.3.3 Middle Eday Sandstone Formation

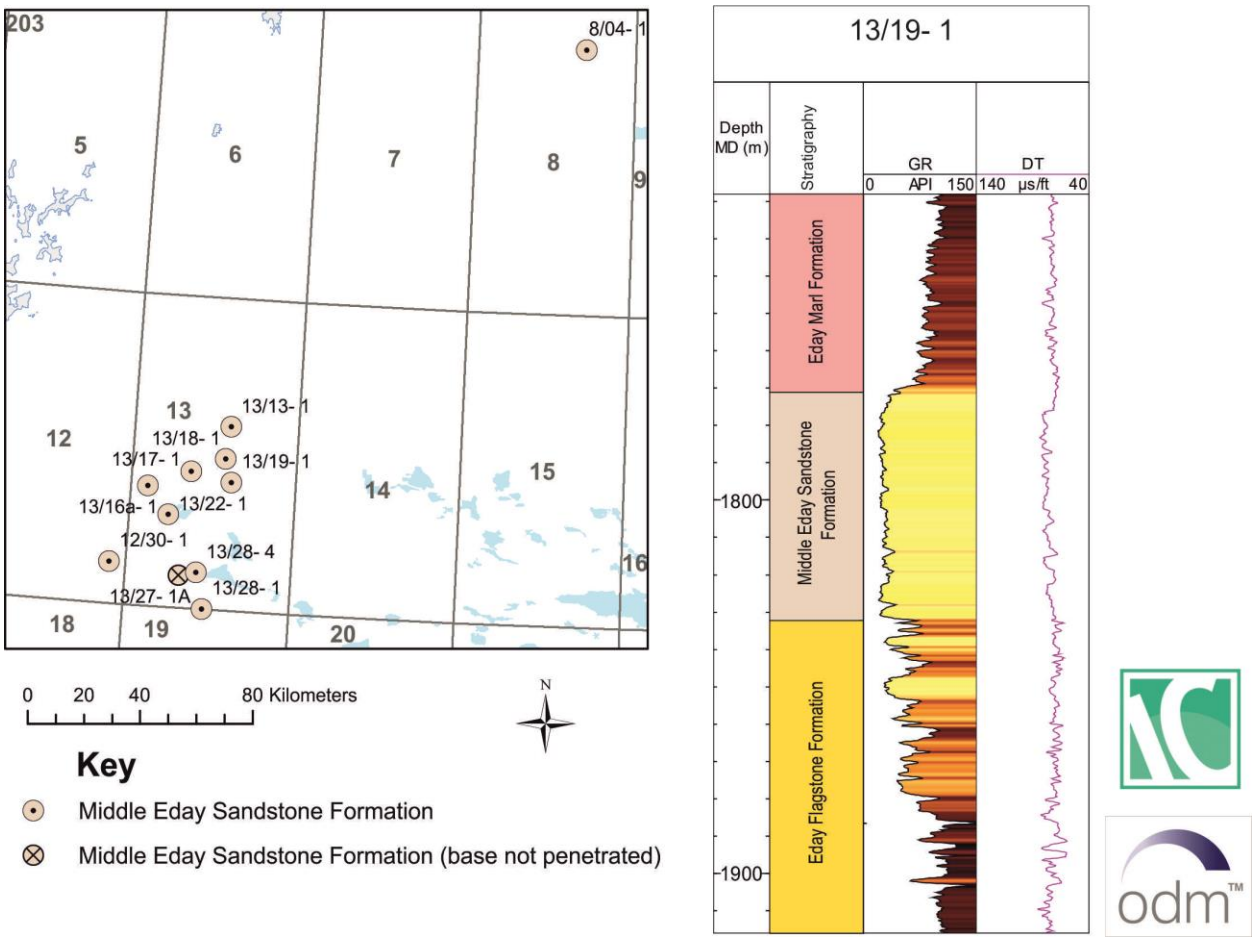


Figure 12 - Map showing the location of wells in which the Middle Eday Sandstone Formation has been interpreted and a key well profile that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Middle Eday Sandstone Formation has been given to a sandstone unit that can be recognised between the lacustrine strata of the Eday Flagstone Formation and the Eday Marl Formation in onshore sections on Orkney (e.g. Astin, 1985; British Geological Survey, 1999; Trewin and Thirlwall, 2002). The application of the name was extended to equivalent strata identified in offshore areas by Marshall and Hewett (2003).

Geographical extent

The Middle Eday Sandstone Formation is found onshore in Orkney and occurs widely across the eastern sector of the Inner Moray Firth Basin, in Quadrant 13, where it varies from 20 to 100 m in thickness. On Orkney, the unit thins to the east and is locally absent (British Geological Survey, 1999).

The Middle Eday Sandstone, or its lateral equivalent, may be present as far east as well 8/04- 1, where 36 m of sandstone lies between the Eday Flagstone Formation and an anhydrite considered to be a lateral equivalent of the Eday Marl Formation (Marshall and Hewett, 2003).

Lithology

The Middle Eday Sandstone Formation typically comprises very fine- to medium-grained sandstone, in places containing sparse gravel or pebbles, deposited in alluvial fan and marginal marine environments. Where exposed in Orkney, the sandstone is cross-bedded and contains thin beds of sandy claystone and calcareous siltstone bearing fish fossils (British Geological Survey, 1999). In well 13/28- 1, the unit is conglomeratic and contains clasts of granite and metasedimentary rocks. The pebbly sandstone on Orkney also contains exotic volcanic pebbles including rhyolite and lava (British Geological Survey, 1999)

The Middle Eday Sandstone Formation has the highest porosity and permeability of the Devonian stratigraphic succession in the Orcadian area (Hannis, 2016). Marshall and Hewett (2003) report oil staining within Middle Eday Sandstone Formation of Orkney and non-commercial oil has been reported in several wells, including 13/28- 4 (Occidental Petroleum Ltd., 1984).

Key Wells

The upper and lower contacts of the Middle Eday Sandstone Formation with the Eday Marl Formation and the Eday Flagstone Formation are proved in well 13/22- 1, where the age is also palynologically constrained (Owens, 1986b), and in well 13/19- 1 (Figure 12). The conglomeratic facies of the Middle Eday Sandstone Formation occurs in well 13/28- 1.

Lower boundary

The Middle Eday Sandstone Formation is underlain by the lacustrine strata of the Eday Flagstone Formation (Marshall and Hewett, 2003).

Upper boundary

The Middle Eday Sandstone Formation is overlain by the calcareous siltstone and claystone of the Eday Marl Formation (Marshall and Hewett, 2003).

Age

The Middle Eday Sandstone is palynologically dated as Givetian in age, for example in well 13/22- 1 (Owens, 1986b; cf. Marshall and Hewett, 2003).

Correlation with onshore UK

The Middle Eday Sandstone Formation crops out on Orkney (British Geological Survey, 1999; Trewin and Thirlwall, 2002).

Associated correlation panels

The relationship between the Middle Eday Sandstone Formation and other Eday Group strata is shown in the well correlation panels in Figures 20, 21 and 22.

2.3.4 Eday Marl Formation

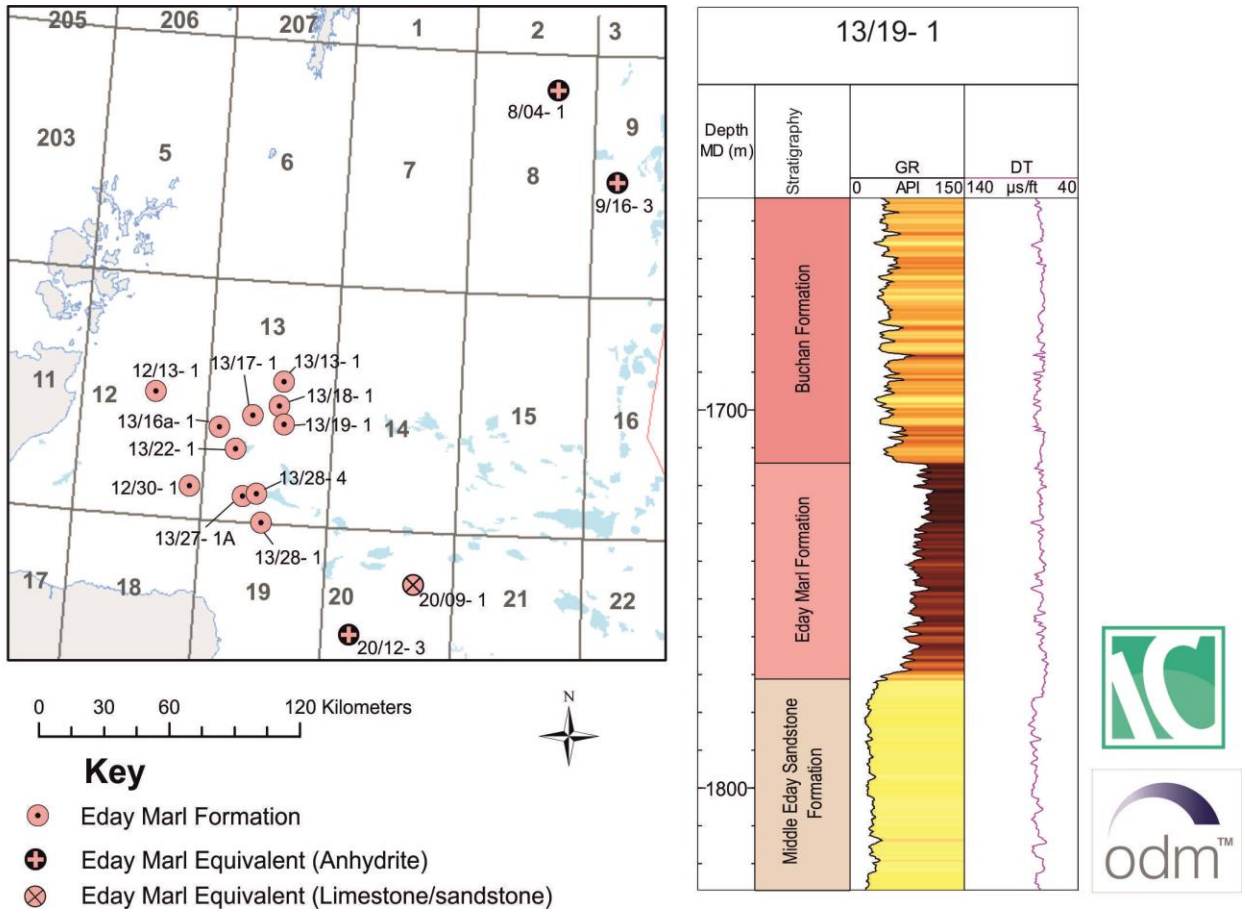


Figure 13 - Map showing the location of wells in which the Eday Marl Formation has been interpreted and a key well profile that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Eday Marl Formation has been given to a succession of calcareous mudstone and siltstone lying between the Middle Eday Sandstone Formation and the Upper Eday Sandstone Formation in onshore sections in Orkney (e.g. British Geological Survey, 1999; Trewin and Thirlwall, 2002). The application of the name was extended to equivalent strata identified in offshore areas by Marshall and Hewett (2003).

Geographical extent

The Eday Marl Formation occurs onshore in Orkney and is widespread across the eastern sector of the Inner Moray Firth Basin where it varies between 50 and 100 m in thickness. The Eday Marl Formation is considered to be a marginal marine succession that is the age equivalent of the Kyle Limestone (Kyle Group) of the southern sector of the Central North Sea (e.g. well 30/16- 5, cf. Marshall and Hewett, 2003).

Anhydrite beds in wells 9/16- 3, 8/04- 1 and 20/12- 3 along with limestone facies in well 20/9- 1 are also considered to be related to Late Givetian marine transgression and lateral equivalent to the Eday Marl Formation (Marshall et al., 2011; Marshall and Hewett, 2003; see Figure 27 below).

Lithology

The Eday Marl Formation comprises red-brown or green, calcareous siltstone and mudstone with minor sandstone. The unit is typically anhydritic both in onshore sections, where nodular evaporites have been replaced by calcite, and in offshore wells.

Marshall et al. (1996) describe thin sandstone beds seen in sections on Orkney as indicative of fluvial channel and sheet flood deposition. The siltstone and mudstone facies are intensely reddened, bioturbated and desiccated, and are considered to have been deposited on a muddy sabkha plain. Marshall et al. (1996) also report microfossil evidence of marine incursion from an onshore section of the Eday Marl Formation in Orkney.

The unit has a distinctive gamma-ray log profile and is associated with high sonic velocity and density relative to the underlying and overlying sandstone strata (Figure 20; Marshall et al., 2011; Marshall and Hewett, 2003).

Key Wells

Approximately 60 m of Eday Marl Formation strata are proved in well 13/19- 1, between the overlying Buchan Formation and underlying Middle Eday Sandstone Formation (Figure 13).

Lower boundary

The Eday Marl Formation is underlain by the Middle Eday Sandstone Formation. Where the Middle Eday Sandstone Formation is locally absent, as in well 12/13- 1, the Eday Marl Formation directly overlies lacustrine facies of the Eday Flagstone Formation and the boundary between the two units may be hard to determine due to similarities in the log character (Marshall and Hewett, 2003).

Upper boundary

In offshore areas, the Eday Marl Formation is typically overlain by the Buchan Formation and the top of the unit thus represents the boundary between the Middle and Late Devonian.

In Orkney, the Upper Eday Sandstone Formation overlies the Eday Marl Formation, but this unit is not distinguishable in offshore well records. The Upper Eday Sandstone Formation of Orkney and succeeding sandstone units ascribed Late Devonian ages are thus considered to be lateral equivalent to the Buchan Formation.

Where Buchan Formation strata are locally absent, as in well 13/22- 1, the Eday Marl Formation is unconformably overlain by Permian or Mesozoic strata

Age

The Eday Marl is palynologically constrained as Givetian in age (Marshall et al., 1996; Marshall et al., 2011; Marshall and Hewett, 2003).

Correlation with onshore UK

The Eday Marl Formation crops out on Orkney (British Geological Survey, 1999; Marshall et al., 1996; Trewin and Thirlwall, 2002).

Associated correlation panels

The relationship between the Eday Marl Formation and other Eday Group strata is shown in the well correlation panels in Figures 20, 21 and 22.

2.4 LATE DEVONIAN TO CARBONIFEROUS

2.4.1 Buchan Formation

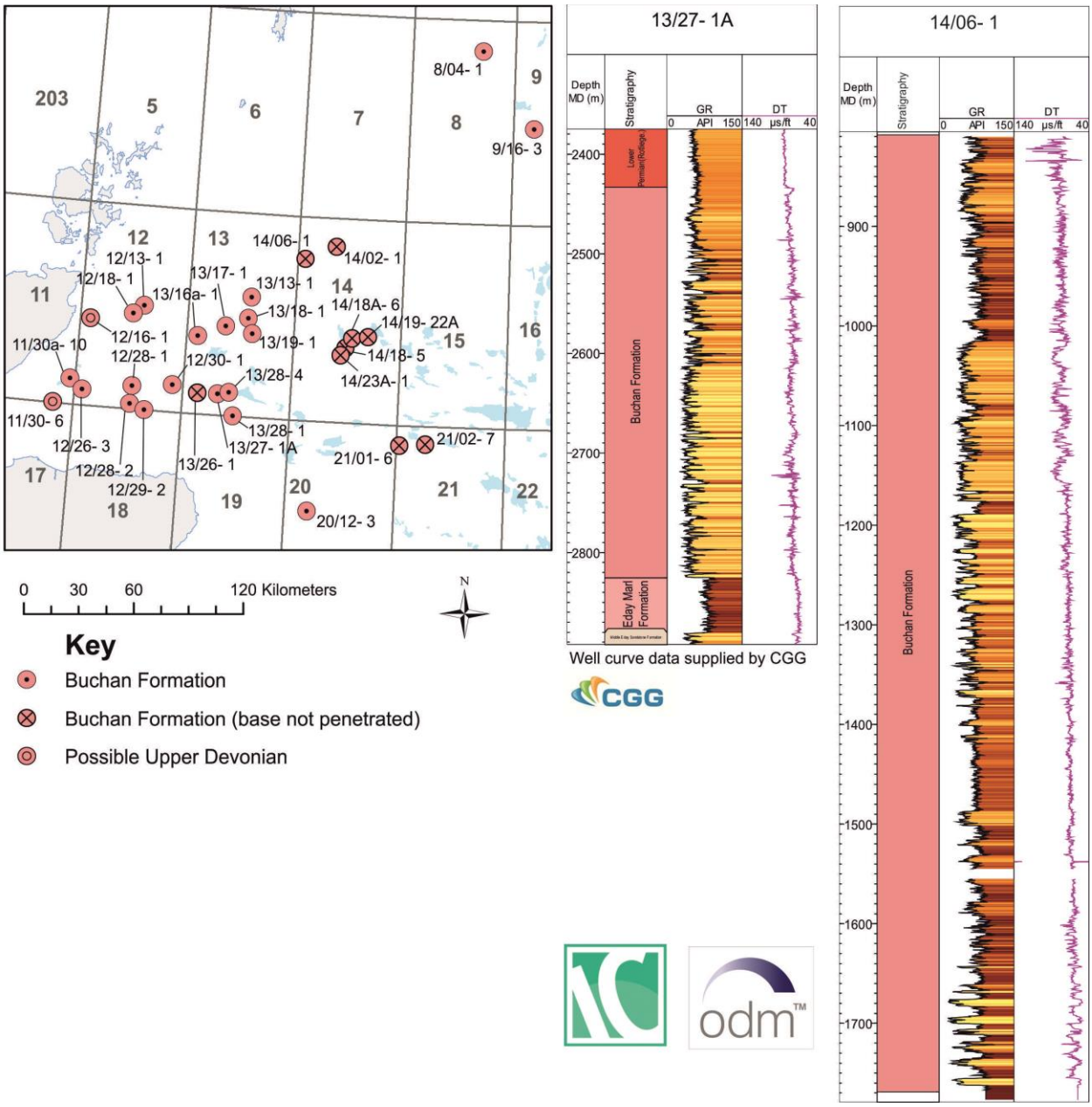


Figure 14 - Map showing the location of wells in which the Buchan Formation has been interpreted and key well profiles that illustrate the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Buchan Formation was introduced by Cameron (1993) for the largely sandstone sedimentary strata of Late Devonian to Early Carboniferous age in the central and northern North Sea. The term was previously used informally in the area of the Buchan Field.

Geographical extent

The Buchan Formation is widespread throughout the Orcadian area. The unit is locally thin or absent over structural highs, but elsewhere its thickness commonly exceeds 200 m. Up to 600 m of Buchan Formation strata have been penetrated in the Inner Moray Firth Basin and c. 960 m encountered in the East Orkney Basin. Equivalent strata are present onshore along the margins of the Moray Firth, in Caithness and on Orkney where they range between c. 450 m and 1200 m in thickness. The Buchan Formation may be locally absent over structural highs, as in well 12/27- 1 where the Strath Rory Formation is unconformably overlain by strata of Permian age (Figure 21).

Previous assessments of the distribution of the Buchan Formation by Andrews et al. (1990) and Cameron (1993) indicated that the unit was largely absent from the Inner Moray Firth Basin. This interpretation was substantially revised by Marshall and Hewett (2003) during their reassessment of the stratigraphy of the Devonian - Permian succession. In the Orcadian area, Marshall and Hewett (2003) reassigned a considerable portion of strata assigned by operators to the Rotliegend Group to the Middle and Late Devonian on the basis of new palynological constraints and well correlation. As a result of this revision, Buchan Formation strata are now considered to be present in wells throughout the Inner Moray Firth Basin, except where it has been locally eroded over structural highs.

Lithology

The Buchan Formation is typically dominated by fine- to medium-grained sandstone, with some pebbly sandstone and conglomerate, and sparse claystone and siltstone. The succession represents the regional development of fluvial depositional systems across the former Orcadian lake. The fluvial facies are dominated by broad sandy braid and alluvial plains, which were locally associated with aeolian dune systems and sabkha environments (Marshall et al., 1996; Trewin and Thirlwall, 2002).

Marshall and Hewett (2003) note that marl facies occurs in the lower parts of the Buchan Formation in the northern sector of Quadrant 14. The marl succession in well 14/06- 1 has been palynologically dated as Frasnian in age and is associated with marine incursions identified by the presence of marine microfossils (Marshall et al., 1996). Marshall and Hewett (2003) suggest that sabkha conditions persisted in the northern area of Quadrant 14 from late Givetian times into the Frasnian, and the region experienced periodic marine inundation before fluvial systems invaded the area during the latter parts of the Late Devonian.

Within the area of the Buchan Field, Richards (1985b) and Edwards (1991) have identified four different units within the 'Upper Old Red Sandstone' strata, ranging from Fammenian to Visean in age. Overall, the succession displays a generally fining upwards sequence with an upwards increase in cyclicity and the proportion of siltstone and claystone. The uppermost unit identified in the area of the Buchan Field, 'Unit D' of Richards (1985b), is here assigned to the Tayport Formation due to the cyclic nature of the interbedded sandstone – siltstone – claystone sequence (see correlation panel in Figure 24).

Key Wells

Approximately 436 m of Buchan Formation overlain by Tayport Formation occurs in well 21/01-6. Previously, the whole section of strata below the Cretaceous (c. 730 m) in this well was assigned to the Buchan Formation (Cameron, 1993). The upper 296 m of the section has been assigned to the Tayport Formation in this study (as described above). The contact between the Buchan Formation and overlying Tayport Formation can also be seen in well 21/02- 7. A 960 m section through Buchan Formation strata is seen in well 14/06- 1 (cf. Marshall et al. 1996; Figure 14).

Lower boundary

The Buchan Formation is underlain in the Inner Moray Firth Basin by strata of the Eday Group. In the eastern part of the basin, the base of the Buchan Formation is taken at the base of the sandstone unit overlying the calcareous siltstone and claystone of the Eday Marl Formation. In the western area of the basin, the contact between the Buchan Formation and sandstone-dominated strata of the Eday Group has been tentatively assigned on the basis of variations in log character, such as slight increases in sonic velocity as seen in wells 12/28- 2 and 12/29- 2. To the south of the Highland Boundary Fault, the Buchan Formation unconformably overlies strata of Middle to Early Devonian age (e.g. wells 20/12- 3 and 26/12- 1).

On the Isle of Hoy in Orkney a local unconformity, associated with development of the Hoy lavas, occurs between the onshore equivalent of the Buchan Formation, the Hoy Sandstone Formation, and strata of Middle Devonian age (Trewin and Thirlwall, 2002).

Upper boundary

Throughout the Inner Moray Firth, the Buchan Formation is overlain by strata of Permian or Mesozoic age. Within Quadrants 14 and 15, and in the Outer Moray Firth Basin the predominantly sandstone strata of the Buchan Formation are locally overlain by cyclic sandstone, siltstone and mudstone of the Tayport Formation (e.g. well 21/01- 6 and 21/02- 7).

Marshall and Hewett (2003) note the relative rarity of wells in which the boundary between the Buchan and Tayport Formations are encountered, and suggest that the units may be, to some extent, laterally equivalent. However the, albeit limited, palynological evidence does not suggest overlap in the age ranges of the two units and the lack of observed contact between the Buchan and Tayport formations may be due to a lack of full well penetrations of the Tayport Formation within basinal areas.

Age

The Buchan Formation has been palynologically constrained as Frasnian (well 14/06- 1; Marshall et al., 1996) to latest Famennian in age (well 14/19- 22A; Rusca, 1988), although the unit is commonly barren and there are few positive age constraints (Marshall and Hewett, 2003).

Correlation with onshore UK

The Buchan Formation is partially equivalent to the Upper Eday Sandstone Formation and Hoy Sandstone Formation of Orkney, the Dunnet Head Sandstone Formation of Caithness, and the Forres Sandstone Group of the Inverness and Moray Firth coast area.

Associated correlation panels

The relationship between the Buchan Formation and other Palaeozoic strata is shown in the well correlation panels in Figures 19, 20, 21 and 22.

2.4.2 Tayport Formation

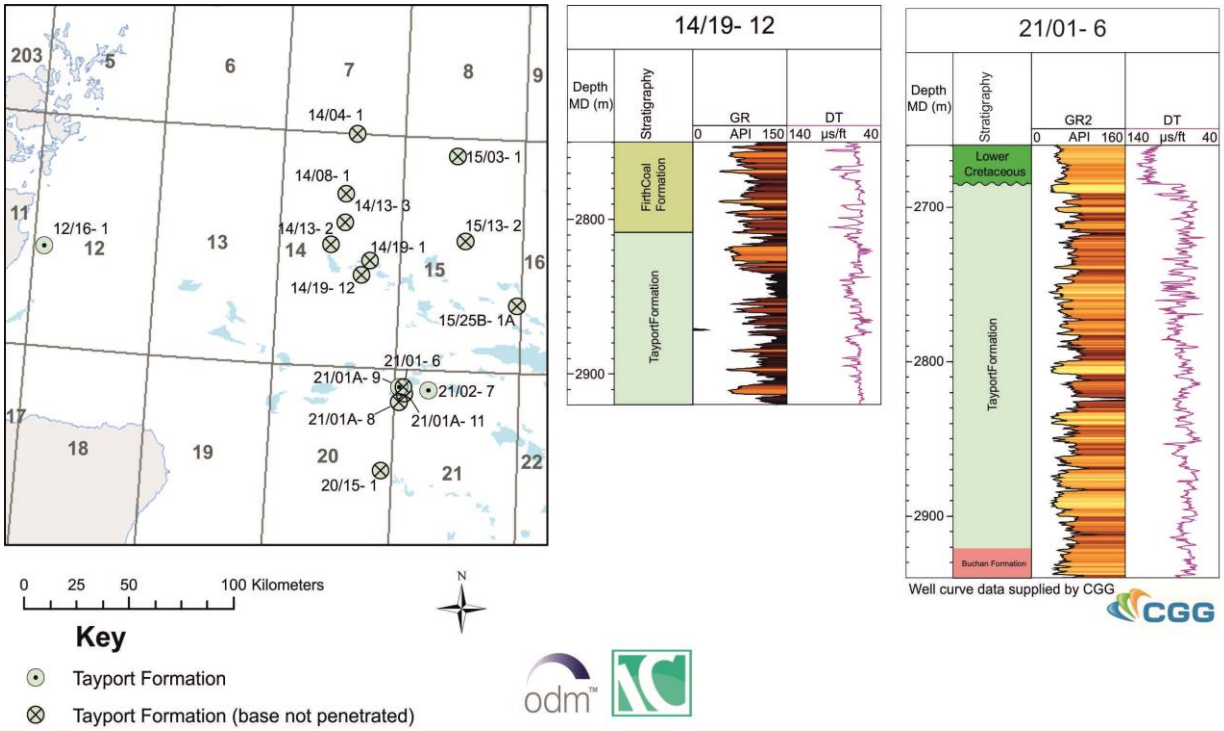


Figure 15 - Map showing the location of wells in which the Tayport Formation has been interpreted and key well profiles that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Tayport Formation was introduced by Cameron (1993) to describe a sandstone and siltstone unit which is widespread throughout the Outer Moray Firth and the region of the Buchan Basin, to the south of the Halibut Horst. The unit lies stratigraphically between the Firth Coal Formation, of Carboniferous age, and the Late Devonian Buchan Formation.

Extension of the Tayport Formation beneath the Cementstone Formation to the south and east of the Mid North Sea High was suggested by Cameron (1993), and has been supported by the recent interpretation of Tayport Formation strata in wells near the Dogger Granite, in Quadrants 36, 37, 38, 42 and 44, by Kearsey et al. (2015) (Figure 5). However, in the Outer Moray Firth and Buchan Basin, the Tayport Formation has a greater age range than in the Central North Sea area, extending throughout the Tournasian, meaning that it becomes laterally equivalent to the Cementstone Formation in this area (Figure 5).

Geographical extent

The Tayport Formation is proved in wells in Quadrants 12, 14, 15, 20, and 21 (Figure 15) in the Witch Ground Graben, Outer Moray Firth basin and in the Buchan Basin. There is a single well in Quadrant 12 which contains the Tayport Formation, although, based on seismic data, this appears to be a localised, fault controlled, basin and not connected to the basins to east.

Lithology

North of the Mid North Sea High, the Tayport Formation is dominated by cyclic alternations of sandstone, mudstone units and rare limestones, less than 1 m thick. The sandstones are

predominantly 15 m thick (Bruce and Stemmerik, 2003), and are interpreted to have formed in a proximal fluvial channel system with associated overbank deposits (Leeder and Boldy, 1990). The Tayport Formation also contains occasional tuffaceous intervals and rhyolitic bands, typically 1 – 5 m thick (Cameron, 1993); examples occur in well 15/25b- 1A.

Key Wells

The lower contact of the Tayport Formation with the Buchan Formation is proved in well 21/01- 6, and the formation is unconformably overlain by Cretaceous strata in this well (Figure 15). In Quadrants 14 and 15, the upper contact with the overlying Firth Coal Formation has been interpreted in wells 14/19- 12 (Figure 15) and 14/19- 1. In well 12/16- 1, the Tayport Formation unconformably overlies strata of Devonian age and is overlain by a sandstone unit that occurs in a stratigraphic position equivalent to the Fell Sandstone Formation.

Lower boundary

The conformable lower boundary of the Tayport Formation with the Buchan Formation is associated with a transition in wireline log character from the cyclic sandstone – siltstone succession of the upper unit to the sandstone-dominated lower unit. The contact is seen in well 21/01- 6, where the base of the Tayport Formation is taken at the base of the first mudstone-dominated cycle (Figure 15).

Upper boundary

The Tayport Formation is overlain by the Fell Sandstone Formation in Quadrants 20 and 21 (and a similar sandstone unit in well 12/16- 1), and by the Firth Coal Formation in Quadrants 14 and 15. Where overlain by the Fell Sandstone Formation, the top of the Tayport Formation is taken at the base of an abrupt transition to a succession of thick sandstone units. The transition between the Tayport Formation and the overlying Firth Coal Formation is marked by the development of coals within the cyclic sandstone – siltstone succession; the top of the Tayport Formation is taken at the base of the first significant coal.

Age

A latest Fammenian to Tournaisian age for the Tayport Formation is proved palynologically (Zones LN and CM) in well 15/25b- 1A (CDA, unknown date). In Quadrant 14 the unit extends up into the base of the Holkerian (PU Zone; Church et al., 1974). The Tayport Formation in this area is age equivalent to the Cementstone Formation in the Central North Sea and Forth Approaches (Figure 5).

Correlation with Onshore UK

The Tayport Formation has no direct onshore equivalent. The unit is partially age equivalent to the Cementstone Formation (offshore) and the Ballagan Formation which occurs onshore in southern Scotland (Figure 5; Kearsey et al. 2015), however the facies associated with deposition of the Tayport Formation succession was apparently restricted to present day offshore areas during this time.

Remarks

A thick sandstone unit previously assigned to the Tayport Formation in well 26/7- 1 by Cameron (1993) and Bruce and Stemmerik (2003) has now been reinterpreted as the Fell Sandstone Formation due to its age and log character (Kearsey et al. 2015).

Associated correlation panels

The relationship between the Tayport Formation and surrounding strata is shown in the well correlation panels in Figures 23 and 24.

2.4.3 Fell Sandstone Formation

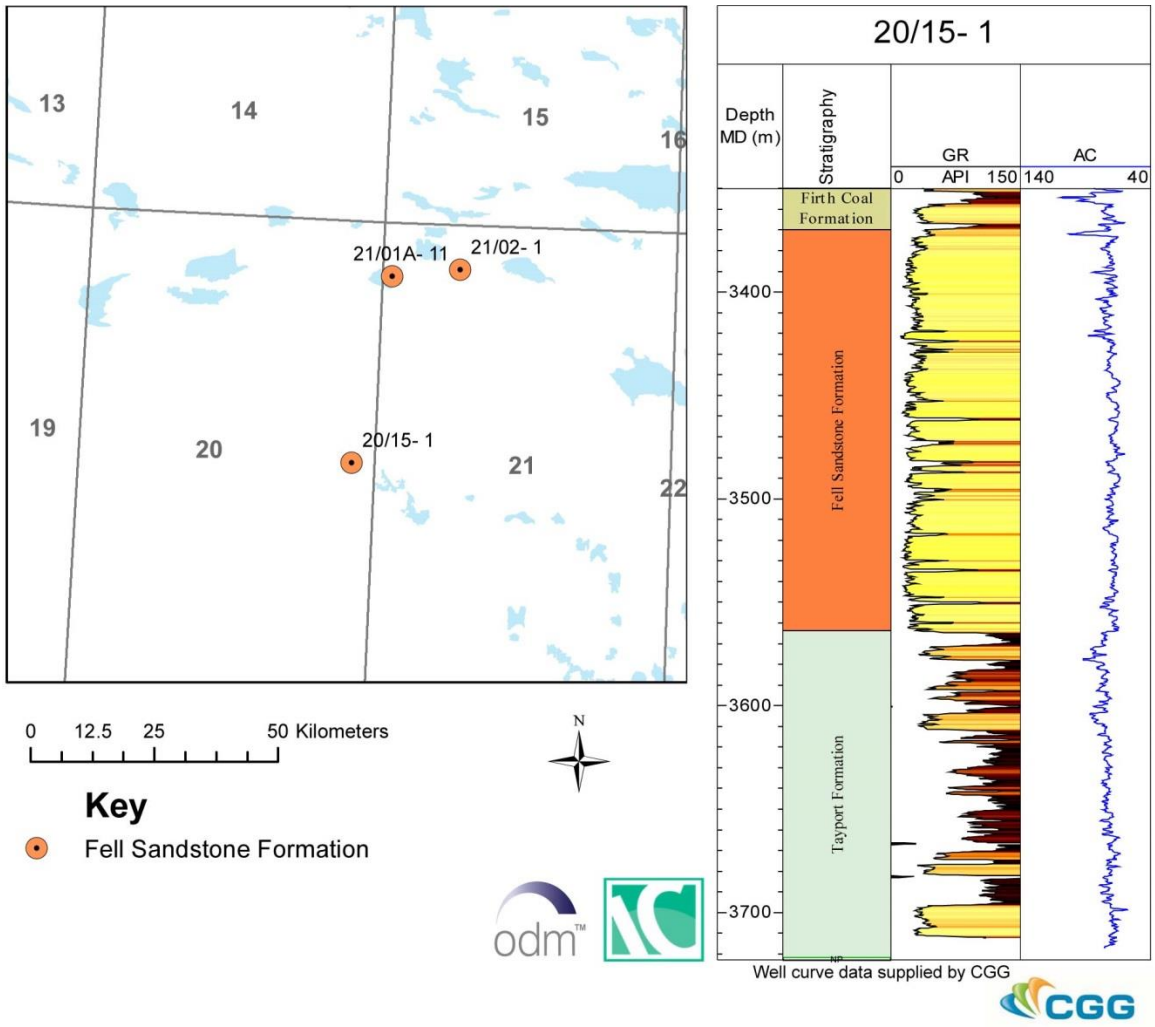


Figure 16 - Map showing the location of wells in which the Fell Sandstone Formation has been interpreted and a key well profile that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit.

Name

The term Fell Sandstone Formation has been applied in Northumberland (north-east England) and Berwickshire (south-east Scotland) since the 19th century to a thick unit of predominantly cross-stratified coarse-grained sandstone of Chadian to Holkerian age. The definition of the Fell

Sandstone in the current study follows that of Cameron (1993), and Bruce and Stemmerik (2003).

Geographical extent

The Fell Sandstone Formation occurs in the Forth Approaches (Kearsey et al., 2015) and its northern extension into Quadrants 20 and 21, south of the Grampian High and Halibut Horst. The unit is not found north of the Grampian High, except for the isolated occurrence of a sandstone unit of similar age and facies that occurs in well 12/16- 1.

The Fell Sandstone Formation occurs widely in the Central North Sea, but prior to this study and that of Kearsey et al. (2015) it had not been identified north of the Mid North Sea High.

Lithology

The Fell Sandstone Formation is typically characterised by massive sandstone units up to 50 m thick, interbedded with siltstone and mudstone units up to 20 m thick. In some wells (e.g. 20/15-1), the siltstone and mudstone interbeds reduce to 1-3 m thick. The Fell Sandstone Formation is interpreted to be the deposit of a major sandy braided-river system (Turner and Munro, 1987), formed of stacked multi-storey channel fills and separated by mudstone intervals. The source of the braided river system is from the north-east (Robson, 1956; Kearsey et al., 2015).

Key Well

The conformable top and basal contacts of the Fell Sandstone Formation have been observed in well 20/15- 1 (Figure 16).

Lower boundary

The base of the Fell Sandstone Formation is taken at the abrupt change from thick sandstone units to interbedded sandstone, siltstone and mudstone of the underlying Tayport Formation. This transition is marked by a distinct change in wireline log character (Figure 16).

Upper boundary

The top of the formation is taken at the top of the uppermost thick sandstone unit below a succession of coal-bearing interbedded mudstone, siltstone and sandstone of the Firth Coal Formation.

Age

Palynological evidence from well 21/02- 1 indicates that the Fell Sandstone Formation is Chadian to Arundian in age (Palaeoservices Ltd, 1975).

Correlation with onshore UK

The Fell Sandstone Formation occurs onshore in northern England, and is equivalent to the Fell Sandstone Formation that occurs in offshore areas. Sedimentary rocks of this age are not known in the Midland Valley of Scotland; at this time in the present day onshore area, volcanic activity gave rise to the extrusive igneous rocks of the Garleton Hills Volcanic Formation

Associated correlation panels

The relationship between the Fell Sandstone Formation and surrounding strata is shown in the well correlation panels in Figures 23 and 24.

2.4.4 Firth Coal Formation

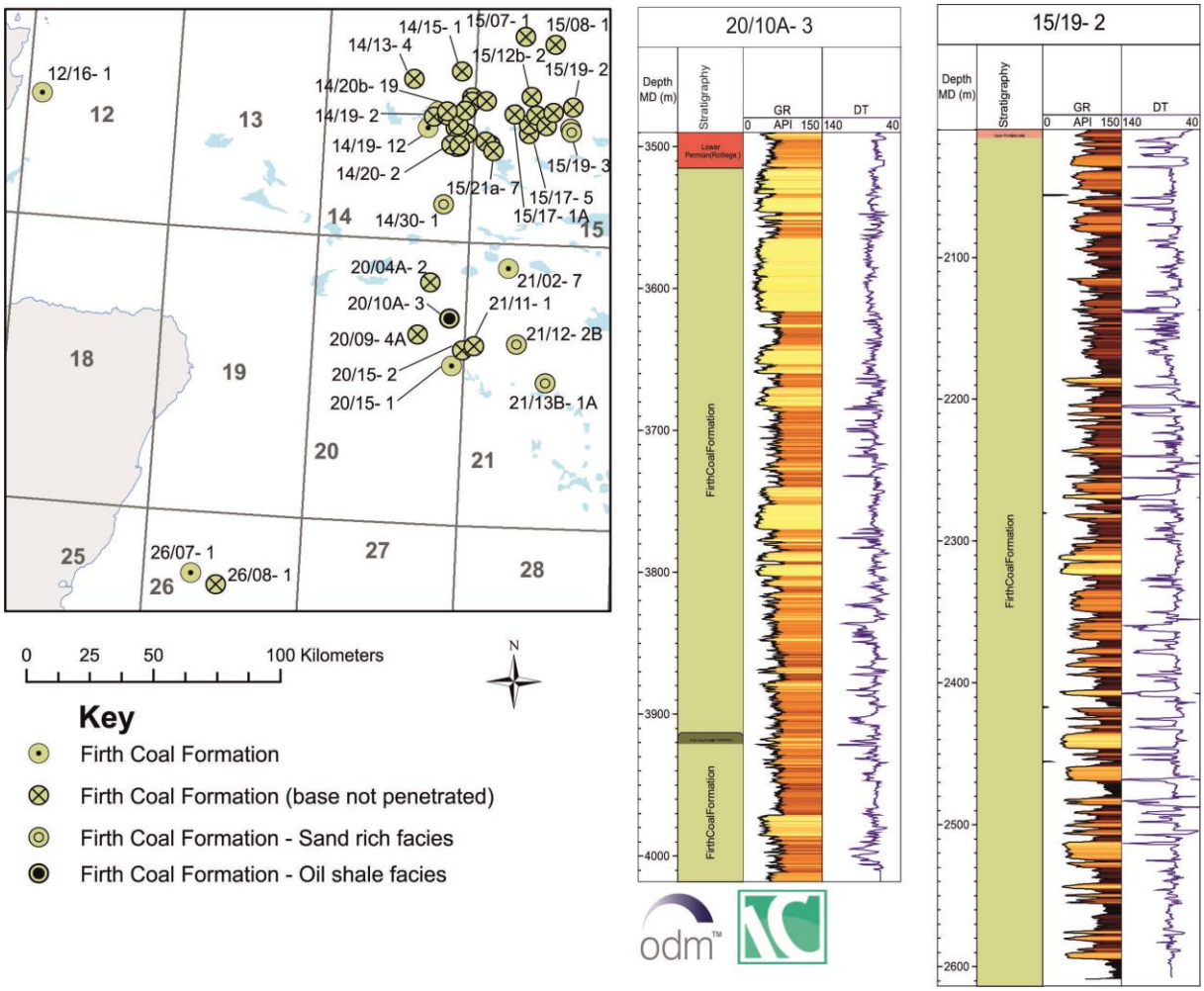


Figure 17 - Map showing the location of wells in which the Firth Coal Formation has been interpreted and key well profiles that illustrates the principal variation in wireline log signature (gamma and sonic logs) and lithology of the unit. Note that not all wells are labelled in the location map; all wells containing Firth Coal Formation are listed in the associated Well Tops database.

Name

The name Firth Coal Formation was introduced by Cameron (1993) to describe coal bearing facies to the north and south of the Buchan Horst in Quadrants 14, 15, 20, 21 and 26. Kearsey et al. (2015) noted the equivalence of the Firth Coal Formation seen in the wells in Quadrant 26 to the Scremerston Formation of the Central North Sea area, based on its relationship with the underlying Fell Sandstone Formation, and late Holkerian to Asbian age. North of Quadrant 26, the Firth Coal Formation becomes thinner (Figure 23) and ranges from Chadian to Kinderscoutian in age. To reflect this difference we have retained the name Firth Coal Formation in wells north of Quadrant 26, although it is lithologically similar to the Scremerston Formation.

Geographical extent

The Firth Coal Formation is encountered in Quadrants 14 and 15, in the Witch Ground Graben and on to the East Shetland Platform. The unit has also been recorded in the Outer Moray Firth Basin in Quadrants 20 and 21. Johnson et al. (1993) suggest that, apart from these intervals, non-deposition and erosion were prevalent north of Quadrants 14 and 15 during the Carboniferous.

Lithology

The Firth Coal Formation is identified by the presence of coal-rich intervals within a mudstone-dominated sequence, with alternations of sandstone, siltstone and some thin limestones. The coal horizons vary in thickness from a few decimetres to 3 m (Leeder and Boldy, 1990). Sparse conglomerate units and thin sandstones have been identified (Cameron, 1993), although the succession is dominated by mudstone and siltstone. Leeder and Boldy (1990) suggest it was deposited in a range of environments including fluvio-deltaic, lacustrine, wetland and marine-influenced bay associated with a major deltaic system.

A sand-rich facies of the Firth Coal Formation, typically characterised by massive sandstone units up to 40 m thick, separated by siltstones and mudstone interbeds 10 – 20 m thick, has been identified in wells in Quadrants 14, 15 and 21 (e.g. 15/19- 1, 15/21a- 7 and 21/13b- 1a). However, in well 15/19-2, strata of similar age are represented by a mudstone dominated, coal rich sequence suggesting that the sand-rich facies of the Firth Coal Formation may represent channel bodies.

Bruce and Stemmerik (2003) identify organic-rich lacustrine oil shales in well 20/10a- 3 (Figure 17 at 3915 m). This unit is 6 m thick and is identified by its high resistivity values. Offshore, oil-shale facies are only identified in this well, but onshore in the Midland Valley of Scotland equivalent facies occur extensively within the West Lothian Oil-Shale Formation.

Key Wells

The conformable basal contact of the Firth Coal Formation has been observed in wells 14/15-1 and 20/15-1.

Lower boundary

The base of the Firth Coal Formation is taken at the bottom of the first significant coal seen in both the sonic log and in core chippings.

Upper boundary

The Firth Coal Formation is overlain unconformably by Permian or Cretaceous strata.

Age

The age range of the Firth Coal Formation spans the Visean to the mid Namurian. The earliest palynological date for the unit is lowest Visean (Chadian, Pu zone) in well 15/17- 1A (Bagnall et al., 1973). The youngest biostratigraphy age is Namurian (Kinderscoutian, KV zone) in well 20/15- 2 (Harris et al., 1998). The Firth Coal Formation in Quadrants 20 and 21 has a Holkerian to Kinderscoutian stratigraphic age range (Figure 5). Wells in Quadrants 14 – 15 span Chadian to Pendleian biostratigaphic dates (Bagnall et al., 1972; Figure 5).

Correlation with onshore UK

The Firth Coal Formation in Quadrants 14, 15, 20 and 21 is equivalent in age to the Strathclyde Group and much of the Clackmannan Group in the Midland Valley of Scotland. It equates with the fluvio-deltaic to marine Sandy Craig, Pittenweem, Anstruther, Fife Ness, Aberlady and Gullane formations of Fife and the Lothians, to the dominantly lacustrine and organic-rich West Lothian Oil-Shale Formation and to the coal-bearing Lower Limestone, Limestone Coal and Upper Limestone Formations. The coals and organic-rich mudstones within these units represent an important potential source rock and/or unconventional resources (Underhill et al., 2008; Monaghan, 2014).

Remarks

Leeder and Boldy (1990) have suggested that the Firth Coal Formation was locally sourced from the surrounding Grampian Highlands. However, analysis of zircons from the Firth Coal Formation has shown that the source region included a wide range of mid-Proterozoic and Archean rocks in addition to material derived locally (Morton et al., 2001). Morton et al. (2001) suggest that the zircon populations of the Firth Coal Formation are similar to those seen in the Namurian Ashover Grit and Rough Rock in the Pennine Basin, indicating a common provenance for both systems which lay to the north of the modern North Sea. This finding supports the hypothesis that the sand-rich facies of the Firth Coal Formation may represent feeder channel systems for the coeval Yoredale Formation delta-front system south of the Mid North Sea High.

Associated correlation panels

The relationship between the Firth Coal Formation and surrounding strata is shown in the well correlation panels in Figures 23 and 24.

2.5 IGNEOUS ROCKS

Numerous episodes of intrusive and extrusive igneous activity occurred within Scotland during Late Silurian to Early Devonian times (Figure 18). Widespread emplacement of granites occurred across the Grampian Highlands between c. 420 – 395 Ma, forming the suite of plutons in north-east Scotland, between the Cairngorms and Peterhead and possibly also the South Halibut Granite, located offshore at the north-east end of the Grampian High (Stephenson and Gould, 1995).

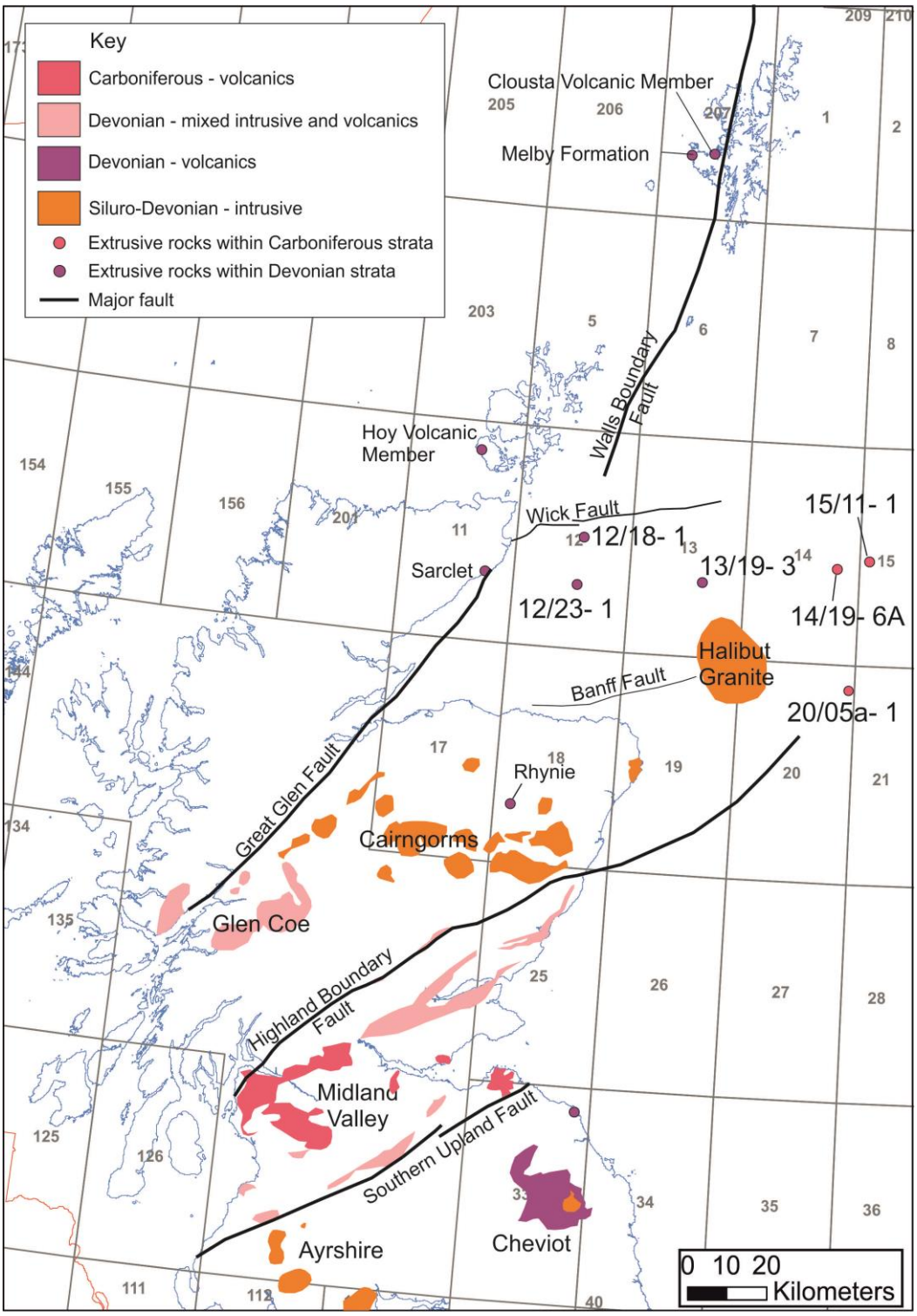


Figure 18 - Map showing the distribution of Devonian igneous strata in Scotland. Named localities are discussed in the text.

Significant volcanism and intrusion of igneous rocks also occurred during this time in Glen Coe in western Scotland (c. 400 Ma), and widely throughout the Midland Valley and Southern Uplands. Volcanic and basic intrusive rocks aged between 407 – 411 Ma are widespread in the Midland Valley (Cameron and Stephenson, 1985). In Ayrshire, a suite of granitic plutons were emplaced between 410 – 397 Ma (McMillan et al., 2012). The igneous rocks of the Cheviot area include volcanic and contemporaneous intrusive rocks of Emsian age (394 – 398 Ma; cf. Trewin and Thirlwall, 2002). Basaltic andesites and volcaniclastic rocks with chemical composition similar to that seen in the Devonian age volcanic rocks of the Midland Valley occur near St. Abbs Head and Eyemouth (c. 400 Ma; Trewin and Thirlwall, 2002).

In the Moray Firth region of north-east Scotland, Early Devonian volcanic activity has been inferred in the vicinity of Sarclet in Caithness from the presence of clasts of volcanic lithologies within the conglomerate of the Sarclet Group (Trewin and Thirlwall, 2002). Volcanic activity is also known to have occurred in the Rhynie area of the Grampian Highlands. Here, a sequence of lavas and cherts, formed from siliceous sinters, are intercalated with Early Devonian sediments; the chert has been palynologically and radiometrically dated, yielding an age of 396 ± 12 Ma (Rice et al., 1995).

Extrusive igneous rocks of late Middle Devonian age are known from Orkney, where thin lavas are intercalated within the siltstone and sandstone beds of the Eday Flagstone Formation (Mykura, 1976). Somewhat later, in Late Givetian to Early Frasnian times, the beds of tuff and volcaniclastic sediments and olivine-basalt lavas of the Hoy Volcanic Member were formed; the volcanic strata unconformably overly the Eday Flagstone and Lower Eday Sandstone formations. The Hoy Volcanic Member has been radiometrically dated, yielding K-Ar ages of 300 – 333 Ma and a ^{40}Ar-^{39}Ar age of 370 ± 10 Ma (Halliday et al. 1977). However they may be somewhat older than these dates suggest; Marshall and Hewett (2003) consider that Hoy Sandstone Formation, including the lavas of the Hoy Volcanic Member, to be Givetian in age.

Volcanic and intrusive igneous rocks of Eifelian and Givetian age are also known from the Melby Formation and Clousta Volcanic Member (Sandness Formation) on Shetland (Stephenson et al., 1999; Trewin and Thirlwall, 2002).

With the exception of the Halibut Granite in the region of the Grampian High, igneous rocks are rarely encountered in offshore wells in the Orcadian area. Igneous rocks including dolerite, basalt and tuff were encountered within strata assigned to the Middle Devonian in wells 12/23- 1 and 12/18- 1. Radiometric dating (K-Ar) has indicated a Carboniferous age of 316 ± 10 Ma, forming the basis for the early interpretation of overlying strata as Permian in age (Andrews et al., 1990). This assignment has been revised by Marshall and Hewett (2003) on the basis of new palynological constraints; the igneous horizon in these wells is now considered to be Eifelian in age and occur at the base of the Orcadia Formation.

Fine-grained basaltic rock has also been encountered at the base of well 13/19- 3. Radiometric dating yielded K-Ar ages of 365 ± 7 Ma and 332 ± 13 Ma, however these are considered to be minimum estimates. Marshall and Hewett (2003) suggest that the igneous unit in well 13/19- 3 may be equivalent to those encountered in the north of Quadrant 12 and therefore possibly Eifelian in age.

2.5.1 Carboniferous volcanic rocks

Long-lived volcanism within the Midland Valley of Scotland has been dated from the latest Tournaisian to Westphalian times, and is associated with extrusive lavas and tuff as well as shallow sills and dykes (Cameron and Stephenson, 1985; Monaghan and Parrish, 2006).

Offshore, extrusive volcanics including 10 – 20 m bands of basalt or andesite occur within parts of the Firth Coal Formation in Quadrants 14 and 15 (e.g. wells 14/19- 6A, 15/11- 1; Leeder and Boldy, 1990). These are thought to be Asbian in age (Bruce and Stemmerik, 2003).

Undated volcanics, including amygdaloidal, feldspathic lavas and breccias, are interbedded with sandstone units in well 20/05a- 1. The volcanic horizon is overlain by 11 m of late Visean to early Namurian siltstones and sandstones, and underlain by sandstones of Givetian to Famennian age, and is thus likely to be early Carboniferous in age.

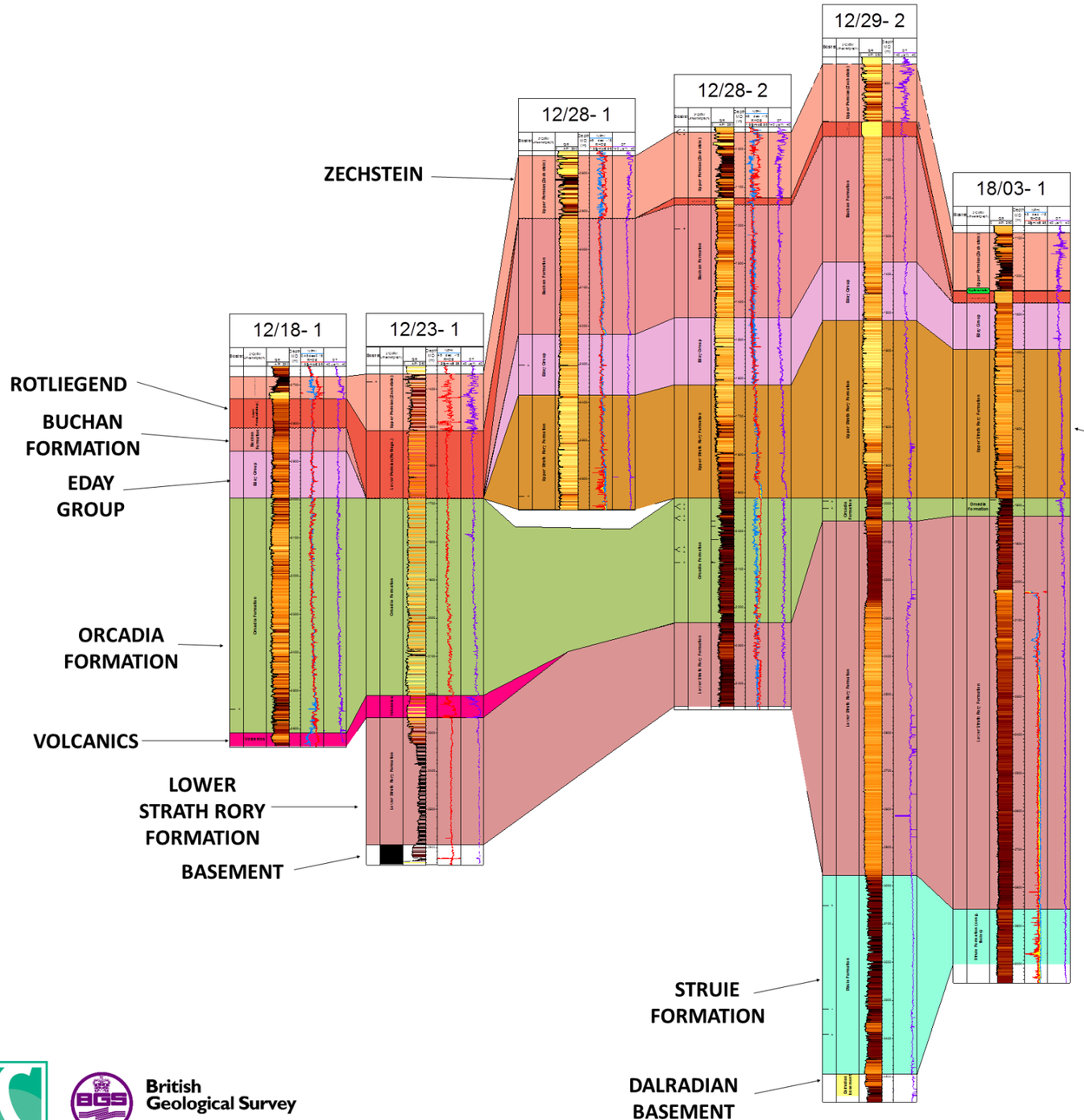
3 Correlation Panels

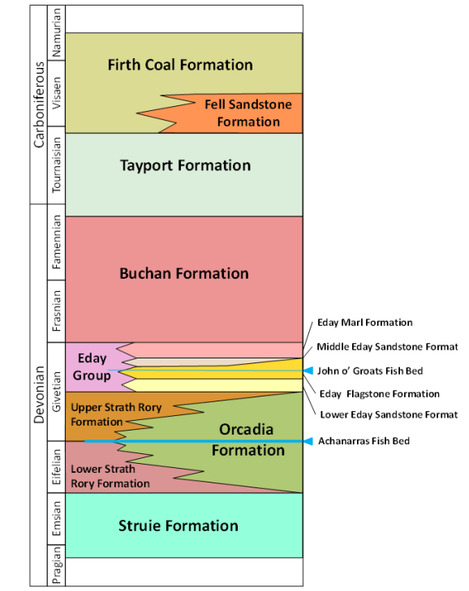
To illustrate the stratigraphical relationships and lithofacies variations of the Carboniferous and Devonian rocks of the Orcadian Area, six correlation panels have been constructed across the area (Figure 3 for location of panels). The panels were also used to aid seismic interpretation. Positions where biostratigraphic constraints were utilised in wells are marked with a plus (+) symbol in the biostratigraphy column. Formation picks are based on log responses as discussed in section 2 and on biostratigraphic constraints where available.

Panel 1: Devonian strata from the Struie Formation to the Buchan Formation in the Inner Moray Firth

N

S





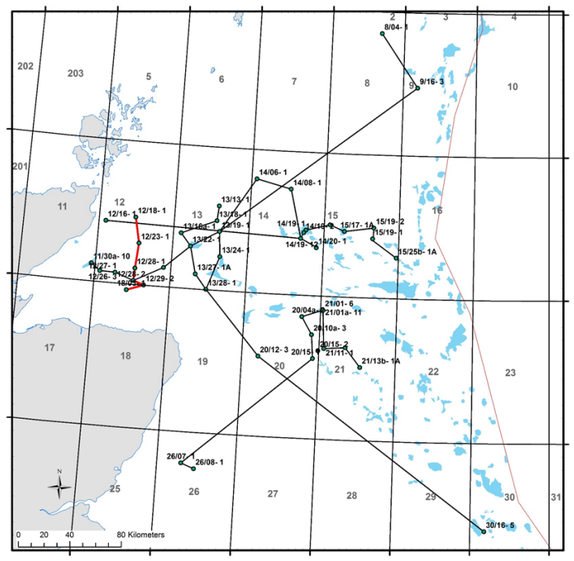


Figure 19 – Panel 1: Devonian strata from the Struie Formation to the Buchan Formation in the Inner Moray Firth, showing the relationship of lacustrine strata of the Struie Formation (Early Devonian) and Orcadia Formation (Middle Devonian) with Middle and Upper Devonian sandstone dominated successions.

Panel 2: Middle to Late Devonian strata of the Eday Group to Buchan Formation in Quadrant 13

N

S

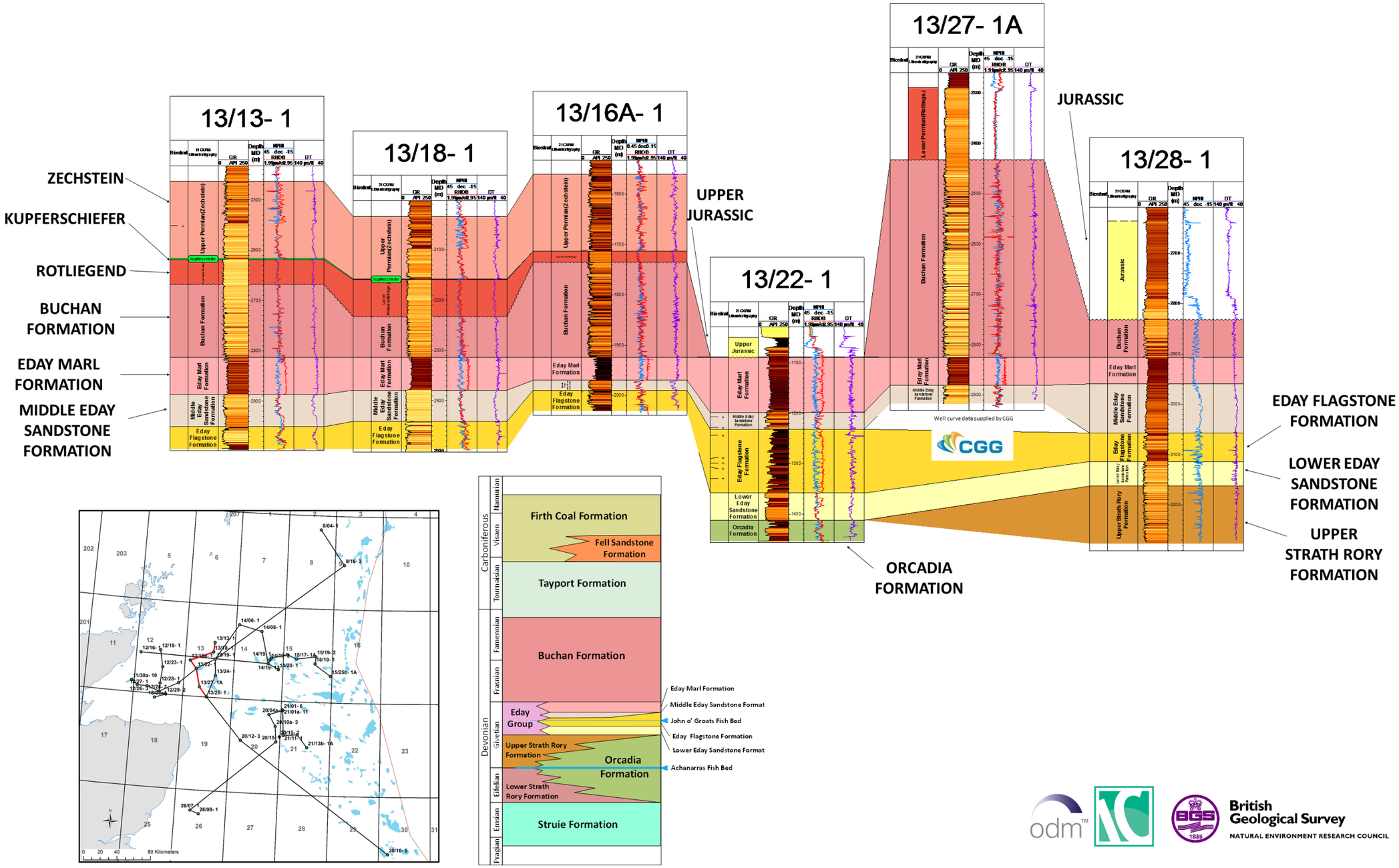


Figure 20 – Panel 2: Middle to Late Devonian strata of the Eday Group to Buchan Formation in Quadrant 13, showing the stratigraphic relationships of formations within the Eday Group. These strata were formerly considered to be part of the Rotliegend Group but were assigned to the Middle Devonian Eday Group by Marshall and Hewett (2003).

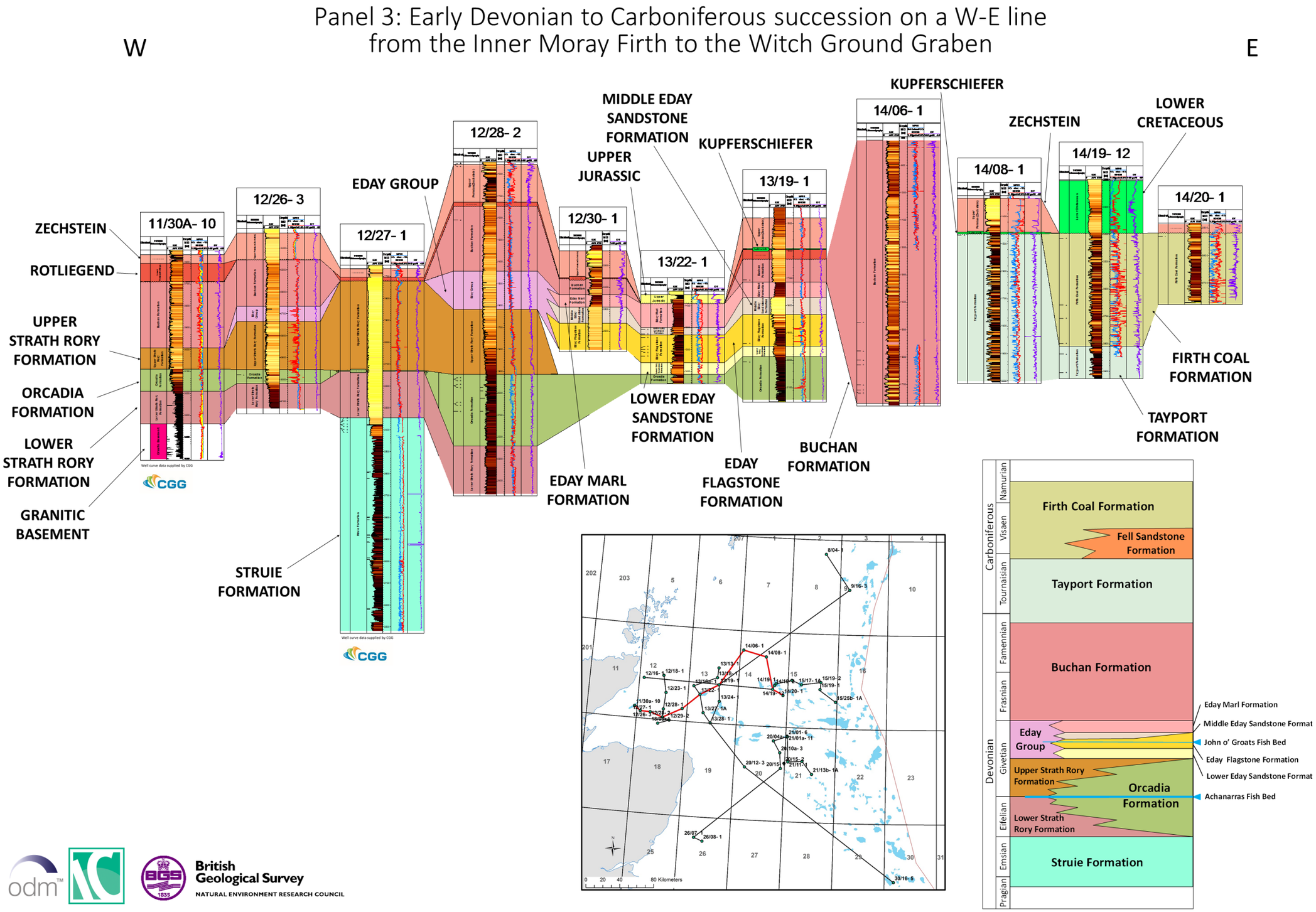


Figure 21 – Panel 3: Early Devonian to Carboniferous succession on a W-E line from the Inner Moray Firth to the Witch Ground Graben.

Panel 4: Middle to Late Devonian Eday Group to Kyle Limestone correlation from Quadrant 9 to Quadrant 30

N

S

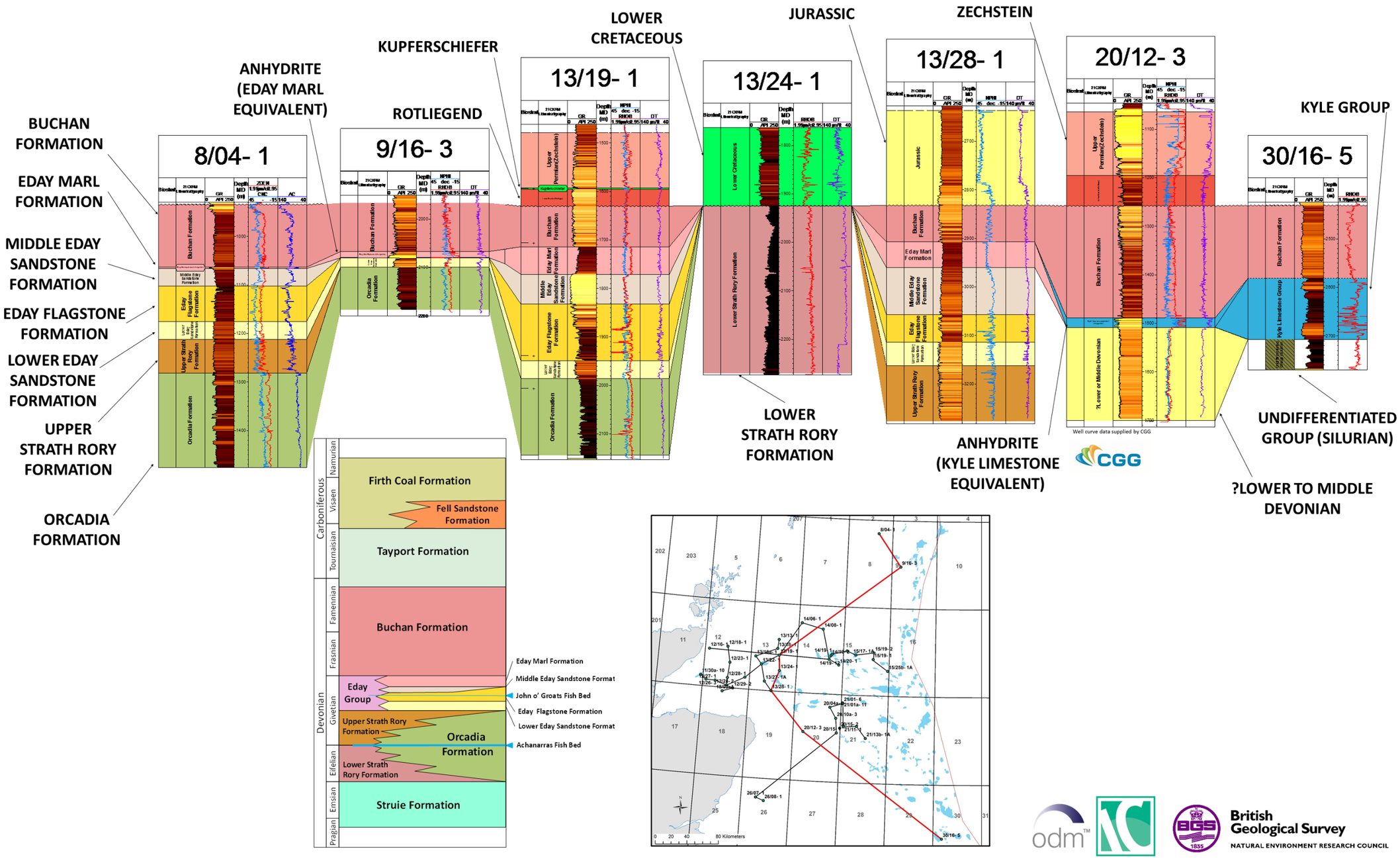


Figure 22 – Panel 4: Middle to Upper Devonian Eday Group to Kyle Limestone correlation from Quadrant 9 to Quadrant 30. A regional marine transgression is marked by a transition from proximal sabkha environments of the Eday Group in the Orcadian Area to the marine carbonates of the Kyle Group in the Central North Sea.

Panel 5: The Carboniferous of the Witch Ground Graben and surrounding areas

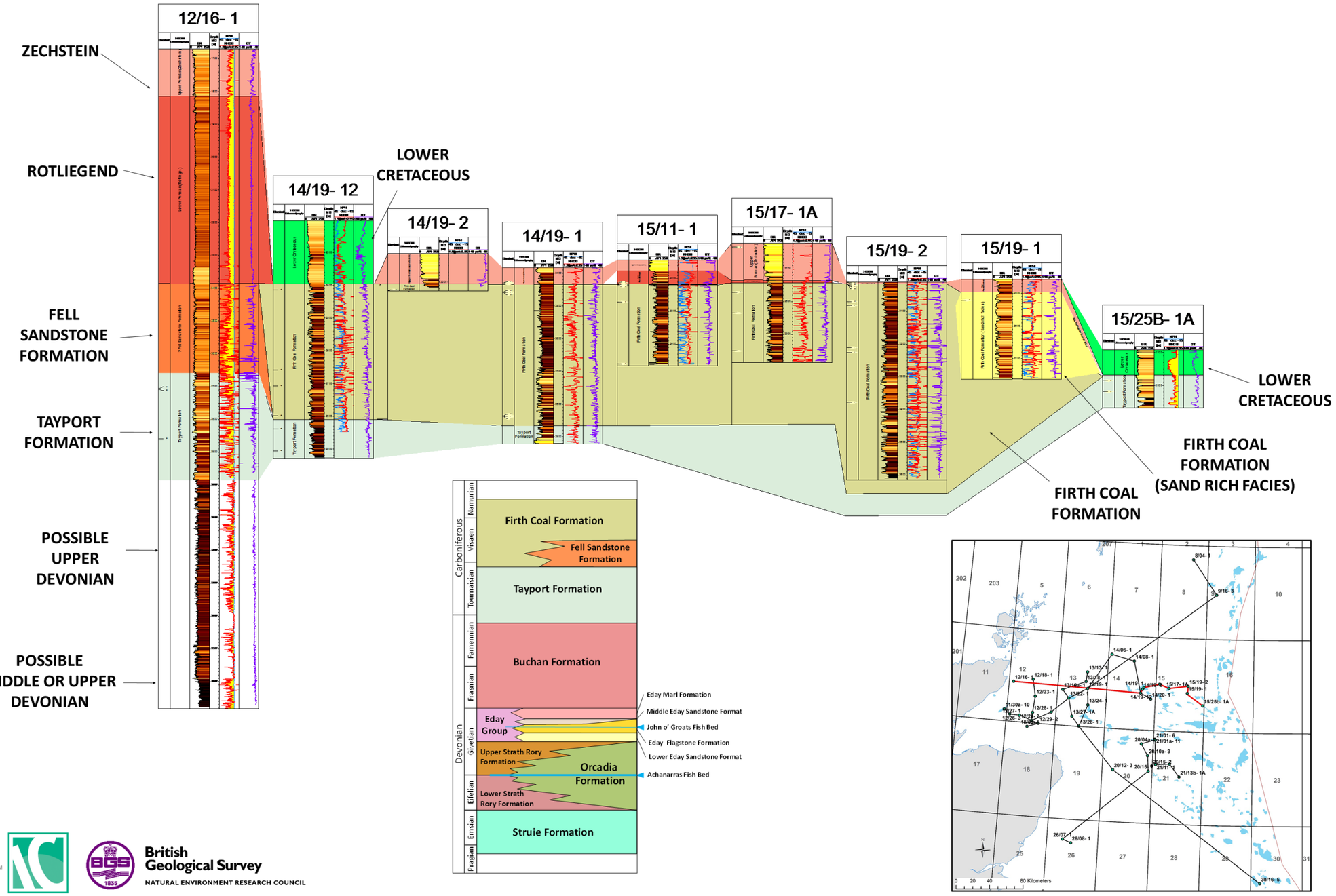
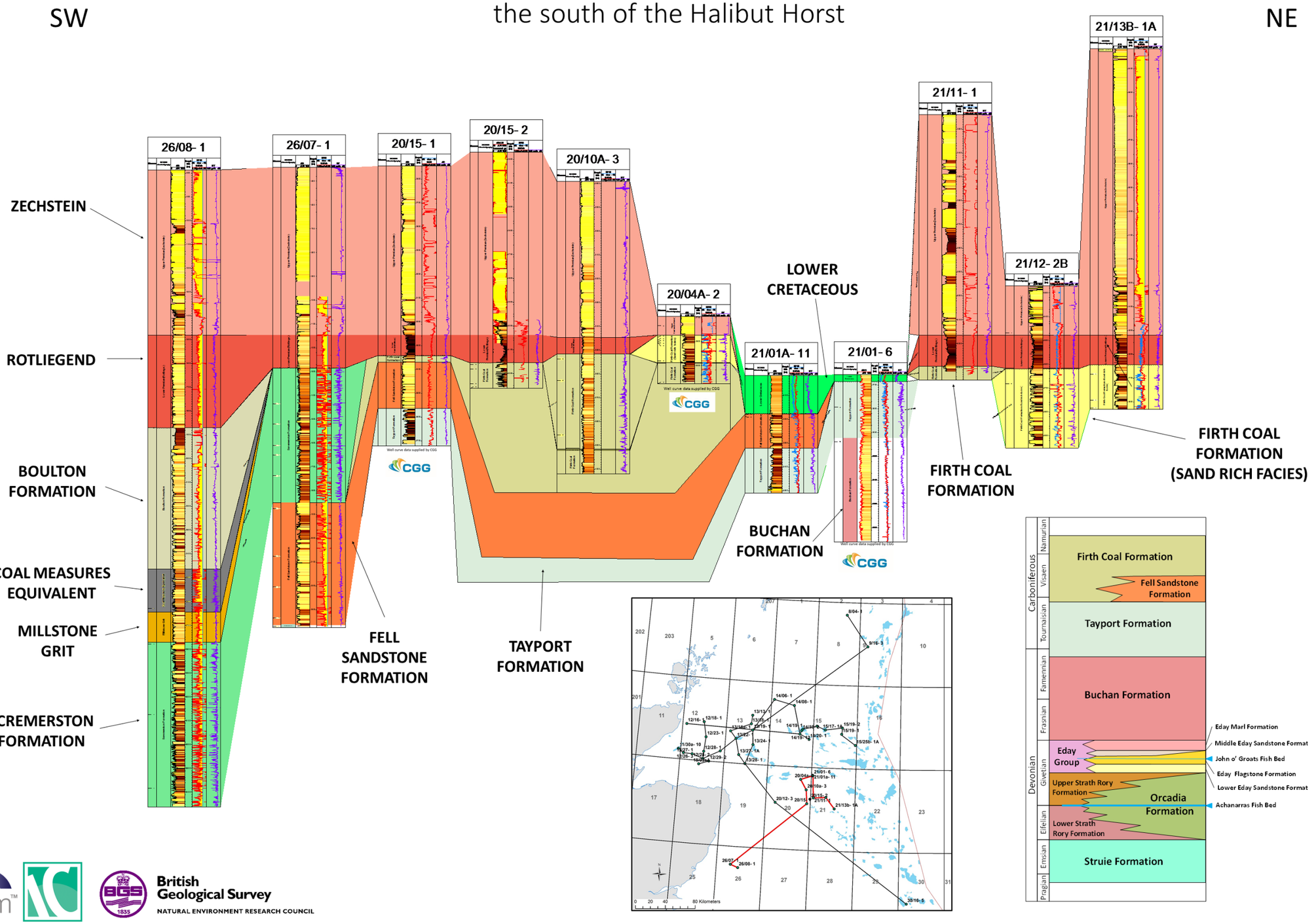


Figure 23 – Panel 5: The Carboniferous of the Witch Ground Graben and surrounding areas.

Panel 6: The Carboniferous succession of the Forth Approaches to the south of the Halibut Horst

SW

NE



British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Figure 24 – Panel 6: The Carboniferous succession of the Forth Approaches to the south of the Halibut Horst.

4 Palaeogeography

Palaeogeographic reconstructions for six time slices from the Devonian to Mississippian are presented in Figures 25 – 30. The maps were constructed using lithostratigraphy and lithofacies information from well records, dated using palynological constraints, and incorporated the detailed, formation level seismic mapping of Arsenikos et al. (2016).

The Devonian to Carboniferous successions were deposited within structural basins developed during periodic phases of extension/transtension. Sedimentation within the Orcadian Basin was more-or-less continuous throughout Devonian times with formation of fault-bound graben and half-graben basins during a phase of Early Devonian extension giving way to regional subsidence during Middle and Late Devonian times. The presence of thick sequences of Middle Devonian strata in the Orcadian Basin contrasts with the situation in the Midland Valley of Scotland, to the south of the Highland Boundary Fault. Here, Late Devonian strata unconformably overlie folded and eroded Early Devonian rocks, indicating that a period of uplift and basin inversion occurred in the Midland Valley during the Middle Devonian.

In the Orcadian area, the environments of deposition were terrestrial and lacustrine to shallow marine throughout Devonian to early Carboniferous times. Alluvial fan conglomerates and fluvial sandstones with some aeolian facies are widespread along the basin margins, where they overly pre-Devonian rocks, and are found around the margins of structural highs within the basin.

Lacustrine facies strata were deposited locally within grabens during the Early Devonian (Figure 25), and more widely across the basin during the Middle Devonian. Two main phases of mid-Devonian lake development have been recognised (Marshall and Hewett, 2003). The first, during the Eifelian to mid Givetian, was the most widespread and prolonged and gave rise to the Orcadia Formation (Figure 26). A second phase of lake development occurred in the late Givetian and is associated with the Eday Flagstone Formation which is known from Orkney and numerous offshore wells in Quadrant 13. The latter lake was superseded by sabkha and marginal marine conditions associated with a global marine highstand (Figure 27).

Late Devonian times were characterised by widespread extension of fluvial environments across the basin and adjacent areas, resulting in deposition of the sandstone-siltstone dominated Buchan Formation. The Buchan Formation forms the main reservoir rocks of the Buchan Field, where the porosity of the tight sandstone is enhanced by fractures.

By early Carboniferous times the widespread fluvial deposition of the Buchan Formation was superseded by the development of local basins in the areas of the Witch Ground Graben, Forth Approaches and in the vicinity of the Buchan Graben. A small Carboniferous basin may also have been developed to the east of Orkney, in the West Fair Isle Basin. Within these basins fluvial-deltaic and associated floodplain strata were deposited, and coal swamps had developed on the floodplains by Chadian times.

In the Inner Moray Firth area, strata of Carboniferous age have been encountered only in well 12/16- 1, and the absence of Carboniferous strata indicates that the area was either upland (e.g. Leeder and Boldy, 1990), or that any Early Carboniferous sediments were eroded prior to the onset of Permian deposition. Well 12/16- 1 is located in a structurally complex region adjacent to the Wick Fault and appears from seismic interpretations to be a local basin unconnected to the larger Carboniferous basin of the Witch Ground Graben to the east.

Thicker successions of channel sandstone of early Visean age, correlated with the Fell Sandstone Formation of the CNS area (Figures 29 and 30), occur in the region to the south-east of the Halibut Horst. These sandstone units are relatively thin, but may represent feeder channel

systems supplying sediment to the well-developed fluvio-deltaic system that lay to the south at this time.

4.1 EARLY DEVONIAN: PRAGIAN - EMSIAN

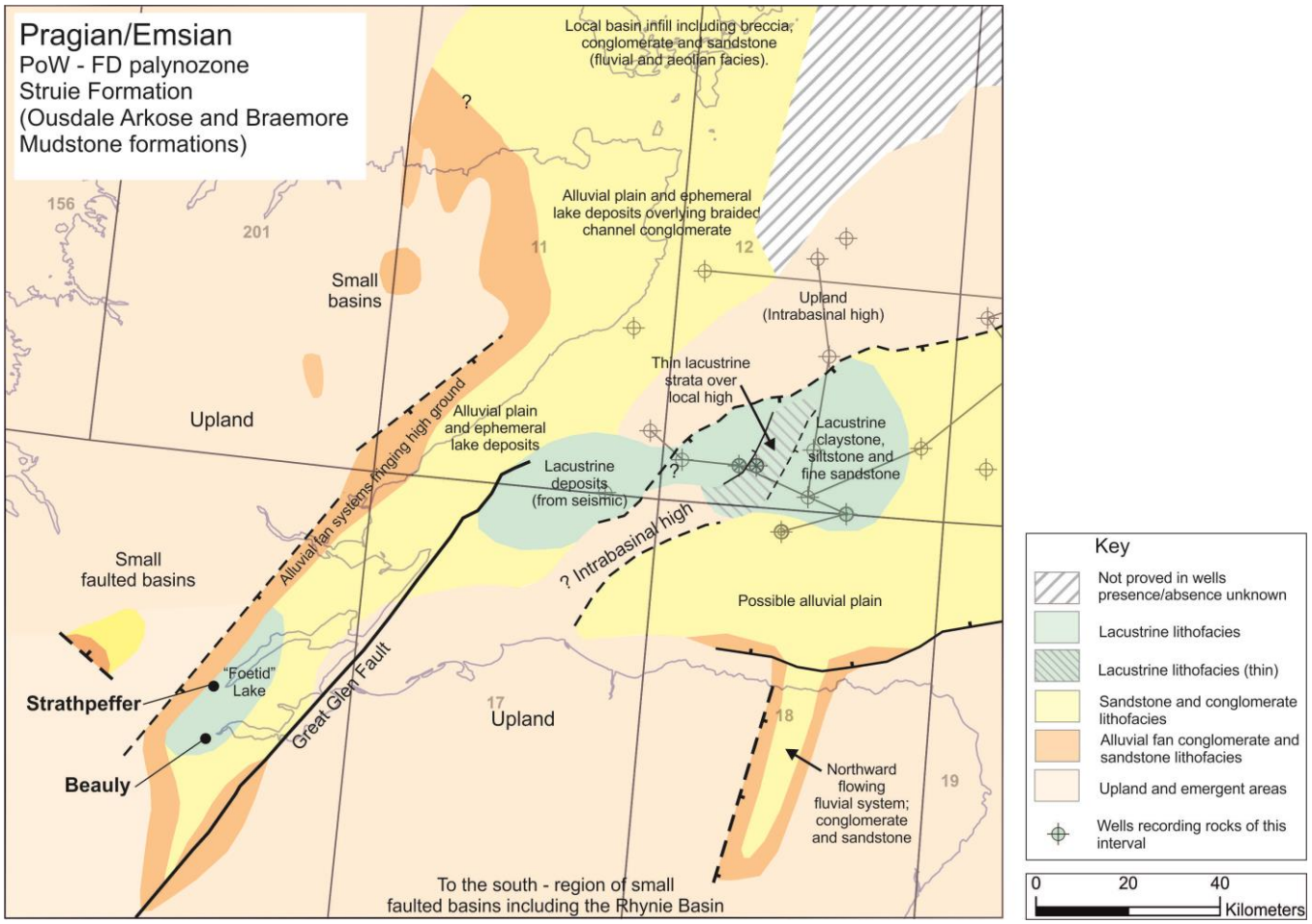


Figure 25 – Palaeogeographic reconstruction of the Inner Moray Firth area for Pragian to Emsian times (Struie Formation).

Pragian – Emsian (PoW – FD palynozone)

Offshore: Struie Formation
Onshore: Braemore Mudstone Formation, Ousdale Arkose Formation

In Early Devonian times, regional extension resulted in the development of localised, fault-bound graben and half graben basins within the mountains of the Grampian Highlands. Deposition of sedimentary rocks within these basins began with the collection of local breccia deposits, perhaps as scree and lag related physical weathering processes, and the formation of extensive alluvial fans comprising coarse-grained cobbles and pebbles at the outlets of rivers draining the mountainous uplands along the basin margins.

Finer-grained fluvial sandstones were deposited in the distal portions of the alluvial fans and in the central areas of the basins where distal fluvial systems and alluvial plains with ephemeral lakes developed. Fluvial drainage paths at this time tended to flow to the north or north-east, following the axes of the developing basins (Richards, 1985a; Trewin and Thirlwall, 2003).

Locally, deeper, more permanent lakes developed within the basins giving rise to successions of lacustrine siltstone and claystone with high organic content (Clarke and Parnell, 1999). Lacustrine successions of Early Devonian age are known on shore from the Strathpeffer – Beauly area and offshore in the southern sector of Quadrant 12 (Clarke and Parnell, 1999; Richards, 1985a). Within the Inner Moray Firth Basin, the Struie Formation succession thins locally over a north-east to south-west oriented intrabasinal high, which may have been bound by active normal faults. An extension of the lacustrine facies west into the southern sector of Quadrant 11 is indicated by the seismic interpretations provided by this study (Arsenikos et al., 2016).

Volcanism occurred locally during Early Devonian times, notably in the area of the Rhynie basin, onshore within the Grampian Highlands. Here, lavas and tuffs are intercalated with fluvial and lacustrine strata that were laid down on an alluvial-plain within the basin (Rice et al., 2002). Locally, geysers and hot-springs produced siliceous sinters that formed cherts preserving the silicified remains of early land plants growing on the alluvial plain, and an associated arthropod fauna (Trewin and Thirlwall, 2002).

Trewin and Thirlwall (2002) suggest that whilst semi-arid conditions tended to dominate during Early Devonian times, temperate conditions persisted for considerable periods; as indicated by the prevalence of fine-grained sediment, plant debris and grey-green mudstone and siltstone in the Early Devonian successions.

4.2 MIDDLE DEVONIAN: EIFELIAN TO MID GIVETIAN

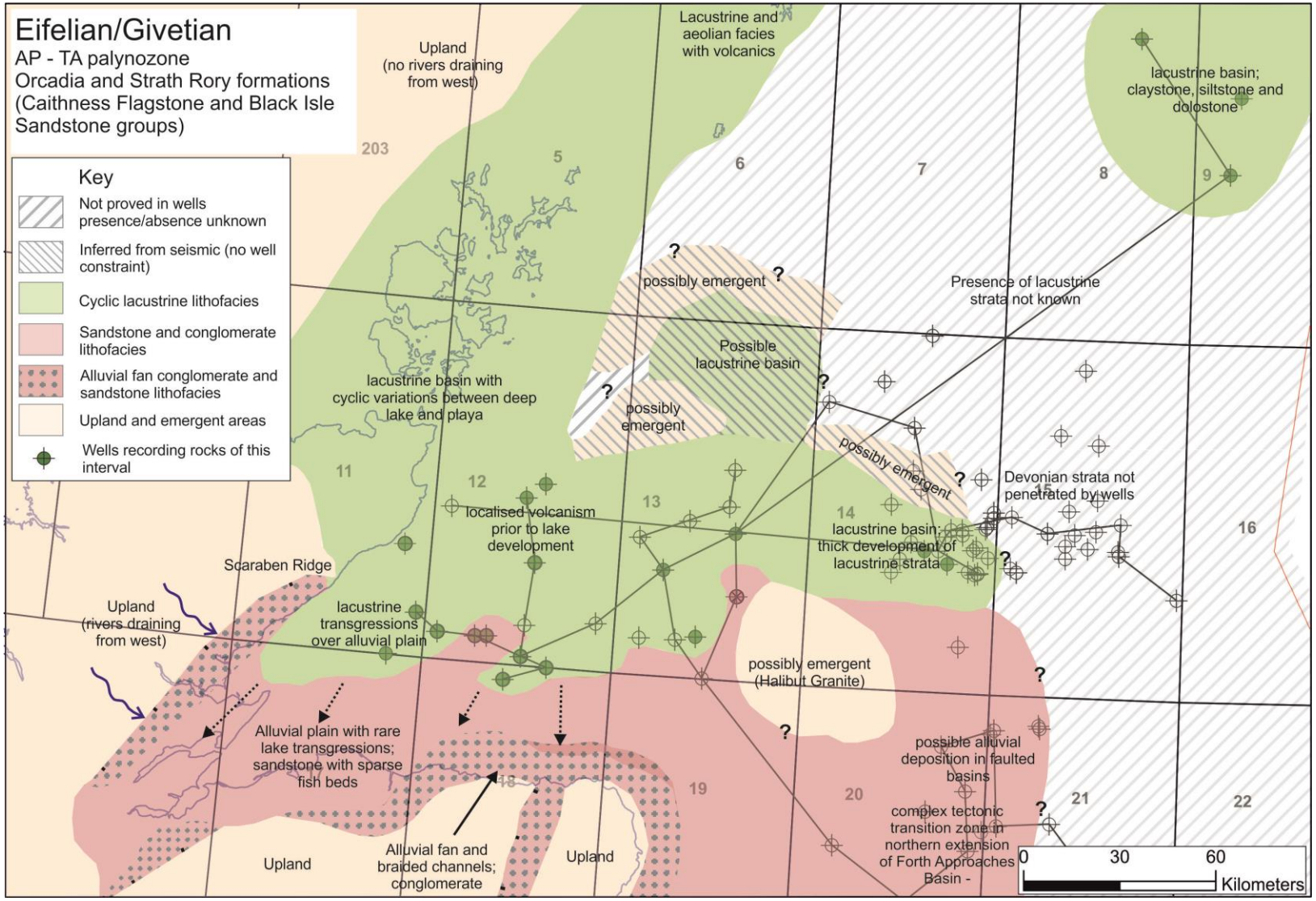


Figure 26 - Palaeogeographic reconstruction of the Orcadian area for Eifelian to Mid Givetian times (Orcadia and Strath Rory formations).

Eifelian – Mid Givetian (AP – TA palynozone)

Offshore: Strath Rory and Orcadia formations
Onshore: Caithness Flagstone Group, Stromness Flagstone Group, Black Isle Sandstone Group

Middle Devonian times were characterised by the widespread development of lacustrine conditions within the Orcadian area. The local basin development of the Early Devonian gave way to more regional subsidence accompanied by an initial phase of regional alluvial fan and alluvial-plain development. Fluvial deposition, fed by rivers draining upland areas to the west and south, continued throughout the Middle Devonian in marginal areas along the southern edge of the basin. To the north, early alluvial deposition was superseded by the development of the Orcadian Lake which extended from Orkney and Caithness eastwards, into offshore areas of Quadrants 11, 12 and 13. Lacustrine facies strata of Eifelian to Givetian age also occur in Quadrant 9 and in Norway (Duncan and Buxton, 1995). Localised volcanism occurred prior to the onset of lacustrine deposition in the region of the Smith Bank High, which was not an active structure at this time (Marshall and Hewett, 2003).

The lacustrine succession is comprised of interbedded organic rich or calcareous claystone, laminated or thinly bedded siltstone, and thin to medium-bedded, very fine to fine-grained sandstone. The strata are notable for their widespread fish bed horizons which are associated with thin sequences of laminated claystone. The cyclic nature of the lacustrine succession is considered to be related to variations in lake depth driven by orbital cycling (Trewin and Thirlwall, 2002).

The fish beds represent lacustrine high-stand events (Duncan and Hamilton, 1988), during which the lake transgressed the basin margins, and occur periodically within alluvial sandstone facies strata along the southern edge of the basin. The most widespread transgressive event occurred in the Late Eifelian to Earliest Givetian and is associated with the Achanarras Fish Bed (equivalent to the Sandwick Fish Bed of Orkney). On the basis of chemical analysis of the Orcadian lacustrine strata, Duncan and Hamilton (1988) speculated that evaporite deposits may have formed in central parts of the Orcadian lake basin during lake low stands, but there remains no offshore evidence to confirm this.

Along the basin margins, the lacustrine facies strata give way to predominantly fluvial sandstone and conglomerate successions to the south, along the edge of the Grampian uplands. The fluvial facies strata of the basin margins are locally associated with lake marginal and aeolian facies sandstone, and there is an increase in the relative proportion of sandstone to finer-grained lacustrine facies to the north. Along the western basin margin in Caithness, lacustrine facies strata overstep Lower Devonian onto basement, indicating that there was a lack of fluvial input along the basin margin in this area.

Widespread lacustrine deposition ceased in Mid Givetian times and alluvial systems deposited fluvial sandstone and conglomerate across much of the former lake basin.

4.3 MIDDLE DEVONIAN: MID TO LATE GIVETIAN

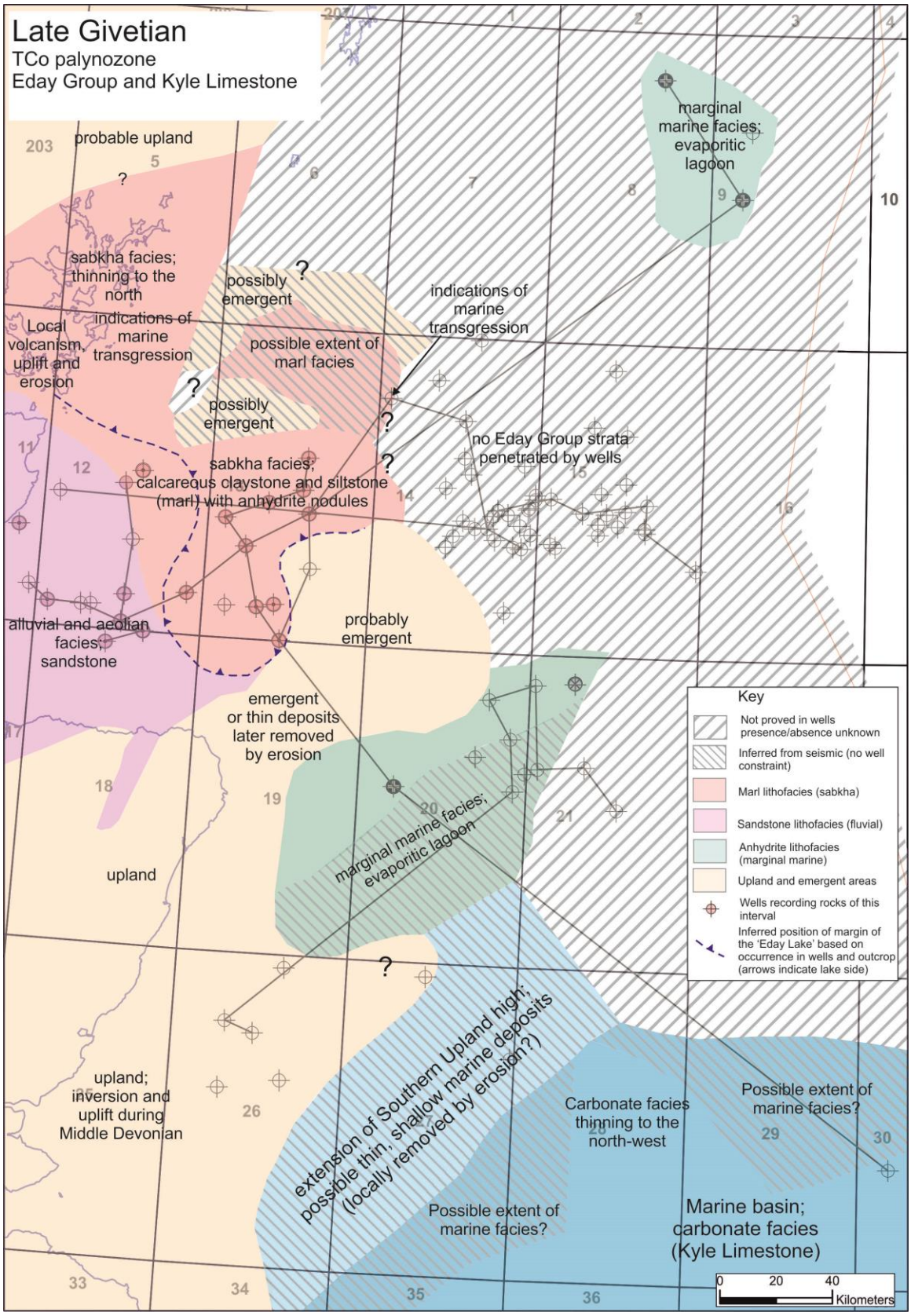


Figure 27 - Palaeogeographic reconstruction of the Orcadian area and Central North Sea for Mid to Late Givetian times, showing the association of the Eday Marl Formation and equivalent marine carbonate (Kyle Group) and marginal evaporite units.

Mid to late Givetian (TCo palynozone)

Offshore: Eday Group and Kyle Limestone (Kyle Group)
Onshore: Eday Group, John o'Groats Sandstone Formation

A redevelopment of lacustrine conditions during the Mid to Late Givetian within the northern part of the Orcadian Basin has been recognised from strata assigned to the Eday Group. The cyclic lacustrine succession of the Eday Flagstone Formation occurs in Orkney and can be recognised offshore throughout the southern half of Quadrant 13 (Marshall and Hewett, 2003). A major high-stand phase in the lake level has been associated with the presence of the John o'Groats fish bed within lake marginal fluvial successions in Caithness and on the Black Isle (Marshall et al., 2011). The presence of the thin fish bed horizon, which can be regionally correlated due to its distinct fish fauna, intercalated within the marginal fluvial sequence indicates a phase of lake transgression across much of the Inner Moray Firth Basin.

Lacustrine conditions were preceded and succeeded by the development of alluvial fans and alluvial plains with local aeolian facies and minor ephemeral lakes, forming the Lower and Middle Eday Sandstone formations (e.g. Astin, 1985; Marshall and Hewett, 2003). Following the deposition of the latter unit, an extensive sabkha plain developed giving rise to the Eday Marl Formation. The sabkha extended from Orkney into the central area of Quadrant 13 where it has been penetrated by numerous wells (Marshall et al., 2011; Marshall and Hewett, 2003). The Eday Marl may also be present in the East Orkney Basin, where a seismic package comparable to the strong Eday Flagstone - Eday Marl reflectors in the Inner Moray Firth Basin can be identified however there are no wells in this basin to confirm the seismic pick (Arsenikos et al., 2016).

Marshall et al. (1996) reported marine microfossils from exposures of the Eday Marl Formation on Orkney, and from similar facies strata of Frasnian age in well 14/6- 1, indicating that several marine transgressions occurred in Late Givetian to Frasnian times (Figure 27). Marshall and Hewett (2003) proposed that the Eday Marl Formation is a proximal equivalent of the Kyle Group (marine carbonate facies) in the Central North Sea. They also highlight evaporites (anhydrite) of Givetian – Frasnian age encountered in wells in Quadrants 8 and 9, and to the south of the Grampian High in Quadrant 20, noting that these units may be associated with evaporitic lagoons formed along the former marine margin. The strata associated with the Eday Group, Kyle Limestone and evaporites are relatively thin, but all are associated with distinctive seismic reflectors or packages, thus providing a regionally important marker horizon at the top of the Middle Devonian (Arsenikos et al., 2016).

Figure 27 shows a partial reconstruction (based on the available well and seismic interpretations) of the relationship between the fluvial, sabkha, evaporitic lagoons and marine facies within the Orcadian and north Central North Sea areas during the Late Givetian (cf. Marshall and Hewett, 2003).

The marine carbonate facies of the Kyle Group of the Central North Sea, penetrated in well 30/16- 5, thin to the north, and may pass laterally into clastic-dominated strata consistent with shallow marine conditions over the north-eastward extension of the Southern Upland block. In this area, lack of deposition of Middle Devonian strata, or erosion of a thin shallow marine succession during Late Devonian to Permian times is indicated by the presence of an unconformity between Permian and Early Devonian or Silurian strata in well 27/03- 1 (Figure 27).

Middle Devonian uplift and inversion of the Midland Valley of Scotland is indicated onshore by an angular unconformity between Early and Late Devonian strata. The effects of the basin inversion are inferred to continue offshore to the north-east into the Forth Approaches Basin,

where no evidence for strata of Middle Devonian age has been found. However, it should be noted that wells penetrating Carboniferous rocks in the centre of the Forth Approaches Basin do not reach strata of Devonian age.

A marginal marine area, with evaporitic lagoons and shallow marine sedimentation, was present to the south of the Grampian High, which was possible emergent during this time. Further evaporite facies, intercalated with palynologically dated strata of Givetian/Eday Group association, occur in well 9/16- 3 (Duncan and Buxton, 1995). These were originally interpreted as part of a continuous sequence of lacustrine sedimentation associated with the Orcadian Lake, but this interpretation has been revised and the anhydrites are now considered to be related to deposition of the Eday Marl Formation and associated marine marginal strata (Marshall and Hewett, 2003; Marshall et al., 2011).

The sabkha facies strata of the Eday Marl Formation occur in an embayment to the north of the Grampian High. The nature and location of the transition between the sabkha and the marginal marine system is poorly known due to a lack of well penetrations through overlying Carboniferous strata to the east and north-east of the Grampian High. The association of the marine carbonates, marginal evaporites and sabkha is consistent with a seaway located to the south and east (Marshall et al., 2011).

4.4 LATE DEVONIAN: FRASNIAN TO FAMENNIAN

Across much of the basin, sabkha conditions were superseded by a return to predominantly alluvial deposition in the Late Devonian. However, in parts of the basin, sabkha plains persisted intermittently into Frasnian times, as indicated in well 14/06- 1, where a palynologically constrained Frasnian succession comprises a sequence of interbedded marl and sandstone (Marshall et al., 1996 and 2011).

The alluvial plain and braid-plain conditions that gave rise to the Buchan Formation were widespread throughout the region. Buchan Formation strata are encountered in wells throughout the Inner Moray Firth and on structural highs adjacent to the Carboniferous basins (Witch Ground Graben and basins south of the Halibut Horst). The unit also occurs widely within the Midland Valley and Forth Approaches basins, and across much of the Central North Sea (Kearsey et al., 2015). Buchan Formation strata are typically barren and palynological constraints are rare, making the unit difficult to distinguish from overlying Permian ‘red beds’ (cf. Marshall and Hewett, 2003).

The Buchan Formation has only been penetrated beneath Carboniferous strata on the top of the Buchan Horst, where it underlies the Tayport Formation. Around the margin of the Carboniferous Basin in the Witch Ground Graben, Buchan Formation strata are encountered on structural highs with Tayport or Firth Coal formations in adjacent basin areas. Marshall and Hewett (2003) speculate that the two units may be in part lateral equivalent due to a notable lack of well penetrations encountering both Formations. However there is no evidence for overlap in their age ranges. The limited depth of well penetrations into Carboniferous strata in Quadrants 14 and 15 precludes further interpretation of the nature of the relationship between these two units.

4.5 EARLY CARBONIFEROUS: TOURNAISIAN – CHADIAN

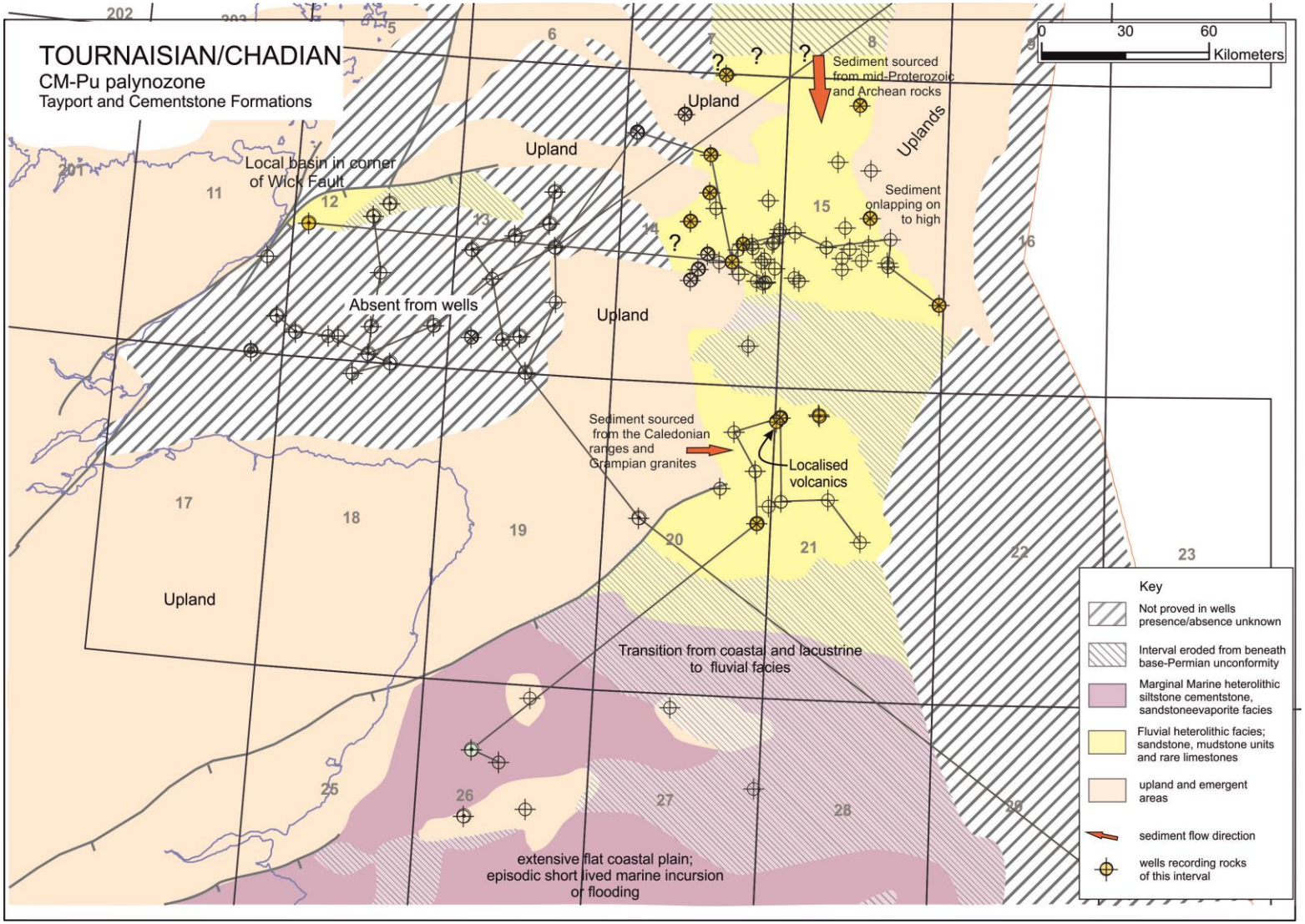


Figure 28 Tournaisian to Chadian palaeogeography (CM- early Pu palynozone)

Tournaisian – Chadian (CM-Pu (early) Palynozone)

Offshore: Cementstone and Tayport formations

Onshore: Ballagan Formation

During this interval deposition in Quadrants14, 15, 20 and 21was dominated by fluvial channel systems, associated overbank deposits and small lakes (Leeder and Boldy, 1990) classified here as the Tayport Formation. This probably represents a narrow alluvial plane between uplands to the east and west. Detrital zircons in the Tayport Formation have been studied in well 14/13- 3 and suggest that the rivers were sourcing material from the Caledonian ranges and a wide range of mid-Proterozoic and Archean rocks (Morton et al., 2001). It has been suggested that the source of these systems lay to the north of the modern North Sea (Morton et al., 2001). Localised volcanism also occurred in the Buchan Graben during this period. In the Inner Moray Firth area, a lack of Carboniferous sediments proved in wells indicates that the area was either upland (e.g. Leeder and Boldy, 1990), or that sediments were deposited and later eroded.

From the Forth Approaches Basin southwards, coastal plain and lacustrine conditions were widespread during deposition of the Cementstone Formation. In the Midland Valley of Scotland and Forth Approaches Basin, coastal-plain siltstones are interbedded with lacustrine siltstones and cementstones; the latter, typically in beds up to 1 m thick were probably deposited in saline lagoons (Anderton, 1985; Scott, 1986; Andrews et al., 1991). The transition between this and the fluvial facies to the north is not seen in any wells, however there is an unconformity identified in the underlying Upper Devonian in the area between the Grampian High and Forth Approaches basin (Arsenikos et al., 2016). This may have formed a minor topographic high in the Carboniferous and limited the extent of which the coastal plain extended northwards.

Onshore, the Ballagan Formation mudstones have low TOC values and probably do not have significant source-rock potential (Monaghan, 2014). The channel sand-bodies present are typically less than 20 m thick, but any substantial lateral continuity has not been proved.

4.6 EARLY CARBONIFEROUS: ARUNDIAN

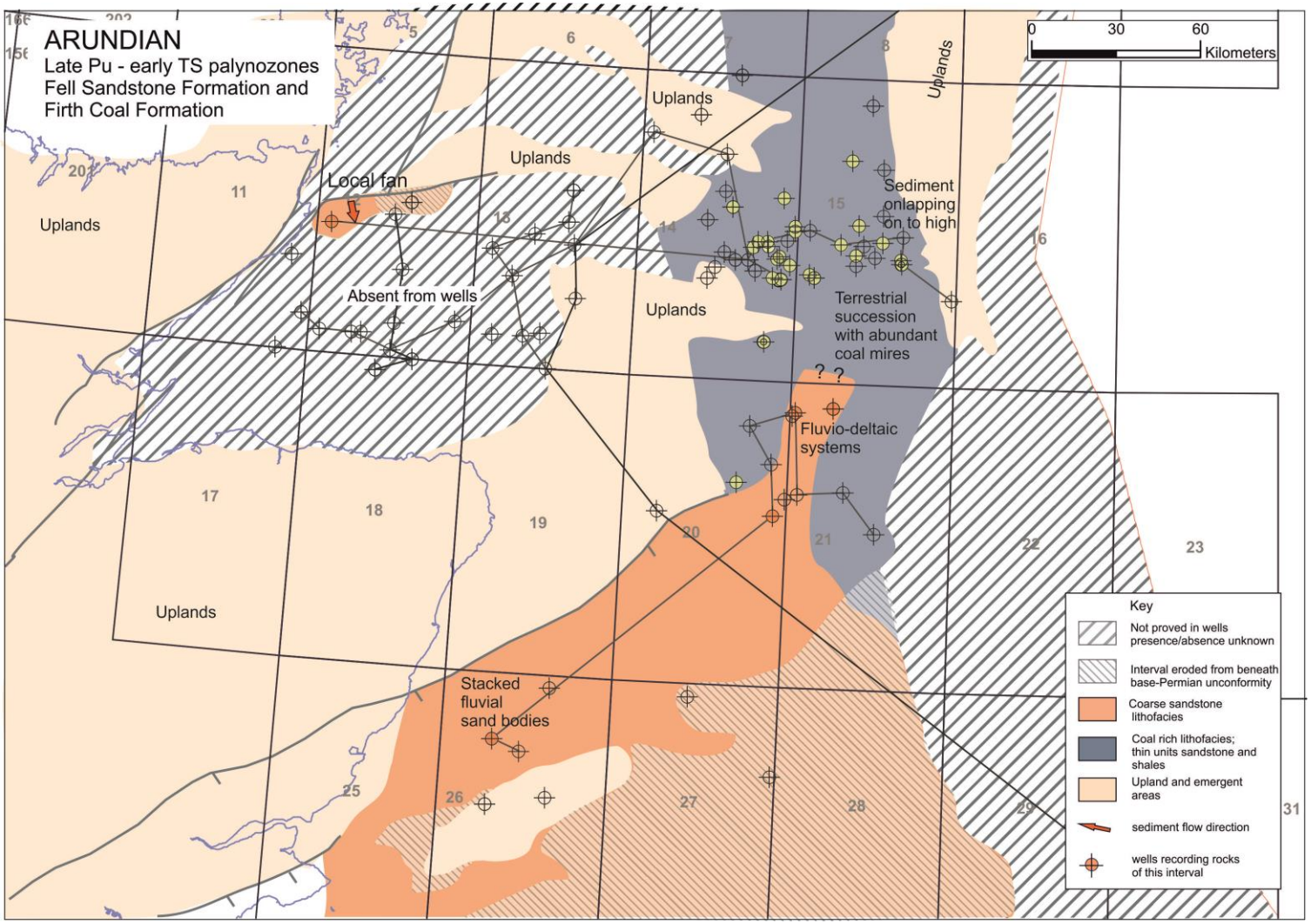


Figure 29 Arundian palaeogeography (Late Pu to early TS Palynozone)

Arundian (Late Pu – early TS Palynozones)

Offshore: Fell Sandstone Formation and Firth Coal Formation.

Onshore: Fell Sandstone Formation (Northern England), Garleton Hills Volcanic Formation (Midland Valley of Scotland).

During Arundian times, the first establishment of a major Carboniferous clastic system occurred across the region. A braided fluvial system, probably originating in the Caledonide Mountains or further to the north, spread coarse-grained sandstone in stacked, multi-storey sheets southward (Turner & Munro, 1987; Morton et al., 2001). This formed the Fell Sandstone Formation deposits south of the Mid North Sea High (Kearsey et al., 2015). In Quadrants 20 and 21, the Fell Sandstone co-exists with the siltstone dominated terrestrial succession and abundant coal mires of the Firth Coal Formation. The association of these units may suggest that in Quadrants 20 and 21 the fluvial system has reached its apex point and the braided fluvial system of the Fell Sandstone Formation is becoming channelised. To the north, in Quadrants 14 and 15, the Firth Coal Formation represents the facies of the alluvial plain developed upstream from the major braid plain, where coal mires, fluvial sandstones, and minor lacustrine units were dominant. On seismic data, the Firth Coal Formation strata can be seen to onlap onto the basin bounding highs located to the east and west.

Onshore, in the Midland Valley, a hiatus and volcanism are observed at this time (Stephenson et al., 2004).

The Fell Sandstone Formation has potential as a reservoir rock. The Firth Coal Formation contains both potential reservoir and source rocks (see Vane et al., 2016). The stratigraphic juxtaposition of these two facies has the potential to set up a source-reservoir association between these two units.

4.7 EARLY CARBONIFEROUS: ASBIAN

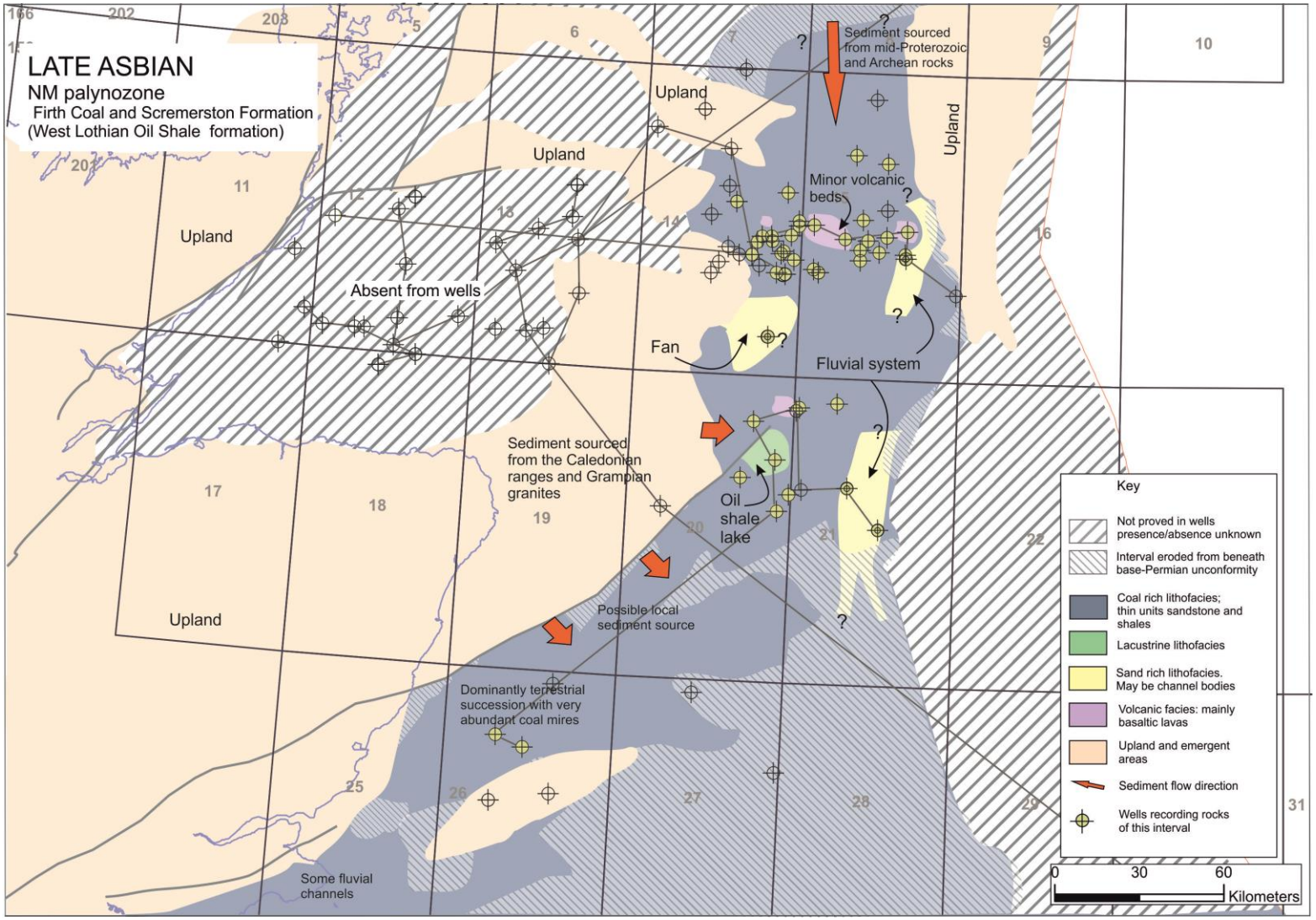


Figure 30 Late Asbian palaeogeography (NM Palynozone)

Late Asbian (NM Palynozone)

Offshore: Scremerston and Firth Coal formations,

Onshore: West Lothian Oil Shale Formation and lateral equivalents

During the Late Asbian, coal mires and fluvial facies continued to develop within the Carboniferous basins of the Quadrants 14, 15, 20 and 21. Coal-rich lithofacies are present across the region and the occurrence of sand-rich lithofacies in some wells indicates that there may have been large scale channel systems running north to south across the area. This is further supported by detrital zircon evidence from the Firth Coal Formation which has similar zircon populations to those seen in the Namurian Ashover Grit and Rough Rock in the Pennine Basin, indicating a common provenance for both systems (Morton et al., 2001). The sand-rich facies recorded in Quadrants 14, 15 and 21 may represent feeder channel systems for the coeval Yoredale Formation delta front on the southern side of the Mid North Sea High. These may be several kilometres wide, similar to those seen in the onshore Scremerston Member in Northumberland (Jones, 2007).

A large lake was established in the eastern part of the Midland Valley, accumulating organic-rich muds that formed the West Lothian Oil Shale Formation (Greensmith, 1962). Oil shale has been identified in well 20/10a- 3 south of the Highland Boundary Fault. Coal and oil-shale within the Firth Coal Formation have the potential as a hydrocarbon source (see Vane et al., 2016).

5 References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

ANDERTON, R. 1985. Sedimentology of the Dinantian of Foulden, Berwickshire, Scotland. *Transactions of the Royal Society of Edinburgh, Earth Sciences*, Vol. 76, 7-12.

ANDREWS, I. J., LONG, D., RICHARDS, P. C., THOMSON, A. R., BROWN, S., CHESHER, J. A. AND MCCORMAC, M. 1990. United Kingdom Offshore Regional Report: The Geology of the Moray Firth. London, HMSO for the British Geological Survey.

ANDREWS, J. E., TURNER, M. S., NABI, G. AND SPIRO, B. 1991. The anatomy of an early Dinantian terraced floodplain: palaeo-environment and early diagenesis. *Sedimentology*, Vol. 38, 271-287.

ANDREWS, S. D., AND HARTLEY, A. J. 2015. The response of lake margin sedimentary systems to climatically driven lake level fluctuations: Middle Devonian, Orcadian Basin, Scotland. *Sedimentology*, Vol. 62, 1693-1716.

ANDREWS, S. D., CORNWELL, D. G., TREWIN, N. H., HARTLEY, A. J. AND ARCHER, S. G. 2016. A 2.3 million year lacustrine record of orbital forcing from the Devonian of northern Scotland. *Journal of the Geological Society*, doi:10.1144/jgs2015-128.

ARSENIKOS, S.,QUINN, M., JOHNSON, K., SANKEY, M AND MONAGHAN, A .A. 2016. Seismic interpretation and generation of key depth structure surfaces within the Carboniferous and Devonian of the Orcadian Basin, Quadrants 7-9, 11 – 15 and 19 - 21 area. *British Geological Survey Commissioned Report*. CR/16/033.

ASTIN, T. R. 1990. The Devonian lacustrine sediments of Orkney, Scotland; implications for climate cyclicity, basin structure and maturation history. *Journal of the Geological Society*, Vol. 147, 141 – 151.

ASTIN, T. R. 1985. The palaeogeography of the Middle Devonian Lower Eday Sandstone, Orkney. *Scottish Journal of Geology*, Vol. 21, 353 – 375.

BAGNALL, J. M., Batten, D. J, Church, J. W., Haskins, C. W., Hoskin, I. R., Kirkman, A. C., Neville, R. S. W., 1972. Micropalaeontology, palynology and stratigraphy of the Occidental 15/11 -1 North Sea Well. Robertson Research International Limited, *Report downloaded from CDA.*

BAGNALL, J. M., CHURCH J. W., HASKINS, C. W., KNOWLES, R. A. AND NEVILLE, R. S. W., 1973. The Micropalaeontology, palynology and stratigraphy of the Occidental 15/17 -1a North Sea Well. Robertson Research International Limited, *Report downloaded from CDA.*

BECKER, R. T., GRADSTEIN, F. M. AND HAMMER, O. 2012. The Devonian Period. In: F. M Gradstein, J. G. Ogg, M. Schmidtz and G. Ogg (Editors), *The Geological Time Scale 2012*. Elsevier, Oxford. 559 – 601. ISBN: 978-0-44-459390-0

BRAHAM, W, JOHNSON, J. E. W, MARSHALL, J. E. A, AND RAC, S. F. 1985. Kerr McGee 12/29- 2 British North Sea Well: Biostratigraphy of the interval 560' – 11692' (core) T.D. Gearhart Geo Consultants Limited, *Report confidential to DECC*

BRITISH GEOLOGICAL SURVEY, 1999. Orkney Islands. Scotland Special Sheet. Solid and Drift Geology 1:100,000. Keyworth, Notthingham, British Geological Survey.

BROWNE, M. A. E., SMITH, R. A. AND AITKEN, A. M. 2002. Stratigraphical framework for the Devonian (Old Red Sandstone) rocks of Scotland south of a line from Fort William to Aberdeen. *British Geological Survey Research Report*, RR/01/04.

BRUCE, D. AND STEMMERIK, L., 2003. Carboniferous. In: D. Evans, C. Graham, A. Armour and P. Bathurst (Editors), *The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea*. The Geological Society of London, pp. 7-1: 7-11.

CAMERON, T.D. J. 1993. 4. Triassic, Permian and Pre-Permian (Central and Northern North Sea). In: R. Knox and W. Cordey (Editors), Lithostratigraphical Nomenclature of the UK North Sea. *British Geological Survey.*

CAMERON, I. B, AND STEPHENSON, D. 1985. British Regional Geology: The Midland Valley of Scotland (3rd Edition). *British Geological Survey*. HMSO, London.

CDA. Unknown Date (possibly 1984) Biostratigraphic Log of unknown origin. File 15_25b-_1A_log_LOG_BIO_131833059.tif

CHURCH J. W., HASKINS, C. W., LOMAS, C. G., NEVILLE, R. S. W. AND RILEY, L. A., 1974. The Micropalaeontology, palynology and stratigraphy of the Occidental 14/19 -2 British North Sea Well. Robertson Research International Limited, *Report downloaded from CDA.*

CHURCH J. W., HASKINS, C. W., NEVILLE, R. S. W., RILEY, L. A. AND UNDERWOOD, J. 1976. The biostratigraphy of the interval 4020' – 7386' from the occidental 14/19- 11 British North Sea Well. Robertson Research International Limited, *Report downloaded from CDA.*

CLARKE, P. AND PARNELL, J. 1999. Facies analysis of a back-tilted lacustrine basin in a strike-slip zone, Lower Devnonian, Scotland. *Palaeogeography, Palaeoclimatology, Palaeoecology,* Vol. 151, 167 – 190.

DONOVAN, R. N. 1980. Lacustrine cycles, fish ecology and stratigraphic zonation in the Middle Devonian of Caithness. *Scottish Journal of Geology*, Vol. 16, 35-50.

DOWNIE, R.A. 1998. Devonian. In: K.W. Glennie (Editor), *Petroleum Geology of the North Sea*. 4th Edition. Blackwell Science Ltd, London. 85 - 103.

DUNCAN, A. D. AND BUXTON, N. W. K. 1995. New evidence for evaporitic Middle Devonian lacustrine sediments with hydrocarbon source potential on the East Shetland Platform, North Sea. *Journal of the Geological Society, London*. 152, 251 – 258.

DUNCAN, A. D. AND HAMILTON, R. F. M. 1988. Palaeolimnology and organic geochemistry of the Middle Devonian in the Orcadian Basin. In: A. J. Fleet, K. Kelts and M. R. Talbot (Editors), *Lacustrine Petroleum Source Rocks*. Geological Society Special Publication No. 40, 173 – 201.

EDWARDS, C. W. 1991. The Buchan Field, Blocks 20/5a and 21/1a, UK North Sea. *United Kindgom Oil and Gas Fields, 25 Years Commemorative Volume,* Geological Society Memoir no. 14, 253 - 259.

GEOSTRAT, 1990. Ultramar U.K.C.S. Well 12/13- 1: Biostratigraphy of the interval 2140 ft. – 11,148 ft. (core). GeoStrat, *Report confidential to DECC*

GREENSMITH, J. T. 1962. Rhythmic deposition in the Carboniferous oil-shale group of Scotland. *Journal of Geology* 70: 355-364.

HALLIDAY, A. N., MCALPINE, A., and MITCHELL, J. G. 1977. Age of the Hoy Lavas, Orkney. *Scottish Journal of Geology*, Vol. 13, 43 – 52.

HANNIS, S. 2016. Reservoir evaluation of 3 wells in the Palaeozoic of th Orcadian Basin (UK North Sea): Petrophysical interpreations of clay volume, porosity and permeability estimations. *British Geological Survey Commercial in Confidence Report*. CR/16/035.

HARDING, A. M., NEVILLE, R. S. W., SHIPP, D. J., AND WREGLESWORTH, I. 1984. Tenneco 12/28-2 British North Sea Well: Biostratigraphy of the interval 515' – 8084' T.D. Robertson Research International Limited, *Report downloaded from CDA.*

HARRIS, C. R., MARSHALL, K. L., MATHESON, F. E., MCNAUGHTAN, S. Y., AND RICH, B., 1998, Well: 20/15-2, British North Sea, Biostratigraphy of the Intervals, Robertson Research International Limited, *Report downloaded from CDA.*

JOHNSON, H., RICHARDS, P. C., LONG, D., AND GRAHAM, C. C. 1993. United Kingdom offshore regional report: the geology of the northern North Sea. (London: HMSO for British Geological Survey.)

JONES, N. S. 2007. The Scremerston Formation: results of a sedimentological study of onshore outcrop sections and offshore Well 42/13-2. *British Geological Survey Commissioned Report*, CR/07/101. 70pp

KEARSEY, T., ELLEN, R., MILLWARD, D. AND MONAGHAN, A. A. 2015. Devonian and Carboniferous stratigraphical correlation and interpretation in the Central North Sea, Quadrants 25 – 44. *British Geological Survey Commissioned Report*, CR/15/117. 808180pp

KELLY, S. B. 1992. Milankovitch cyclicty recorded from Devonian non-marine sediments. *Terra Nova*, Vol. 4, 578-584.

LEEDER, M. R., AND BOLDY, S. A. R. 1990. The Carboniferous of the Outer Moray Firth Basin, Quadrants 14 and 15, Central North Sea. *Marine and Petroleum Geology*, Vol. 7, 29-37.

MARSHALL, J. E. A, ASTIN, T. R., BROWN, J. F., MARK-KURIK, E. AND LAZAUSKIENE, J, 2007. Recognising the Kačák Event in the Devonian terrestrial environment and its implications for understanding land-sea interactions. In: R. T. Becker and W. T. Kirchgasser (Editors), *Devonian Events and Correlations*. The Geological Society, London, Special Publications, 278, 133 – 155.

MARSHALL, J. E. A., BROWN, J. F. AND ASTIN, T. A, 2011. Recognising the Taghanic Crisis in the Devonian terrestrial environment and its implications for understanding land-sea interactions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, Vol. 304, 165 – 183.

MARSHALL, J. AND FLETCHER, T. P., 2002. Middle Devonian (Eifelian) spores from a fluvial dominated lake margin in the Orcadian Basin, Scotland. *Review of Palaeobotany and Palynology*, Vol. 118, 195 – 209.

MARSHALL, J. AND HEWETT, T., 2003. Devonian. In: D. Evans, C. Graham, A. Armour and Bathurst (Editors), The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. *The Geological Society of London*, pp. 6-1: 6-16.

MARSHALL, J., RODGERS, D. A. AND WHITELEY, M. J. 1996. Devonian marine incursions into the Orcadian Basin, Scotland. *Journal of the Geological Society, London*. Vol. 153 pp. 451-466.

MCMILLAN, A. A, FLOYD, J. D, BARNES, R. P. AND PHILLIPS, E. R. 2012. British Regional Geology: South of Scotland (4th Edition). *British Geological Survey*, Keyworth, Nottingham.

MONAGHAN, A. A. AND PARRISH, R. R. 2006. Geochronology of Carboniferous - Permian volcanism in the Midland Valley of Scotland: implications for regional tectono-magmatic evolution and the numerical timescale. *Journal of the Geological Society of London*, 163, 15–28.

MONAGHAN, A. A. 2014. The Carboniferous shales of the Midland Valley of Scotland: geology and resource estimation. British Geological Survey for Department of Energy and Climate Change, London, UK.

MONAGHAN, A. A., JOHNSON, K. AND THE PROJECT TEAM. 2016. Palaeozoic Petroleum Systems of the Orcadian Basin to Forth Approaches, Quadrants 6-21, UK. *British Geological Survey Commissioned Report*, CR/16/038.

MONAGHAN, A. A., BROWNE, M. A. AND BARFOD, D. N., 2014. An improved chronology for the Arthur's Seat volcano and Carboniferous magmatism of the Midland Valley of Scotland. *Scottish Journal of Geology*, Vol. 50(2): 165-172

MORTON, A. C., CLAOUÉ-LONG, J. C., & HALLSWORTH, C. R. 2001. Zircon age and heavy mineral constraints on provenance of North Sea Carboniferous sandstones. *Marine and Petroleum Geology*, Vol. 18(3), 319-337.

MYKURA, W. 1976. British Regional Geology: Orkney and Shetland, Orkney. *Institute of Geological Sciences.* HMSO, Edinburgh.

OCCIDENTAL PETROLEUM LTD. 1984. U.K. North Sea well 13/28- 4, 6th round. Occidental Petroleum (Caledonia) Limited, *Report confidential to DECC.*

OWENS, B. 1986a. Palynological report Devonian sediments from well 14/19- 11. *BGS commercial in confidential palynological report PD/86/153.*

OWENS, B. 1986b. Palynological report on cutting samples of Devonian age from well 13/22- 1. BGS palynological report, *Report downloaded from CDA.*

PALAEOSERVICES LTD. 1975. Zapex (U.K.) Limited well 21/2- 1: Stratigraphical/Palaeontological Final Report. Palaeoservices Limited, *Report downloaded from CDA.*

RICE, C. M., ASHCROFT, W. A., BATTEN, D. J., BOYCE, A. J., CAULFIELD, J. B. D., FALLICK, A. E., HOLE, M. J., PEARSON, M. J., ROGERS, G., SAXTON, J. M., STUART, F. M., TREWIN, N. H. AND TURNER, G. 1995. A Devonian auriferous hot spring system, Rhynie, Scotland. *Journal of the Geological Society, London*, Vol. 152, 229 – 250.

RICE, C. M., TREWIN, N. H. AND ANDERSON, L. I. 2002. Geological setting of the Early Devonian Rhynie cherts, Aberdeenshire, Scotland: and early terrestrial hot spring system. *Journal of the Geological Society, London*, Vol. 159, 203 – 214.

RICHARDS, P. 1985a. A Lower Old Red Sandstone lake in the offshore Orcadian Basin. *Scottish Journal of Geology*, Vol. 21, 381 – 383.

RICHARDS, P. 1985b. Upper Old Red Sandstone sedimentation in the Buchan oilfield, North Sea. *Scottish Journal of Geology*, Vol. 21, 227 – 237.

RICHARDSON, J. B. AND MCGREGOR, D.C. 1986. Silurian and Devonian spore zones of the Old Red Sandstone region. *Geological Survey of Canada Bulletin*, Vol. 364, 1 – 79.

ROBSON, D. A. 1956. A sedimentary study of the Fell Sandstone of the Coquet Valley, Northumberland. *Quarterly Journal of the Geological Society*, Vol. 112: 241-262

RUSCA V. 1988. Occidental 14/19- 22A British North Sea well: Biostratigraphy of the interval 7200' to 11222' TD. Robertson Research International Limited, *Report downloaded from CDA.*

SCOTT, W. B. 1986. Nodular carbonates in the Lower Carboniferous, Cementstone Group of the Tweed Embayment, Berwickshire: evidence for a former sulphate evaporite facies. *Scottish Journal of Geology*, Vol. 22, 325-345.

STEPHENSON, D., BEVINS, R. E., MILLWARD, D, HIGHTON, A. J., PARSONS, I., STONE, P., AND WADSWORTH, W. J. 1999. Caledonian Igneous Rocks of Great Britain. *Geological Conservation Review Series*, Vol. 17. Joint Nature Conservation Committee, Peterborough.

STEPHENSON, D. AND GOULD, D. 1995. British Regional Geology: The Grampian Highlands (4th Edition). *British Geological Survey*, HMSO, London.

STEPHENSON, M. H., WILLIAMS, M., MONAGHAN, A. A., ARKLEY, S., SMITH, R. A., DEAN, M., BROWNE, M.A.E. & LENG, M. 2004. Palynomorph and ostracod biostratigraphy of the Ballagan Formation, Midland Valley of Scotland, and elucidation of intra-Dinantian unconformities. *Proceedings of the Yorkshire Geological Society* 55: 131-143

STREEL, M. 2009. Upper Devonian miospore and conodont zone correlation in western Europe. In: P. Königshof (Editor), *Devonian Change: Case Studies in Palaeogeography and Palaeoecology*. The Geological Society, London, Special Publications, 314, 163 – 176.

STREEL, M., HIGGS, K., LOBOZIAK, S., RIEGEL, W. AND STEEMANS, P. 1987. Spore stratigraphy and correlation with faunas and floras in the type marine Devonian of the Ardenne-Rhenish region. *Review of Palaeobotany and Palynology*, Vol. 50, 211 – 229.

TREWIN, N. H., and HURST, A. 2009. Excursion guide to the geology of East Sutherland and Caithness. Dunedin Academic Press Ltd., Edinburgh. ISBN 0 7073 0731 7.

TREWIN, N. H., and THIRLWALL, M. F. 2002. Old Red Sandstone. In: Trewin, N. H. (Editor) *The Geology of Scotland*. The Geological Society, London. 213 – 249.

TURNER, B. R. AND MONRO, M. 1987. Channel formation and migration by mass-flow processes in the Lower Carboniferous fluviatile Fell Sandstone Group, northeast England. *Sedimentology*, Vol. 34(6), 1107-1122.

UNDERHILL, J. R., MONAGHAN, A. A. & BROWNE, M. A. E. 2008. Controls on structural styles, basin development and petroleum prospectivity in the Midland Valley of Scotland. *Journal of Marine and Petroleum Geology* 25: 1000-1022

VANE, C. H., UGANA, C., KIM, A. W. AND MONAGHAN, A. A. 2016. Organic Geochemistry of Palaeozoic Source Rocks, Orcadian Study Area, North Sea, UK. *British Geological Survey Commissioned Report*, CR/16/037. 41pp.

WATERS, C. N., SOMERVILLE, I. D., STEPHENSON, M. H., CLEAL, J. C. AND LONG S. L. 2011. Chapter 3: Biostratigraphy. In *"A revised correlation of Carboniferous rocks in the British Isles."* Geological Society of London.

Appendix 1

Carboniferous biostratigraphic correlations used in this project.

These are all taken from C.N.WATERS, I. D. SOMERVILLE, M. H. STEPHENSON, C. J. CLEAL & S. L. LONG, 'Chapter 3 Biostratigraphy, *in "A revised correlation of Carboniferous rocks in the British Isles."* Geological Society of London, 2011,

Marine band and Ammonoid Zones

REGIONAL STAGES	REGIONAL SUBSTAGES	ZONES Index	ZONES Ammonoid	WESTERN EUROPEAN MARINE BANDS Index	WESTERN EUROPEAN MARINE BANDS Ammonoid
WESTPHALIAN	Langsettian (pars)	G2	*Gastrioceras listeri*		
			Gastrioceras subcrenatum		
NAMURIAN	Yeadonian	G1b	*Cancelloceras cumbriense*	G1b1	*Ca. cumbriense*
		G1a	*Cancelloceras cancellatum*	G1a1	*Ca. cancellatum*
	Marsdenian	R2c	*Bilinguites superbilinguis*	R2c2	*Verneulites sigma*
				R2c1	*B. superbilinguis*
		R2b	*Bilinguites bilinguis*	R2b5	*B. metabilinguis*
				R2b4	*B. eometabilinguis*
				R2b3	*B. bilinguis*
				R2b2	*B. bilinguis*
				R2b1	*B. bilinguis*
		R2a	*Bilinguites gracilis*	R2a1	*B. gracilis*
	Kinderscoutian	R1c	*Reticuloceras reticulatum*	R1c4	*R. coreticulatum*
				R1c3	*R. reticulatum*
				R1c2	*R. reticulatum*
				R1c1	*R. reticulatum*
		R1b	*Reticuloceras eoreticulatum*	R1b3	*R. stubblefieldi*
				R1b2	*R. nodosum*
				R1b1	*R. eoreticulatum*
		R1a	*Hodsonites magistrorum*	R1a5	*R. dubium*
				R1a4	*R. todmordenense*
				R1a3	*R. subreticulatum*
				R1a2	*R. circumplicatile*
				R1a1	*Ho. magistrorum*
	Alportian	H2c	*Vallites eostriolatus*	H2c2	*Homoceratoides prereticulatus*
				H2c1	*V. eostriolatus*
		H2b	*Homoceras undulatum*	H2b1	*H. undulatum*
		H2a	*Hudsonoceras proteum*	H2a1	*Hd. proteum*
	Chokierian	H1b	*Homoceras beyrichianum*	H1b2	*Isohomoceras*. sp. nov.
				H1b1	*H. beyrichianum*
		H1a	*Isohomoceras subglobosum*	H1a3	*I. subglobosum*
				H1a2	*I. subglobosum*
				H1a1	*I. subglobosum*
	Arnsbergian	E2c	*Nuculoceras stellarum*	E2c4	*N. nuculum*
				E2c3	*N. nuculum*
				E2c2	*N. nuculum*
				E2c1	*N. stellarum*
		E2b	*Cravenoceratoides edalensis*	E2b3	*Ct. nititoides*
				E2b2	*Ct. nitidus*
				E2b1	*Ct. edalensis*
		E2a	*Cravenoceras cowlingense*	E2a3	*Eumorphoceras yatesae*
				E2a2a	*C. gressinghamense*
				E2a2	*Eumorphoceras ferrimontanum*
				E2a1	*C. cowlingense*
	Pendleian	E1c	*Cravenoceras malhamense*	E1c1	*C. malhamense*
		E1b	*Cravenoceras brandoni*	E1b2	*Tumulites pseudobilinguis*
				E1b1	*C. brandoni*
		E1a	*Cravenoceras leion*	E1a1	*C. leion*
VISEAN	Brigantian	P2c	*Lyrogoniatites georgiensis*		
		P2b	*Neoglyphioceras subcirculare*		
		P2a	*Lusitanoceras granosus*		
		P1d	*Paraglyphioceras koboldi*		
		P1c	*Paraglyphioceras elegans*		
		P1b	*Arnsbergites falcatus*		
	Asbian	P1a	*Goniatites crenistria*		
		B2b	*Goniatites globostriatus*		
		B2a	*Goniatites hudsoni*		
	Holkerian	B1			
	Arundian	BB	*Bollandites-Bollandoceras*		
	Chadian	FA	*Fascipericyclus-Ammonellipsites*		
TOURNAISIAN	Courceyan		*Pericyclus*		
			Gattendorfia subinvoluta		

Miospore zonation

STAGES	SUBSTAGES	FORMER INDEX	INDEX		ZONES	SUBZONE
AUTUNIAN	Lower Autunian		VC		*Vittatina costabilis*	
STEPHANIAN	Stephanian C	XII	NBM		*Potonieisporites novicus-bhardwajii-Cheiledonites major*	
	Stephanian B		ST		*Angulisporites splendidus-Latensina trileta*	
	Barruelian		OT		*Thymospora obscura-T. thiessenii*	
	Cantabrian					
WESTPHALIAN	Asturian	XI				
	Bolsovian	X	SL		*Torispora securis- T. laevigata*	
		IX	NJ		*Microreticulatisporites nobilis-Florinites junior*	
	Duckmantian	VIII				
		VII				
	Langsettian		RA		*Radiizonates aligerens*	
		VI				
		SS	SS		*Triquitrites sinani-Cirratriradites saturni*	
NAMURIAN	Yeadonian	FR	FR		*Raistrickia fulva-Reticulatisporites reticulatus*	
	Marsdenian					
	Kinderscoutian	KV	KV		*Crassispora kosankei-Grumosisporites varioreticulatus*	
	Alportian	SO	SO	SR	*Lycospora subtriquetra-Kraeuselisporites ornatus*	*L. subtriquetra-Cirratriradites rarus*
	Chokierian			SV		*L. subtriquetra-Apiculatisporis variocorneus*
	Arnsbergian					
		TK	TK		*Mooreisporites trigallerus-Rotaspora knoxi*	
	Pendleian	NC	CN	Vm	*Reticulatisporites carnosus-Bellispores nitidus*	*Verrucosisporites morulatus*
VISEAN	Brigantian			Cc		*Cingulizonates* cf. *capistratus*
		VF	VF		*Tripartites vetustus-Rotaspora fracta*	
	Asbian	NM	NM	ME	*Raistrickia nigra-Triquitrites marginatus*	*Murospora margodentata-Rotaspora ergonulii*
				DP		*Tripartites distinctus-Murospora parthenopia*
		TC	TC		*Perotrilites tessellatus-Schulzospora campyloptera*	
	Holkerian	Pu	TS		*Knoxisporites triradiatus-Knoxisporites stephanephorus*	
	Arundian		Pu		*Lycospora pusilla*	
	Chadian					
TOURNAISIAN	Courceyan	CM	CM		*Schopfites claviger-Auroraspora macra*	
			PC		*Spelaeotriletes pretiosus-Raistrickia clavata*	
		VI	BP		*Spelaeotriletes balteatus-Rugospora polyptycha*	
			HD		*Kraeuselisporites hibernicus-Umbonatisporites distinctus*	
			VI		*Vallatisporites vallatus-Retusotriletes incohatus*	