**The Palaeozoic petroleum system in the north of Scotland - outcrop analogues**

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Abstract: All the components of an exhumed Devonian petroleum system occur in Orkney. These include a good quality mature source rock to bitumen bearing sandstone reservoirs, with several separate accumulations that could have held about 1.88 billion barrels of oil. The exhumed system presents an excellent analogue for deeply buried petroleum systems offshore. Whilst lighter oils are now absent, reported oil shows occur, commonly associated with faults cutting the Eday Group. On Orkney, Middle Devonian source rocks (750 m thick) were thick lacustrine laminites (fish beds) representing some 30% of the sequence*.* RockEval and vitrinite analyses show the organic matter is good quality Type I and II and within the early oil window. These source rocks underwent burial until Permian inversion. Several exhumed reservoirs occur on Orkney in aeolian and fluvial sandstones with porosities from 15-25%. These reservoirs have been “breached” losing the light end hydrocarbons leaving pore space oil stain and bitumen residues. Thin fluvial and sheet-floods sands found within the lake cycles have bitumen residues and provided connectivity between the thicker reservoir units. All types of trap are found including a major, broad anticline running N-S on Mainland Orkney and an unconformity with fault traps and pinch-outs.

In the Devonian Old Red Sandstone (ORS) of Scotland, there is a distinctive northern accumulation of lacustrine, fluvial and aeolian sediments that is known as the Orcadian Basin (Trewin & Thirwall 2002). These sediments were deposited in a series of generally N-S aligned half-graben that formed in response to extensional collapse of the Caledonian Orogen. The southern limit to the Orcadian Basin (Fig. 1) is the Highland Boundary Fault (Marshall & Hewett 2003), with a series of related half-graben extending northwards to East Greenland. Some of the Early and Mid-Devonian sediments that infilled these half-grabens are organic rich lacustrine mudrocks and the proven source rock for the Beatrice Field (Marshall et al. 1996; Marshall & Hewett 2003) in the Inner Moray Firth which produced nearly 0.5 billion barrels of oil. The onshore Orcadian Basin has excellent sections of both exposed source rocks and directly linked reservoired oils, although these are now breached and degraded following surface exposure. There are oil seeps within the system, mostly associated with faults (e.g., in the ‘red mudstone’ core of a fault within the Lower Stromness Flagstone Formation in the Bay of Creekland, south of Bu on North Hoy, HY 237043). Although poorly documented at the time a “gas blowout” was reported (Sandy Firth *pers. comm.*) in WWII when a deep water-well was drilled on the Island of Shapinsay. The “blowout” lasted for three days and is interpreted as representing the trapped gas component of a hydrocarbon system.

We take the opportunity to review the onshore geology of this petroleum system including detailed mapping of a breached, giant oil accumulation. This review will emphasise how recent developments in our understanding of Orcadian Basin structure, stratigraphy, sedimentology and geochronology enable more refined petroleum system models to be developed.

*Structural history*

The structural history of the Orcadian Basin area started in the late Silurian to early Devonian as a consequence of the collision between the Baltic and Laurentian Plates (Fig. 1). This oblique collision between the two continents created sinistral strike-slip movement on the Great Glen Fault (GGF) system. Early Devonian rebound and extensional tectonics formed sets of north-south trending half-graben systems that generally dip to the east on the west side of the basin and dip west on the east side. The centre of the basin following along the original suture lay to the east of Orkney and Shetland, which was located (Torsvik & Cocks 2017) about 25° south of the equator at this time. Rapid infill of these original half-graben basins with coarse sediments and boulder conglomerates created a number of essentially isolated lake basins that eventually coalesced to form the larger Orcadian Basin. At maximum extent this Orcadian Basin was about 2000 km long and 250 km wide with subdued topography apart from foot wall remnants of basement that were emergent above the basin floor as islands. During the Mid Devonian, (approximately early Eifelian to early Givetian), this shallow lake basin was filled with about 1 km of grey and black thinly bedded flagstones that represent the rhythmic lake sediments of Lake Orcadie. The Lake Orcadie waters reached their maximum extent (Marshall *et al.* 2007) in the latest Eifelian during deposition of the Sandwick Fish Bed. During the Early Mid Devonian, episodes of magmatic extrusion occurred particularly in West Shetland (Melby and Eshaness; Mykura 1976; Marshall 2000), and are represented in Orkney by an ash layer in the Sandwick Fish Bed. Extrusive volcanic rocks were only erupted extensively in Orkney after deposition of the Lower Eday Sandstone (Fig. 2). The sedimentary style at this time (late Givetian to early Late Devonian) was of mainly fluvial and aeolian sediments.

During the Early Carboniferous, extensional rifting occurred in southern Scotland. In the late Carboniferous, additional movement on the wrench fault systems created broad folding cut by the Late Carboniferous dykes dated at 313 ± 3 Ma at Garthna Geo, Yesnaby, Orkney (Lundmark *et al.* 2011) and perhaps associated with late Variscan regional extension. In northern Scotland, Late Permian sediments (Marshall *et al*., this volume) were deposited unconformably on the Carboniferous erosion surface. This late Carboniferous to early Permian inversion has been related to continuing Variscan shortening (Woodcock & Strachan 2012).

Subsequent dextral movements on the Great Glen Fault and related reactivation of normal faults as reversed faults with mineralisation and fault breccias has been dated at 264 ± 3 Ma (Dichiarante *et al.* 2016). Late Permian rifting on the western margin of the Orcadian Basin has been related to early breakup of the north Atlantic, while Triassic extensional rifting in the North Sea area between 251-200 Ma led to gentle uplift in the Orcadian Basin area (Goldsmith *et al.* 2003).

During the Late Cretaceous, the central part of the Orcadian Basin, along with the Highlands of Scotland would have been covered by chalk seas. In the latest Cretaceous and Paleogene apatite fission track analysis shows the area underwent a major basin inversion (Thomson *et al.* 1999) and was exhumed to form an eroding land mass. This uplift was driven by the mantle plume that was responsible for the final opening of the North Atlantic. The effects of this uplift can be shown in the East Orkney and Dutch Bank basins directly to the east of the Orkney Islands, where there is a preserved Cenozoic infill (Richardson *et al*. 2005). The deformation of this infill shows there was a general inversion on the faults. The presence of the infill is, in itself, significant as the main sediment source can only have been the emerging and eroding land areas to the west *i.e.* Orkney and generally across the Moray Firth area (Guariguata-Rojas & Underhill 2017). In Orkney itself, this breakup of the North Atlantic and North Sea led to compressional tectonics.

## *The West Orkney Basin*

Recent hydrocarbon exploration (Premier Oil 2013) involved the acquisition and reprocessing of 6000 line km of seismic data. This seismic data has provided a clearer picture of the West Orkney Basin structure (Fig. 3). Two wells were drilled in the basin, in 1984 (202/19-1) and 1991 (202/18-1). Both wells intersected a Permo-Triassic succession over 3 km thick (Hitchen *et al.* 1995) but failed to find hydrocarbons. The presence of a Devonian section in the basin centre became a major question. The new data and correlation of the offshore seismic to the onshore geology (Bird *et al.* 2015) has suggested the Devonian section does indeed extend out into the basin centre.

Bird *et al.* (2015) noted that rift architecture in this area was typically more linear than previously thought. Major faults, as seismically mapped at top basement level, appear to follow rather short linear trajectories. These structures are organised into more complex, segmented fault arrays linked at relay zones higher in the section. It was concluded that these Devonian extensional structures, particularly major detachments, have had a significant influence on later Mesozoic basin geometries.

## *Onshore Faults*

Onshore, in Orkney all the structural elements (Figs 2, 3; folds, faults, shear zones) show a mean ENE-WSW direction. Similarly, the major strike-slip Great Glen Fault system is compatible with this (Fig. 1). The total offset of post Devonian dextral strike-slip along the Great Glen-Walls Boundary Fault system has been a matter of much discussion (Rogers *et al.* 1989). Estimates range from 300 km of dextral offset through to only 25 km dextral offset. However, it is clear that there was no evidence for strike-slip movements contemporaneous with the deposition of the main Early and Mid Devonian sedimentary sequence in the Orcadian Basin.

The kinematics and timing of the fault reactivation episodes and basin inversion in Orkney has been determined by fieldwork (Hippler 1993). In particular, evidence for strike-slip reactivation along large faults on Orkney suggested early sinistral displacement, and two episodes of later dextral displacements on N-S faults. Late Permian dykes (c. 250 Ma as reviewed in Lundmark *et al.* 2011) date these relative movement on major faults. The dykes cross-cut folds associated with the sinistral movements, and intrude the planes of dextral strike-slip faults and therefore post-date the sinistral and earliest dextral deformation.

## *Significance of basin inversion*

Post-Carboniferous uplift of the Orcadian Basin has resulted in inversion geometries (Hippler 1993). In the main Eifelian sequence of lacustrine facies rocks, thrusts have exploited bedding parallel zones forming detachment horizons. Folds and reverse faults also developed because of buttressing against the earlier normal faults. The presence of vein arrays associated with these later reverse faults suggests the existence of high pore fluid pressures. Bitumen in these veins also suggests that the system was oil wet at this time. The fracture arrays and narrow cataclastic zones provided pathways for these migrating mature hydrocarbons (Hippler 1993; Parnell *et al*. 1998). Rogers *et al.* (1989) show that although the offshore data (Coward *et al.* 1989) may be interpreted to suggest a Mid Devonian inversion event, the onshore data shows no evidence for this since the folding noted in the onshore Old Red Sandstone sedimentary rocks formed during a Permian inversion event (Hippler 1993). The contractional structures were most likely related to the later tectonic inversion of the basin, just after hydrocarbon maturation was reached. Evidence for the mobility of carbonate and hydrocarbon fluids is observed in the field and in thin section. Fluids released because of hydrocarbon maturation seem to have contributed to creating the high pore fluid pressures.

Post-Permian extensional structures are seen at Birsay, deforming a Permian dyke. The later extension occurred in a NE-SW direction, but resulted in only minor reactivation of the Mid Devonian extensional faults (Hippler 1993).

## *Fault Movement*

Fault timing determined from outcrop and microstructural evidence (Hippler 1993) suggests that two distinct episodes of movement occurred along the North Scapa Fault (Figs 2, 14). The first domain was deformed and cemented because of earlier faulting. The later event incorporated casts of the cemented sandstone into the breccia zone. Hydrocarbon staining was observed only in the second domain. The Mid Devonian source rocks in the Orcadian Basin reached peak maturation just before Permian basin uplift. The Eday Sandstone is thicker in the hanging wall of the North Scapa Fault during deposition of the lower half of the formation. This thickening suggests the initial movements on the North Scapa Fault were syn-depositional and occurred during basin extension in Eday Group times (Astin 1986). This extensional faulting probably continued as the basin subsided and sediments became lithified while buried to depths of up to 2.5 km.

Many of the faults in the Orcadian Basin reactivated during the Permian uplift. Several undeformed Permian dykes exposed at this locality cross-cut deformation features associated with the North Scapa Fault. Thus, the fault reactivation probably occurred during the Permian just after hydrocarbon expulsion from the underlying source rocks and before dyke intrusion.

# Stratigraphy and depositional environment

## *Basement*

The oldest rocks found in Orkney (Fig. 2) are granitic-gneiss, migmatite and schist exposed in the West Mainland at Yesnaby, Stromness and Graemsay. They represent part of the metamorphic core of an orogen. These basement rocks in Orkney bear a strong resemblance to migmatised Moine rocks found within the Kirtomy Nappe above the Swordly Thrust in eastern Sutherland (Strachan *pers. comm.* 2003; 2003). These rocks, and by inference the Orkney inliers, with mica schists, psammites and subordinate semipelites belong to the Loch Eil Group of Moine sedimentary rocks with a depositional age of about 950 Ma. Rims of zircon crystals, which grew during migmatisation, have given ages of 461 ±13 Ma for the Kirtomy assemblage and 467 ±10 Ma for the Naver assemblage (Strachan 2003). This shows the presence of a Mid Ordovician (Taconic) tectonothermal event. This is in contrast to the age of migmatisation found in Moine rocks of the central Highlands where the main tectonothermal event is 840 ±11 Ma (Woodcock & Strachan 2012). Detrital zircons within the sedimentary protolith of these migmatites fall in the age range of 1,850 to 1,000 Ma showing that deposition of the Moinian sediments in Sutherland probably occurred later than 1,000 Ma (Kinny *et al.* 1999; Kinny *et al.* 2003; Strachan 2003). However, new structural and geochronological data suggest that a pre-Caledonian basement similar to Moine schist was intruded by syn-tectonic Scandian granites in an extensional setting (Lundmark *pers. comm.*).

## *Lacustrine Sediments*

After uplift, exhumation and erosion, these basement hills of metamorphic rocks formed islands in the Mid Devonian (c. 390 million years) Lake Orcadie. Rivers flowed into the lake, bringing mud and silt. This settled on the lake bottom, forming the distinctive grey and black flagstone succession. These characteristic Orkney Flagstone Group (Astin 1990) lacustrine sediments developed as a series of monotonous cycles alternating from deep permanent lacustrine laminites (±2 m thick) to more sand rich shallow playa lake sediments with ripple marks and mud cracks. These flagstones have a distinctive architecture of lacustrine, fluvial and aeolian sediments. The lack of substantive post-Devonian regional tilting gives stratigraphic continuity from the Eifelian to Givetian. The Flagstone Group is formed of Lower and Upper Stromness flagstones along with the Rousay Flagstone Formation and is 752 m thick. “Lake Orcadie” has abundant evidence of emergence and non-deposition within this interval. The wide variety of desiccation features that are present, such as mud cracks and evaporite pseudomorphs (Rogers & Astin 1991) supports this.

In the arid climate (25° palaeosouth) evaporation was high and rainfall seasonal. Extensive sand and mudflats formed at the margins of the permanent lake that expanded and contracted across the area in response to climate change. This repetition of permanent lake deposition (laminites) and desert (playa lake) environment continued for several million years. New data on 108 lacustrine cycles in the Mid Devonian is presented below.

## *A Typical Cycle within the Flagstones*

At the base of the cycle (Fig. 5) there is dark coloured grey flagstone representing deep-water lake sediments, ranging from about 0.2 m to 5.4 m thick. When the lake dried out, the sediment deposition passed through shallow water to subaerial siltstones and mudstones. These sedimentary layers were constantly being dried out and desiccated giving rise to a series of mudcrack types, ranging from large to small and including ‘synaeresis’ cracks (Astin & Rogers 1991). The majority of the synaeresis cracks contain an infilling of sand-sized clastic particles unconnected to any overlying bed of similar grains. These were interpreted (Astin & Rogers 1991) to having formed when sand was transported across a dry lake surface under arid conditions, as opposed to acquiring such an infill under a permanent water column. Shallow water siltstones and mudstones pass up into ripple marked siltstones and sandstones deposited in a sandflat environment, the water level was probably very shallow as this interval was still intermittently drying out. With deepening water the system passed into another laminated mudstone again representing the deep lake facies and concluding the cycle (Fig. 5).

## *Lower Stromness Flagstone Formation*

A basal breccia beach deposit fringing the granite gneiss Basement Complex in the Stromness area and reworked Yesnaby Sandstone at Yesnaby, pass upwards into 277 m (52 cycles) of lacustrine flagstones. The top of the Formation is marked by the distinctive Sandwick Fish Bed, a 20 m thick laminite (Marshall *et al.* 2007). This unit can be easily mapped around the western part of the Mainland of Orkney and can be extended offshore as a key stratigraphic marker as shown in the sections in Fig. 6.

## *Upper Stromness Flagstone Formation*

This unit comprises 285 m (25 cycles) of lake cycle deposits with a higher content of fluvial river sand and sheet flood deposits than the Lower Stromness Flagstones. The clastic sediment input was derived from the northwest (Marshall *et al.* 2007). The top of the Formation is less distinct than the base. Recent stratigraphic revision (Leather 2017) places the top at the transition from a series of very sand rich and thick cycles to a distinct set of much thinner cycles with current ripple marks in the sheet flood sands, indicating flow to the south and southwest.

## *Rousay Flagstone Formation*

The third Formation of the Orkney Flagstone Group is the Rousay Flagstone Formation of Givetian age. The Rousay Flagstone Formation is the most widespread exposed unit found in Orkney, occurring over most of the Northern Isles, East Mainland, SE Hoy and parts of the southern islands. The base of the Rousay Flagstone Formation was originally placed at the first occurrence of the fossil branchiopod *Asmussia* (formerly *Estheria*, Mykura *et al.* 1976; Wilson *et al.* 1935). Subsequently, a lithostratigraphic framework was constructed (Astin 1990) which redefined the Orkney flagstones in terms of correlated lake cycles. In that framework, the Rousay Flagstone Formation was redefined as occurring between the 25th lakes cycle above the Sandwick Fish Bed cycle and the overlying Eday Group.

This basal fish bed of this formation is relatively thick and rich in fossil fish and stromatolites. This fish bed with the first occurrence of *Osteolepis panderi* (Michie *et al.* 2015) occurs above an especially thick cycle with poorly developed lake facies. This is followed by 150 - 230 m (18 cycles) of lake cycle deposits similar to the underlying Upper Stromness Flagstone Formation. While this definition is adequate for the north and western part of Orkney, further south the character of the base of the Rousay Flagstone Formation changes and is more difficult to define.

Near the top of the Formation, at Sacquoy Head, Rousay, is a distinctive pebbly sandstone, of considerable stratigraphic value (Astin 1990). This is known as the Sacquoy Sandstone Member, which thins from 17 m in Rousay to 4 m in the east of Orkney.

# Lake laminite deposition timescale

Time constraints on Orcadian Basin Lake laminite deposition have been discussed by many authors with no real consensus (Andrews & Trewin 2010). Most agree however that it is a Milankovitch cyclicity that is detected in the flagstone sequences (as reviewed in Andrews & Trewin 2010), however it is unclear whether the precession (20,000 years), axial tilt (41,000 years) or eccentricity (100,000 years) cycles are recorded. This timing of deposition is important for constraining the burial history of the lacustrine source rocks.

In order to constrain this problem, knowledge of the absolute timeframe of the Mid to Late Devonian is required along with the stratigraphic divisions. It is now generally accepted that the Givetian-Frasnian boundary in the Orcadian Basin (Fig. 2) is to be found no lower than the upper part of the Eday Group (including the Hoy Sandstones) in Orkney and John o'Groats Sandstone in Caithness (Marshall et al., 2011). This is because the Taghanic Onlap of latest Givetian age can be identified in the uppermost part of the Eday Marl sequence in Orkney and defines the base of the latest Givetian (Marshall et al. 2011).

Although the lower boundary of the late Givetian is well defined in Orkney, the position of the Eifelian/Givetian boundary is less well known. Marshall *et al.* (2007) placed this boundary at the 21st cycle above the Sandwick Fish Bed based on the inception of the Givetian zone fossil *Geminospora lemurata*. The cycle 20 laminite fish beds, approximately 1.5 m thick, is full of disarticulated plates of the placoderm fish *Dickosteus* *threiplandi* and marks its last occurrence.This is followed by five relatively barren cycles until the inception of *Osteolepis panderi* and the base of the Rousay Flagstone sequence.

Trewin & Thirwall (2002) placed an unconformity between the Lower and Middle Old Red Sandstone in the Lower Caithness Flagstone Group as the base of the Eifelian. In Orkney, the lowermost flagstones of the Lower Stromness Group rest on a basal breccia which, although not biostratigraphically constrained, is thought (Marshall 1996) to be close to, but above, the base of the Eifelian.

## *Absolute Age Dating in the Orcadian Basin*

Very little absolute age dating has been done on the rocks of the Orcadian Basin. Most has related to the dyke rocks (Baxter & Mitchell, 1984; Brown 1975; Halliday *et al.* 1977; Lundmark *et al.* 2011; Macintyre *et al.* 1981; Mykura *et al.* 1976) and fault minerals (Dichiarante *et al.* 2016) associated with the Permian inversion (250 Ma to 313 Ma).

## *Annual Varve Measurement in Laminites*

The flagstones, Lower Stromness, Upper Stromness and Rousay Formations represent, on Orkney, a continuous period of cyclical lacustrine sedimentation. The cycles were punctuated by wet periods of laminite (Figs 7 & 8) formation in relatively deep-water conditions. The majority of these laminites have annual varves (Marshall *et al.* 2007) that range in thickness from 50 µm to 600 µm as measured from the Sandwick and Achanarras Fish Beds. New measurements (Fig. 8) have been made of varve thicknesses from different locations within the Sandwick, Achanarras, and Mey (Caithness) fish beds and several other laminites throughout the sequence making a total of 7598 individual measurements. These all have the same varve thickness range as previously reported. This yields an average deposition rate of 160 µm per year (6,250 years per metre). Occasionally thicker intervals are observed consisting of fine silt to sand grain size, possibly indicative of localised sandstorms that brought windblown silt into the lake. Within the Lower Stromness flagstones the lake bed laminites vary in thickness from 20 cm to 5.4 m (Fig. 9), averaging about 1.5 m. A simple calculation, assuming no depositional hiatuses within the laminite, gives an average period for the presence of a deep lake of 9,500 years.

Only the deep water lake laminites in each cycle display continuous deposition. The remainder, about two thirds of the cycle, consists of mudstone, sandstone and siltstone, the deposition of which was discontinuous. The thickness distribution of the individual laminae or varves, as well as of the laminites and the whole cycle thickness, is controlled by the position within the lake basin varying from marginal "near lake” to deep-water “distal lake”. Using only the laminite thicknesses and assuming continuous deposition of annual varves, simple calculations indicate based on 20 cm to 5.4 m thicknesses demonstrates deep-water permanent lake durations of 1,250 years to 34,000 years.

In common with previous authors (e.g. Andrews & Trewin 2010), we consider that each of these lacustrine cycles represents one Milankovitch cycle and the thickness differences are only related to the position within the topography of the lake during each cycle. Since the thickest 5.4 m laminite of Cycle 40 represents 34,000 years this eliminates the 20,000-year-old precession Milankovitch cycle as a candidate.

It is observed (Fig. 9) that there are approximately 11 peaks in the 51 cycles that represent about 417,000 years.

It is noted that both the cycle thickness and the laminites thickness steadily increases up the stratigraphic section until the final major flooding event of the 20 m thick Sandwick Fish Bed estimated as lasting for some 125,000 years using the annual varve assumption and depositional rates summarised above. Whilst some sections have missing cycles, e.g. the gap in the Lower Stromness Flagstone Formation related to the presence of a reverse fault, equivalent sections and an adjacent BGS borehole (Brown, 2002) have been used to form a complete succession for analysis.

## *Which Milankovitch Cycle Controls Principal Lacustrine Cyclicity?*

If the absolute age interval for these Orkney flagstone cycles was known, then it would be a simple matter to divide the time interval by the number of cycles measured, to gain an understanding of the control of Milankovitch cyclity on the lacustrine deposition. The present authors have measured the thickness of 108 cycles within the Orcadian Basin principally on the west coast of Orkney and in the North Isles for the Rousay Formation. Since the Eifelian/Givetian boundary is 20 cycles above the Sandwick Fish Bed (Marshall 1996) then we have measured 72 cycles within the Eifelian. As the basal unconformity of the Orcadian lake is probably close to the base of the Eifelian (Marshall, 1996) it is reasonable to say there are 72 Eifelian lake cycles in Orkney.

The Mid Devonian stratigraphy has been poorly constrained in terms of absolute ages but values from GTS 2012 (Becker *et al.* 2012) give a value of 5.6 Myr for the Eifelian. An order of magnitude answer to the question of which Milankovitch cycle controls cyclicity is given by dividing the 5.6 Myr as the average length of the Eifelian by the 72 cycles measured in the Orkney flagstones, which yields an average age of 78,000 years for each cycle length. Therefore, since the maximum measured deep water laminite as inferred from cycle 40 represents 34,000 years and the order of magnitude calculation indicates a cycle length of 78,000 years, then it is can be conjectured that we are looking at an eccentricity signal between 90,000 and 100,000 years.

**Lake laminite source rock distribution, quantity, quality and maturity**

## *Source Rock Facies*

The source rocks in the Orcadian basin are organic rich, lacustrine laminites averaging 2 m thick. These laminites represent some 30% by thickness of the total flagstone cycles within the "Lake Orcadie" lacustrine basin. They were deposited under standing water and below wave base. Palynological examination reveals the presence of amorphous organic matter (AOM) representing the product of microbial production being the major contributor to the internal lamination, probably indicative of seasonal blooms.

Seismic studies in the west Orkney Basin recognised a sequence overlying the basement that can be correlated with the Devonian onshore lacustrine source rocks (Bird *et al*. 2015). This sequence appears to be truncated at the unconformity associated with the late Carboniferous/early Permian inversion. Continued extension during the Mid Devonian lacustrine phase saw some reactivation along the onshore N-S faults and presumably also in the West Orkney Basin. This contemporaneous fault movement served to create a number of sub-basins (Fig. 10) which have local facies patterns including thickening of the individual cycles across such faults and differing source rock richness. This has been noted with particular reference to the East Scapa Fault (Astin 1986; Hippler 1993; Speed 1999). Much younger movement, post-maturation, on the north-south wrench fault systems separates sub basins that have much higher thermal maturity (Hillier & Marshall 1992).

Geochemical analysis of the lake laminites, (Karlsen *pers. comm*. 2016) shows pristane (Pr) to phytane (Ph) ratios ranging from 0.2 - 0.8 from deep-water lake laminites from the Lower Stromness Flagstone Formation (Fig. 9 - lake cycle numbers: 1-4, 6, 20, 21, and 52). This data is strongly supports the idea of lake bottom waters being anoxic. However Ghazwani *et al.* (2016) on the basis of 19 somewhat unrepresentative “dolomitic and calcareous siltstone” from across the basin showed Pr/Ph ratios between 1.2 and 1.95 indicative of deposition taking place in oxygen depleted but not completely anoxic environments, thus suggesting deposition in fluctuating oxic/anoxic bottom waters that were not necessarily representative of the deep water laminites. Ferrous sulphate levels within the water column are interpreted to have been elevated compared to normal freshwater but lower than seawater (Karlsen *et al.* 2016; Rønningen 2015). High gammacerane indices, as observed in some Orkney rocks, are indicative of saline and stratified water columns and interestingly the highest value recorded in Orkney (Karlsen, *pers. comm.*) relate to one of the stromatolite rich locations near the base of the Lower Stromness Flagstone Formation. Based on the lack of fish remains, this was considered to represent highly saline proximal environments favouring the extensive development of stromatolites free from grazing.

## *Source Rock Quantity and Quality*

Marshall *et al.* (1985) presented RockEval Oil Show Analyser and vitrinite reflectance measurements from over 600 samples across the basin showing the organic matter from onshore Mid Devonian source rock intervals is good quality Type-I and Type-II kerogens. The samples were initially collected for palynological work and were biased towards the 70% of the lacustrine sediments that lacked amorphous kerogen. Subsequently many more samples were collected (Fig. 10), particularly from the laminites of the Orkney Flagstone Group, which had TOC values greater than 0.5%. Samples with less than this value of TOC tended to be highly mature, dominated by phytoclasts and spores of land plant origin and/or contain bitumen which skewed the pyrolysis measurements (Marshall *et al.* 1985) and were thus excluded.

Compilation of available data for TOC for a range of Orcadian Basin lithologies ranges from 0.25% up to 4.5% while 166 samples from the laminites/fish beds (Fig. 11) ranged from 0.7% to 4.5% with an average of 1.96%. The modified van Krevelen diagram (Fig. 12) shows clearly that the laminites in the Orkney area range from Type III to Type I kerogen with excellent oil-generative potential and they are all early to mid-mature for oil on Mainland Orkney.

## Source Rock Maturity

Hillier & Marshall (1992; see also Marshall & Hewett 2003) investigated the maturity distribution from all the rocks in the onshore Orcadian Basin using spore colour and vitrinite reflectance. They noted that all the rocks east of the Melby fault in Shetland and south of Wick in Caithness were over mature. The presence of the Mid Devonian Sandsting Granite in Shetland they considered potentially responsible and suggested the possibility of a similar unexposed Devonian granite south of Wick could have caused the elevated temperatures and thus over maturity. However, their Fig. 6 shows potential relationships to the set of north-south trending wrench faults subparallel to the Great Glen Fault, which as noted above, which could suggest a potential structural control on the maturity.

Various authors have published calculated burial histories for the Orcadian Basin. The representation (Fig. 13) is based on a number of these where it is considered, that at least over the Caithness-Orkney -Shetland post Carboniferous structural high, no more than 2000 m of sediment had been deposited on the Middle Devonian Flagstone units. The green hatched area depicts the calculated Time Temperature Index (TTI) of 7 to 30 i.e. the early mature zone and clearly showing that the majority of the Eifelian-Givetian flagstones throughout this long period of burial do not become over mature, at least on Orkney.

This diagram of the burial history is only representing a single location centred on the structural high. The cross sections are generated by the maturity program *Basin2* showing the evolution of maturity from west to east across the basin at different time intervals. The blue colour is the Eifelian/Givetian lacustrine flagstones while the red represents the calculated maturity at any point and time. These sections clearly show that the laminites within the Orkney Flagstone Group to the west and east of Orkney do not start to mature until the late Carboniferous to early Permian. The deposition of sediments in a passive continental margin environment continued until the Permian within the Orcadian Basin thickening towards the marginal growth faults. Structural and microstructural analyses combined with Re-Os geochronology (Dichiarante *et al.* 2016) have dated syn-deformational fault infills (pyrite) suggesting that faulting, brecciation and fluid flow events are likely to have occurred during the Permian (267.5 Ma).

This event was associated with widespread carbonate-base metal sulphide mineralisation (Dichiarante *et al.* 2016) and this was followed shortly after by the influx of regionally persistent fracture-hosted hydrocarbons that were probably related to the regional phase of hydrocarbon migration. It is thought that this marks the time of uplift and inversion of the Orcadian Basin area and probably synchronous with the main phase of lamprophyre dyke emplacement. This Permian age inversion event created mineralised thrust fault zones and formed regional N-S folding and is responsible for anticline trap formation on Mainland Orkney. Furthermore, the presence of bitumen in faults and sandstone porosity cut by the faults shows that hydrocarbon generation and migration bracket this time range and is consistent with the modelled burial history and maturity.

K/Ar dating of the regional suite of lamprophyre dyke rocks (252 ±12 Ma and 249-268 Ma; Baxter & Mitchell 1984; Brown 1975 respectively) interact with the faults confirming a later Permian age for some of these structures. Astin (1990) recognised hydrocarbons within porosity in the Lower Eday Sandstone in the baked alteration zone of a Permian dyke at Houton Head. As the contact metamorphism seals the porosity these hydrocarbons were present as a reservoired hydrocarbon prior to emplacement of the Permian dyke.

In summary, the source rocks underwent burial until the Permian structural inversion brought them to the surface. Earlier generation and greater maturity would have existed offshore in the half-graben basins to the west and east.

Apart from extensive occurrences of bitumen as degraded oil in onshore Devonian sandstones in Orkney there is a viable source rock system in the Inner Moray Firth that has charged the Beatrice Field and satellites (Jacky). This is a very heavy and degraded oil which gives significant technical issues for the successful separation and identification of biomarkers. This attribution has not been without controversy with the oilfield initial claimed as entirely sourced from the Jurassic, a sequence that we now know to be thermally immature (Marshall 1998). It then was attributed to a mixed source (Peters *et al.* 1989, 1989; Bailey et al. 1990) before a final compilation by Duncan in Marshall & Hewett (2003) that used stable isotope to prove a Devonian lacustrine source.

# Reservoir outcrops, onshore Orkney

## *Reservoirs Properties*

The reservoir rocks consist of fluvial and aeolian sandstones, the latter showing the best reservoir properties. The sandstones are generally fine- to coarse-grained and porosity ranges from 15% - 25% and up to 2700 mD permeability (Owen 1994). Compaction of the sand grains can reduce porosity, which for some rocks can be up to 8% reduction per kilometre of burial.

These reservoirs have been breached (probably by Quaternary glacial erosion) releasing all the light end hydrocarbons, leaving pore space bitumen residues. We describe two thick aeolian reservoirs on the Orkney Mainland, at Houton Head (Lower Eday Sandstone) and Yesnaby (Yesnaby Sandstone). Thin fluvial sands and sheet-flood deposits 10 cm - 50 cm thick within the flagstone cycles also have bitumen residues in the pore space where simple traps existed along the West Mainland Anticline. Also present are former traps based on unconformities, faults and pinch outs. Sealing formations consist of the lake laminite, mudstones (both source and seal), flagstones and volcanic rocks.

The large variations in porosity and permeability observed in Orkney (Owen 1994) relates principally to the presence of calcite cement, quartz overgrowth and detrital grain dissolution. Replacement by residual bitumen (indicative of hydrocarbon migration) is common at Yesnaby and Houton Head. Residual bitumen in sandstone porosity is ubiquitous throughout the Devonian of northern Scotland. Besides being found in the pore space, bitumen occurs in tension gashes, joints and mineral veins (Parnell 1983), it also occurs as blebs and stringers within the sandstones and within the organic rich laminites. This bitumen is sometimes associated with metallic sulphides dated at 267.5 ± 3.4 Ma (Dichiarante *et al.* 2016). This bitumen is also found across Orkney and in the past was called "cloustonite" (Heddle 1880; 1901) after the Orkney naturalist Rev. Charles Clouston of Sandwick who collected and described specimens at Inganess Bay. The bitumen/cloustonite is dead hydrocarbon as it does not fluoresce. There is no consensus on the relative position of the residual bitumen in the pore filling sequence but it is noted as postdating the barite veins at Yesnaby. In some areas the bitumen filling pores can reach up to 22%, particularly at Houton Head.

Liquid hydrocarbons as a component of the fluid phases in fluid inclusions on quartz overgrowths from Devonian sandstones from Yesnaby do fluoresce a green/yellow in UV light (Owen 1994). Monte Carlo simulation of the homogenisation temperatures of the oil-bearing fluid inclusions yields an average of 2.4 ± 1.0 km for the sedimentary overburden on the Caithness-Orkney-Shetland structural high (Owen 1994). At the present time, it is very common for sandstone outcrops in Orkney to contain degraded hydrocarbon in the form of bitumen.

## The Houton Head Lower Eday Sandstone Formation Reservoir

The Lower Eday Sandstone Formation varies in thickness across Orkney from about 30 to 180 m. Three interacting environments are recognised (Astin 1986), sandy braided rivers, aeolian dunes and lake margins. Two river systems were recognised, a northern, south-easterly flowing alluvial fan originating from Caithness and a southern north-easterly flowing alluvial fan from the Eday area. These rivers prograded eastwards across the lacustrine basin. The East Scapa Fault was interpreted to be active at the time of deposition and dominantly N and NW winds reworked the alluvial plain sands building up a thick dune field (Fig. 13) on the western part against the fault scarp (Astin 1986). Stratigraphically the Lower Eday Sandstone Formation fluvial sandstone unit lies above a transition zone from the top of the Rousay Flagstone Formation through "passage beds" into the amalgamated sandstones of the Eday Group. Contemporaneous haematite staining forming the red sandstones probably relates to localised uplift with early diagenesis in the vadose zone (Astin 1986).

The aeolian dune deposits in the Lower Eday Sandstone Formation form an excellent potential reservoir with porosity in the range 16% to 26% and permeability in the range 1mD to 2,700 mD (Owen 1994). Its distribution, up to 80 m thick, exposed on the eastern side of Orkney and linked to a proven basin wide distribution of similar sandstones, makes this an attractive target. The bitumen staining can be seen both in outcrop (Fig. 15 and see Fig. 16c for a surface polished hand specimen) and in thin section (Fig. 16b) where it is pore filling with clear evidence for degradation in the coarser grained layers.

At Houton Head the cross section (Fig. 17b) illustrates 3 potential traps for hydrocarbon accumulation; northern anticline, central dipping fault trap and a southern anticline sealed against the North Scapa fault. Direct evidence for the original presence of hydrocarbon is only observed at the "Houton Outcrop" (Fig. 17a) while the other potential traps are speculative.

The central former trap at Houton was shaped (Fig. 17a, b) by the reservoir sandstones dipping south away from the faults and bottom sealed by the Rousay Flagstone Formation. The top seal (cap rock) was not observed in the area. As the possible seal of the Eday Flagstones outcrops to the SE and E of Houton, the facies affinities of the former cap rock are likely to analogous to the North Hoy facies. In Hoy there is a local unconformity on top of the Lower Eday Sandstone overlain by impermeable cemented volcanic ashes and lava flows.

With a spill point alongside the North Scapa Fault and assuming 23 % porosity, 25 % water saturation, 70 m height of oil column, 1.2 volume factor, the accumulation covering a minimum 728 acres could have contained 184 MMBOOIP (Table 1).

The two other potential reservoir intervals in the vicinity with similar properties - a northern anticline trap and an anticline next to the North Scapa Fault could each speculatively hold over 364 and 218 MMBOIP (Table 1).

## Yesnaby Sandstone Reservoir

In Yesnaby around Crua Breck there is an exhumed hill of granite gneiss and schist (Fig. 18). The palaeogeomorphology is interpreted as an exposed feature in the early Eifelian with an estimated palaeorelief of ~200 m (Fig. 19). Deposited against this basement high are conglomerates, mudstone and pebbly arkosic sandstone forming a scree deposit known as the Hara Ebb Formation. Overlying this and pinching out up the hill are the sands of the Yesnaby Sandstone Formation. These are then unconformably overlain by the Lower Stromness Flagstone Formation. There is some uncertainty about the relative age of these formations with respect to the lacustrine sedimentary rocks of the Lower Stromness Flagstone Formation, but we interpret the Hara Ebb and Yesnaby Sandstone as differing facies equivalents of the basal breccia outcropping in the Stromness area. The Geological Survey (Wilson *et al.* 1935) have regarded the Hara Ebb and Yesnaby Sandstone formations as Lower Devonian (i.e. beneath both an unconformity and dated Mid Devonian sediments). Therefore, they have generally been regarded as pre-Eifelian in age (e.g. Mykura *et al.* 1976) in common with similar but palynologically dated occurrences in Caithness (Collins & Donovan 1977) and the Loch Ness (Mykura & Owens 1983) areas. This was predicated on the recognition of a local 10° angular unconformity and a quartz pebble lag deposit in the Old Millstone Quarry at the Point of Qui Ayre.

Two facies are recognised in the Yesnaby Sandstone Formation. The lower facies lying above the Hara Ebb Formation is a carbonate-cemented fine- to medium-grained well-sorted sandstone (Figs. 16a, 20) with rounded grains which has developed clear cross bedding indicative of aeolian deposition. The orientation of the cross bedding suggests a wind direction coming from the W or NW. Lying above the aeolian sediments, the ripple bedded sandstones in the upper fluvial facies are about 10 m thick contain numerous worm burrows and larger infilled burrows of arthropods. The upper part of the fluvial sandstone passes into reworked lacustrine sedimentary rocks, eventually becoming flagstone and directly correlatable with the Stromness section.

The Yesnaby Sandstone Formation consists of over 200 m of aeolian sandstone on-lapping basement hills. The low porosity facies of the sandstone still holds degraded bitumen clearly visible both at outcrop (Figs 20, 21) and in thin section (Fig. 16a). The higher porosity sandstones were similarly charged with oil, now lost. The reservoir thickness is zero at the pinch out in the south and thickens to over 200 m northwards. Porosity is 13% to 25% with permeability of 3 mD to 2,000 mD (Owen 1994) - this quality of reservoir could give high recovery factors. The source and seal are interpreted as the overlying Lower Stromness Flagstone Formation (Fig. 21).

Potential reservoir volume for this area shown on the map (Fig. 18) was calculated from the isopach map constructed by subtracting the Harra Ebb structure from the Base Stromness Flagstone structure. Confirmation of this isopach comes from the direct measurement of over 200 m of sandstone containing traces of bitumen in a BGS 1973 borehole. This was found near the car park in the northern part of the area (Uisdean Michie *pers. comm.*).

Simple pyramid rule volume calculations (Table 1) with assumed 22 % porosity, 25 % water saturation, and 1.2 volume factor yields 648 MMBOOIP. We can carry the contouring, with less control, towards the north-west beyond the map boundary (Fig. 18). This gives a speculative extension of the structure which could add at least another 477 MMBOOIP.

The boundary fault on the east side of the Yesnaby area (the Borwick Navershaw Fault) has a post Middle Devonian throw of over 250 m with flagstone forming a lateral seal. By analogy with other faults in the area the movement is synchronous with early oil generation and migration (Fig. 13). One can speculate that hydrocarbon charged reservoir rocks of the Yesnaby Sandstone Formation exist at depth on the eastern, downthrown, side of the fault. If the Borwick fault is sealing and splits the potential reservoir and it is also full of hydrocarbon then this would yield a further speculative 1,125 MMBOOIP.

With the exclusion of this speculative trap adjacent to the Borwick Fault, taken together the separate Houton and Yesnaby volumes give a potential total of 1.88 billion barrels of oil formerly in place on Orkney.

# Conclusions

In Orkney the evidence for an exhumed Paleozoic petroleum system has existed since the middle of the 19th Century when the Rev Charles Clouston collected and described samples of bitumen (the Cloustonite of Heddle). These were from Inganess Bay near Kirkwall and in the sandstones at Yesnaby. Since that time, numerous authors have mentioned the presence of this hydrocarbon residue in various Devonian sandstones. These sandstone reservoirs undoubtedly contained liquid hydrocarbons as evidenced by fluorescent liquid in fluid inclusions. We have demonstrated that about 30% of the 750 m of lacustrine sediments of Eifelian and Givetian age consists of deep-water lake laminites with an average TOC of about 2% and contain Type I and Type II kerogens, representing good to excellent potential source rocks. Over Orkney, north-west Caithness and western Shetland (west of the wrench faults sub-parallel to the Great Glen Fault), Tmax, spore colour and vitrinite reflectance all confirm these source rocks are early- to mid-mature.

Dichiarante *et al.* (2016) by establishing their Re-Os age of 267.5 ± 3.4 Ma give a fixed point in time for major reversed faults movements, fault brecciation and mineralisation. Bitumen present in these faults is indicative of hydrocarbon migration concurrent with this faulting episode, which is also probably concurrent with uplift and inversion of the Devonian Basin. The late Permian lamprophyre dyke emplacement (Brown 1975) is post-maturation and at 252 ± 12 Ma gives a fairly tight Permian time bracket for faulting, inversion, maturation, migration and dyke intrusion in this area.

The main anticlinal structure in the West Mainland of Orkney formed during the inversion episode thus this principal trap formation was concurrent with migration, with few later tectonic movements disturbing the integrity of the reservoirs over a long period of time. The Yesnaby Sandstone reservoir is a combination stratigraphic-structural trap. No evidence as yet exists for timing of breaching of the reservoirs and consequent expulsion of the light hydrocarbon fluids, but the extensive bitumen-stained sandstones provide significant insight into an exhumed Paleozoic petroleum system of direct relevance to equivalent strata deeply buried in adjacent offshore basins.

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***Table caption***

Table 1. Potential hydrocarbon volume estimates for 5 sandstone reservoir traps where best estimates are made for extent, porosity, hydrocarbon column height and water saturation.

***Figure Captions***

Fig. 1. Palaeogeographical reconstruction of Devonian Lake Orcadie. GGF is Great Glen Fault.

Fig. 2. Geology and stratigraphy of Orkney. From Brown (2002).

Fig. 3. West Orkney Basin showing location of Fig. 2. Basement highs and sub-crop faults are shown together with key localities described (after Stoker et al. 1993).

Fig. 4. Schematic geological cross-section and topographic profile, West Mainland, Orkney.

Fig. 5. A representative 5 m laminite cycle, West Shore, Stromness. Photo JFB, HY 251 077.

Fig. 6. E-W cross-sections across the West Orkney Basin and Mainland of Orkney showing position of the Sandwick Fish Bed.

Fig. 7. Varves and cycles in the Sandwick Fish Bed, Noust of Netherton, Stromness. (a) shows the general outcrop with location of (b) marked. (b) shows the sub-decimeter scale cycles and location of (c). (c) is an enlargement to show the annual cycles. Note the prominent annual bands every six years. Photo JFB, HY 242 081

Fig. 8. A compilation of lacustrine varve thicknesses from Orkney. Based on 7598 individual measurements that gives an average lamination thickness of 0.16 mm.

Fig. 9. Lower Stromness Flagstone Formation laminite thickness and cycle thickness plotted against cycle number. Note that approximately every fourth cycle is thicker. The cycles appear to become thicker through time. The gap is section cut out by a fault. The missing thickness was determined by correlation with the nearby Warebeth borehole.

Fig. 10. Possible position of sub basins within Lake Orcadie, maps based on position of probable faults active in the Devonian during Stromness Group lake deposition.

Fig. 11. Orcadian Basin Devonian lacustrine TOC% of laminites and siltstones with values greater than 0.5%, Upper Stromness Flagstones, Orkney.

Fig. 12. Modified van Krevelen Diagram showing Rock Eval results for the Orcadian flagstones and laminites with TOC’s greater than 0.5%. Equivalent vitrinite reflectivity lines are shown (Ro) together with the pre-maturation position for Type I-IV kerogens.

Fig. 13. Orkney Burial history curve from the high point of the West Mainline Anticline. The lower cross-sections are derived using the Basin2 maturity program from the West to East Orkney basins. They are at the times shown (t= -380, -330, -260, 0; My- million years). The blue colour is the Eifelian/Givetian lacustrine flagstones while the red represents the calculated maturity at any point and time. Note that the 260 Ma section indicates maximum regional maturity and the potential migration is similar to that concluded by Dichiarante et al. (2016).

Fig. 14. Isopach thickness of the upper aeolian unit of the Lower Eday Sandstone after Astin (1986).

Fig. 15. Visible bitumen in porosity, aeolian sandstone, Lower Eday Sandstone, Houton Head. Scale bar is 25 cm. Photo JFB, HY 304 035

Fig. 16. (a) Thin section of aeolian sandstone from Yesnaby with residual bitumen retained within porosity. (b) Thin section of Houton Head reservoir sandstone showing bitumen (brown-black) filled porosity separated by areas where the bitumen has been removed by surface degradation. (c) Polished surface of a hand specimen of aeolian sandstone from Houton Head. There is a contrast between the bitumen filled and stained layers (black) and coarse grained winnowed sand (white) where the fluid hydrocarbon has been removed by surface degradation. Scale bars as shown.

Fig. 17. (a) Geological map of the Houton Head Lower Eday Sandstone Formation reservoir. (b). Schematic cross-section of the Houton Head hydrocarbon reservoir.

Fig. 18. Geological sketch map of the Yesnaby aeolian sandstone reservoir. Bottom sealed by Harra Ebb Formation, top sealed by the fluvial sands and the Lower Stromness Flagstone. Also shown is the isopach of the oil stained sandstone reservoir thickness up to 280 m as measured in the BGS Yesnaby borehole (HY 2241 1599). These sands thin out over the granite gneiss hillside/island to the zero edge in the south.

Fig. 19. Cross section of the Yesnaby area. The block has been tilted to the NW by about 7° and differential compaction is observed over the basement granite gneiss hill to seal the trap.

Fig. 20. Yesnaby oil stained aeolian sandstone at outcrop. Photo JFB, HY 219 154

Fig. 21. The Castle of Yesnaby showing the bottom seal of the Harra Ebb Formation, oil stained aeolian Yesnaby Sandstone (reservoir facies) with the top comprising marginal fluvial sandstones that are the transition to the overlying lacustrine flagstones that seal the system. Height of sea stack 35 m. Photo JFB, HY 220 153











