Review of the Early Carboniferous source facies of the North Atlantic

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Introduction

The primary focus of this project is on Early Carboniferous lacustrine facies found in basins to the north of the Iapetus suture (Figure 1). These source facies are internally compared and also contrasted with similar aged source facies immediately to the south of the Iapetus suture (Figure 1). With regard to the lacustrine facies, historically, such sources of Early Carboniferous age have been exploited for shale oil in the Midland Valley of Scotland. These rocks have been extensively studied, thus, are well understood. Northern Ireland's Rathlin Basin holds Ireland's only onshore oil discovery.

In many ways, Newfoundland's Deer Lake Basin is comparable to that of Scotland's Midland Valley insofar as its source rocks are set within an onshore graben system and are of low thermal maturity overall. The Sydney Basin straddles the offshore divide of Nova Scotia-Newfoundland. Mesozoic sources that provide hydrocarbon shows and production in other offshore basins of Nova Scotia and Newfoundland are apparently less effective in this basin. As a result the initial Early Carboniferous lacustrine facies are considered as potential primary source. In the province of New Brunswick, there are several basins / sub-basins that contain Early Carboniferous lacustrine sources. These have been exploited for hydrocarbons (oil and gas) both historically and currently.

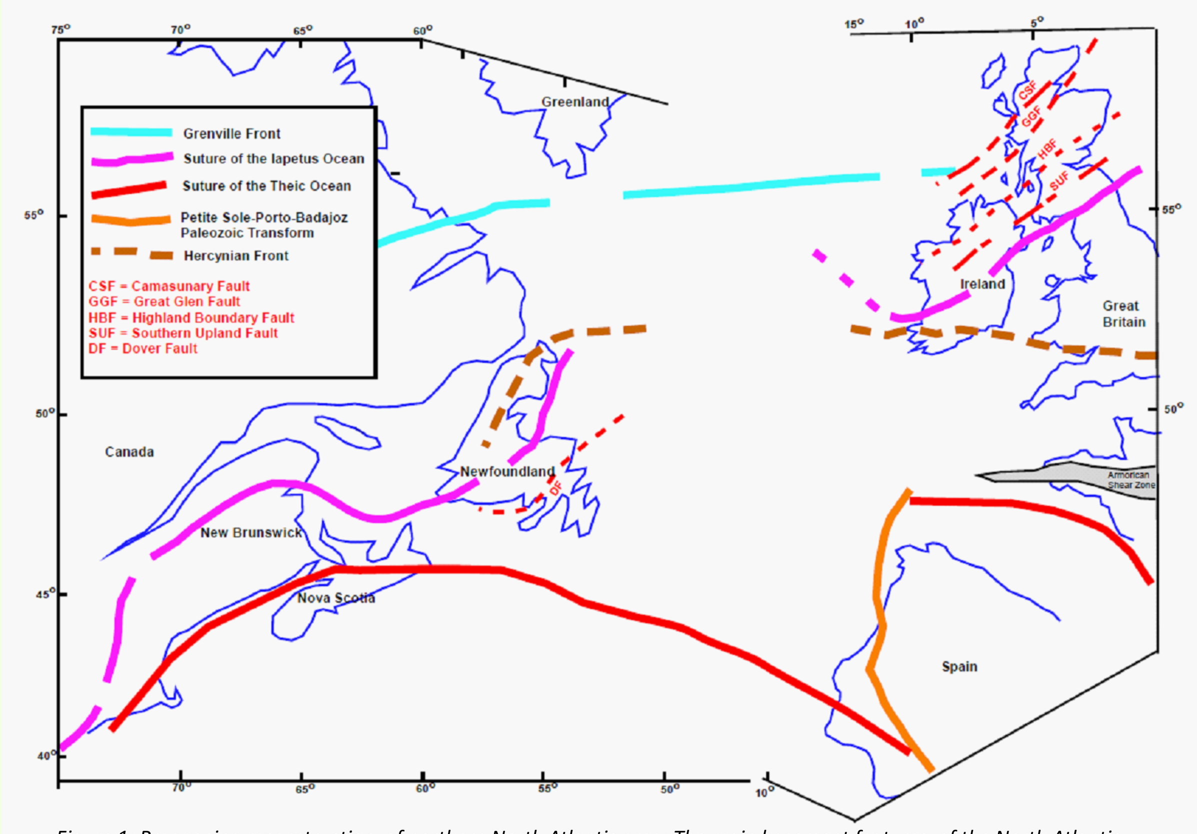


Figure 1: Preopening reconstruction of northern North Atlantic area: The main basement features of the North Atlantic shelves (aparted from Lefort, 1985).

All these basins containing such lacustrine facies lie north of the Iapetus Suture with the exception of the Sydney Basin, some of which at least is to the south of the suture line (Figure 1).

The hydrocarbon producing basins immediately to the south of the Iapetus Suture contain Early Carboniferous sources that produce oil but are considered to have formed under marine conditions. One of the aims of this study is to assess the impact these contrasting source distributions might have on under-explored areas offshore Ireland and Canada.

Tectonic Overview

The amalgamation of the various terranes, continents, and blocks that contributed to the Pangean assembly are key in understanding the development of the differing Early Carboniferous source facies that are recognised across the North Atlantic area today. A series of events that eventually resulted in the Pangea supercontinent that occurred from the Ordovician onwards contributed to the tectonic settings that allowed differing sources to develop in the Early Carboniferous.

To further illustrate the sequence of events that eventually resulted in the Pangean assembly, a series of diagrams (Figures 2A - end Ordovician, 2B - end Silurian, 2C - end Devonian and 2D - end Early Carboniferous) have been produced. These plate movements allowed two critical resultant events to eventually take place. The first was the trans-tensional movement along earlier suture lines (e.g. the Iapetus suture) resulting in the development of a series of pull-apart basins. The second is the Early Carboniferous active extension that took place immediately to the south of the Iapetus Suture (Figure 1B) .

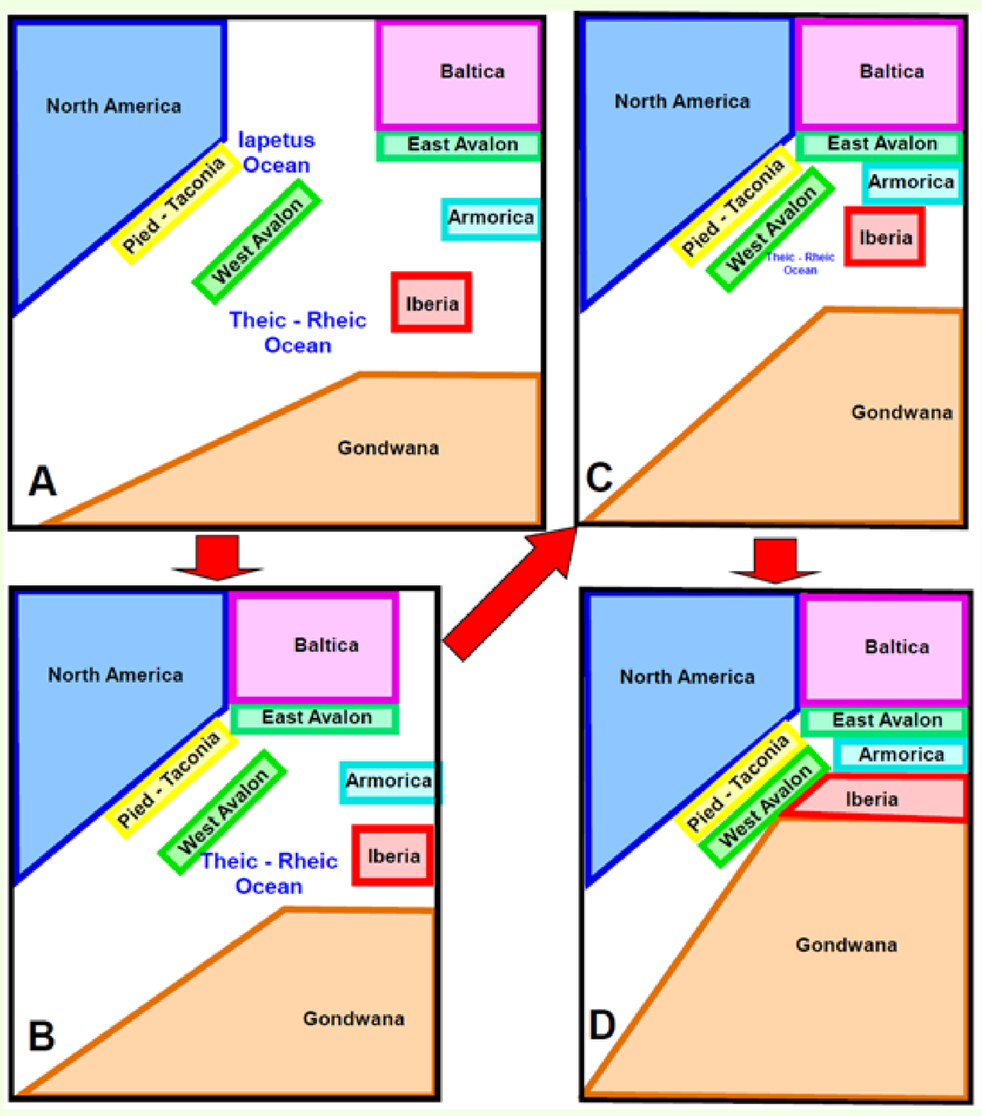


Figure 2A to D Closure of the Iapetus and Theic/Rheic oceans combined with block assembly in the North Atlantic area from Ordovician to Early Carboniferous (developed from Blakey, 2007).

Lacustrine Basins

Each of the settings illustrated in Figure 3 results in distinctive organic facies as characterized by Total Organic Carbon (TOC) and Rock-Eval pyrolysis derived Hydrogen Indices (HI). Geochemically, reduced TOC and HI values together with lower sulphur content and higher Pristane to Phytane ratios in gas chromatograms can point to an oxidizing environment such as that resulting in the over-filled lake setting.

According to Carroll and Bohacs 2001 "Lacustrine deposits may be characterized according to:

- their sedimentary facies, fauna, and flora,
- their internal stratigraphic relations (such as parasequence stacking),
- the character of associated deposits.

In particular, evidence for open vs. closed basin hydrology and the presence and nature of depositional cyclicity provides the fundamental bases for categorizing ancient lake systems according to types."

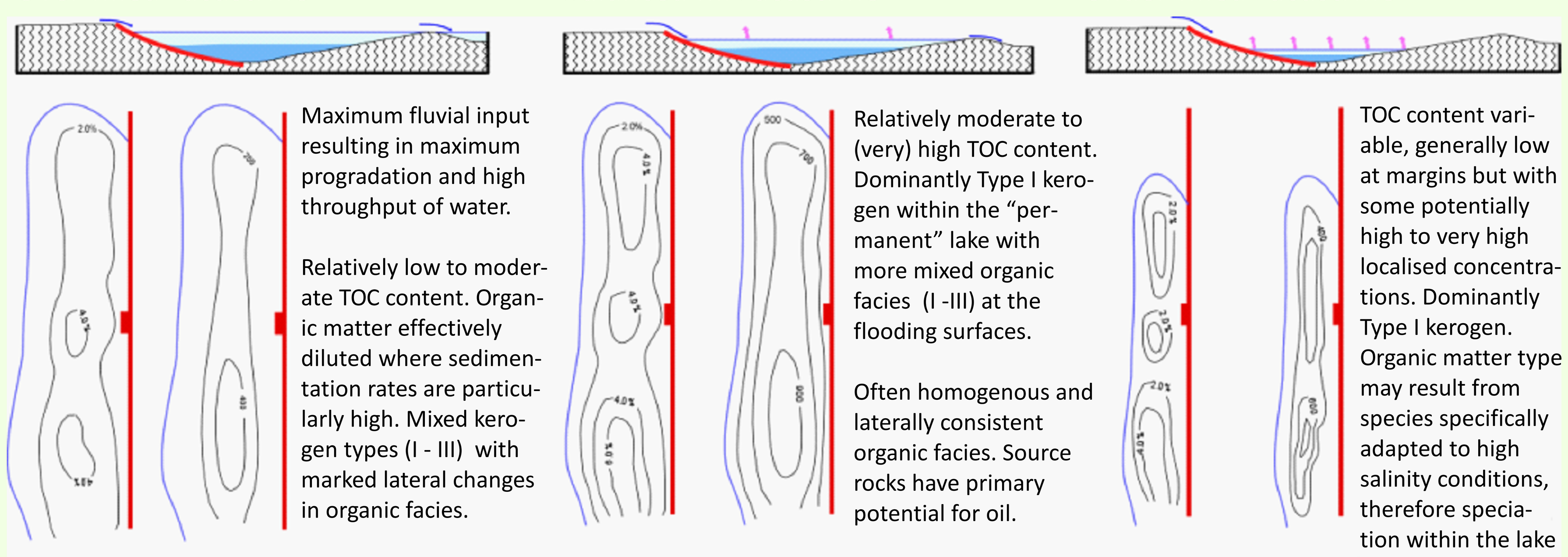


Figure 3: Illustrations of probable original Total Organic Carbon (TOC) and Hydrogen Index (HI) at time of deposition in lacustrine sediment accumulation settings (modified from Lung-Chuan, 1994).

Midland Valley of Scotland

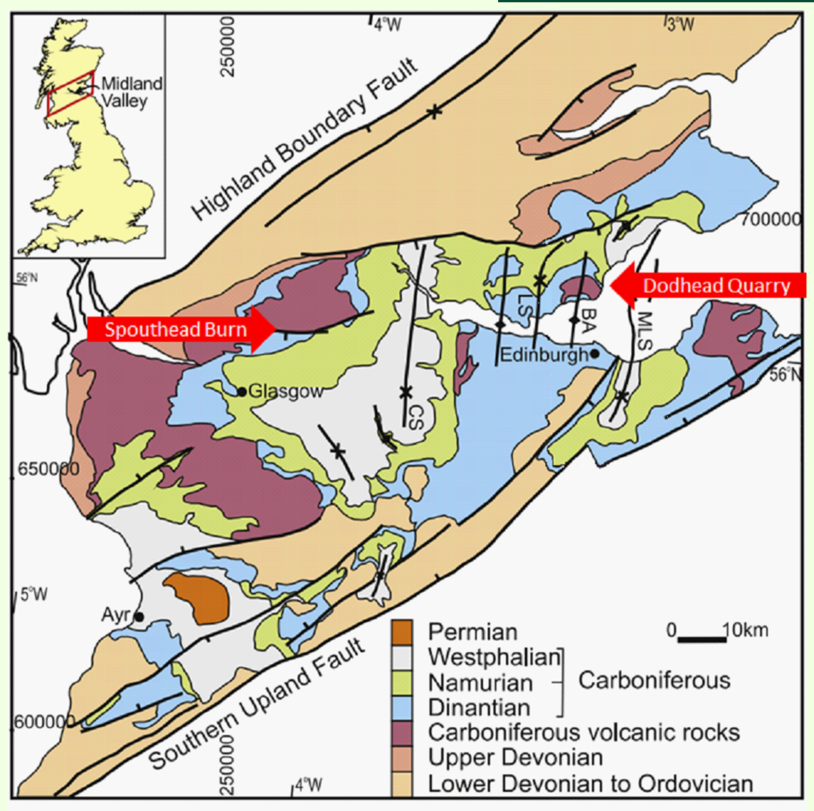


Figure 4: Geological map of the Midland Valley of Scotland Basin with added well locations (modified from Underhill et al, 2008 and George, 1992).

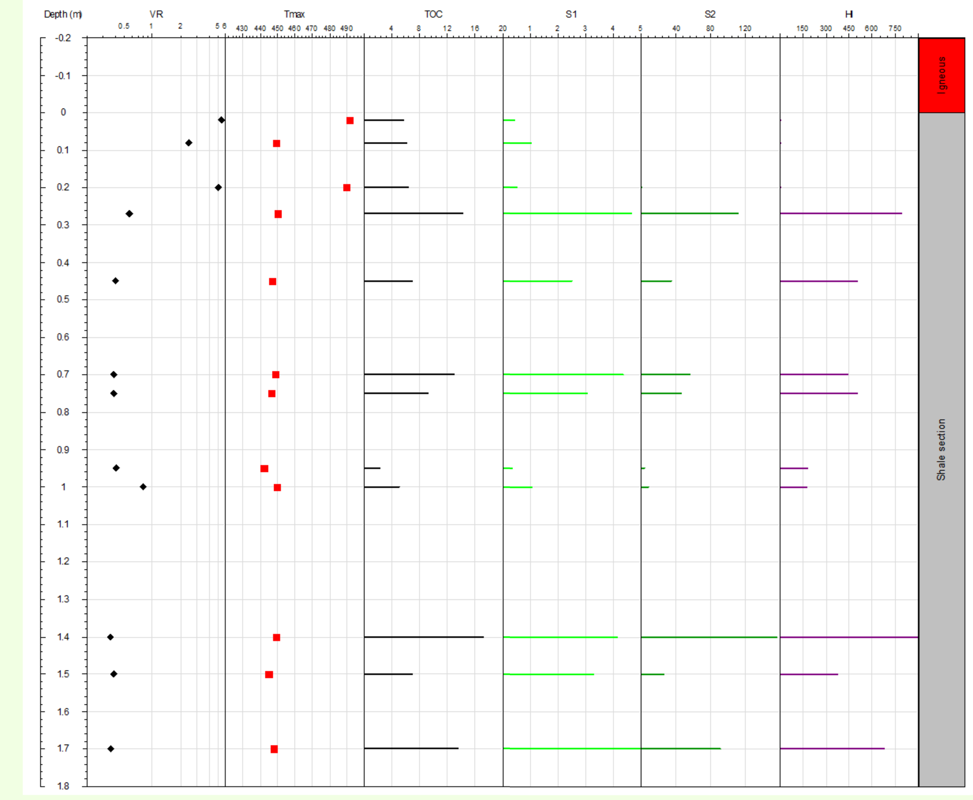


Figure 5: Geochemical log of Total Organic Carbon and Pyrolysis data for samples from the Dodhead location (data from George, 1992).

Scotland's Midland Valley (Figure 4) is a major sedimentary basin that evolved from crustal extension and is predominantly filled with Devonian and Carboniferous sediments and igneous rocks (George, 1992). Carboniferous sediments have previously been considered to source liquid hydrocarbons, especially the Dinantian Oil Shale Group. Whilst the majority of the Carboniferous comprises fine-grained sediments (siltstones, mudstones and coals) that have been deposited in a fluvio-deltaic setting with terrestially derived organic matter, the Oil Shale Group is predominantly lacustrine and its organic matter is primarily algal. Two major suites of igneous bodies are intruding the Carboniferous succession: alkali-dolerite (Namurian) sills and quartz-dolerite (Permian) sills and dykes. Raymond and Murchison (1988) noted that quartz-dolerite sills and dykes had a significantly higher impact on the organic matter of intruded sediments than older alkali-dolerite sills (larger thermal aureoles). Figure 5 is a geochemical log derived from published TOC and pyrolysis data for the Dodhead location. The samples were collected in a short traverse above and below a thin alkali-dolerite sill where it is 0.9 m thick (the lower section is illustrated here, Figure 5). From these samples, there is evidence for very rich hydrocarbon source potential that has been modified by proximity to the sill. Tmax values range from 442°C to 492°C indicating the majority of the samples being within the oil window for much of the section but are locally over-mature where proximal to the igneous intrusion. This accounts in part for the variation in source richness and pyrolysis Hydrogen Index values across the sample set (Figure 6). Essentially these are relatively low maturity source facies.

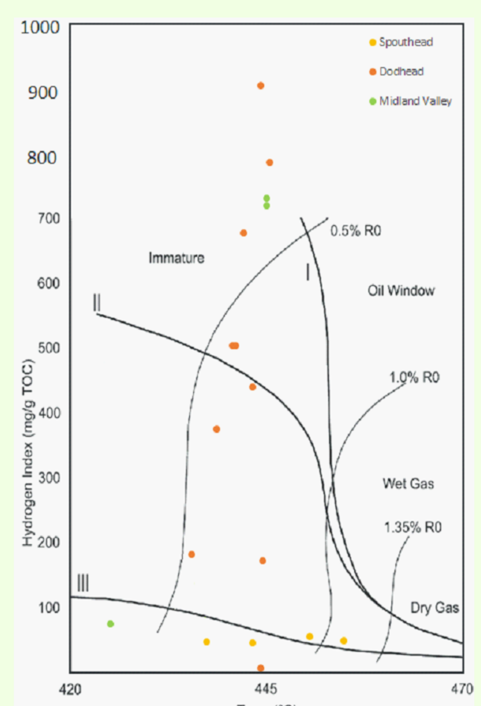


Figure 6. Cross-plot of Hydrogen Index (HI) and pyrolysis (Tmax) temperatures for Midland Valley samples (modified from George, 1992).

Rathlin Basin

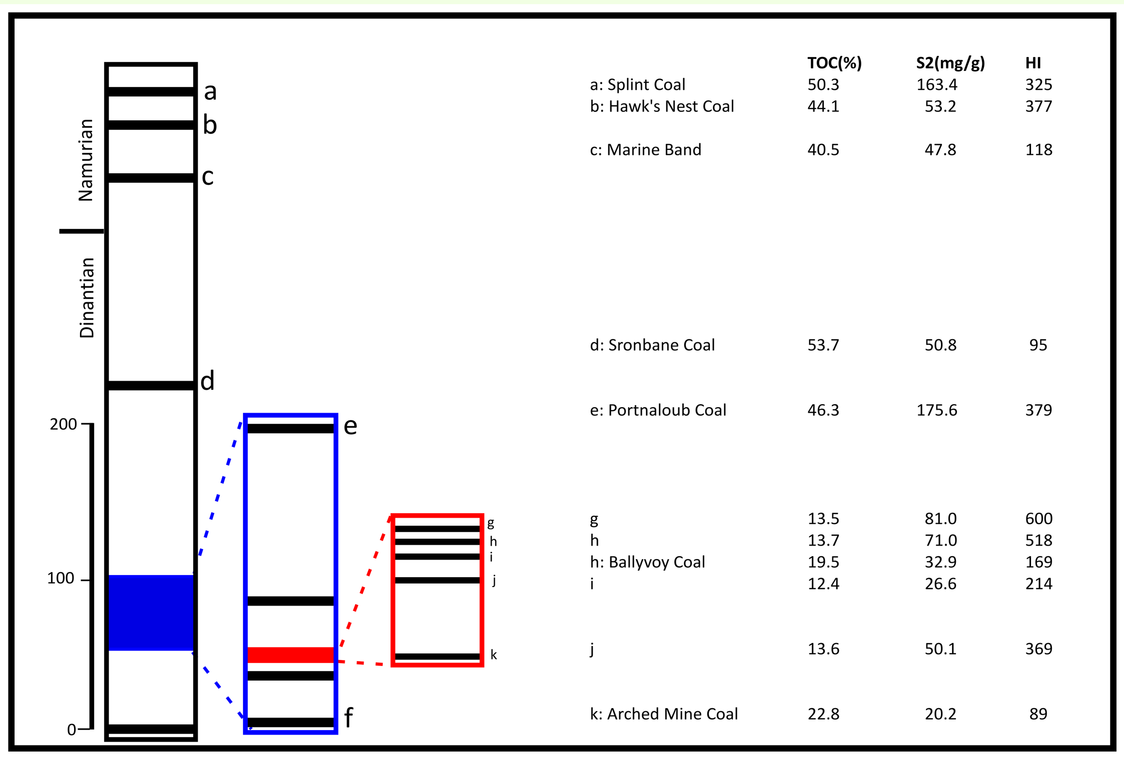


Figure 7: Total Organic Carbon (TOC) and pyrolysis data for shale and coal samples from boreholes and exposures in North Antrim (modified from Parnell, 1991).

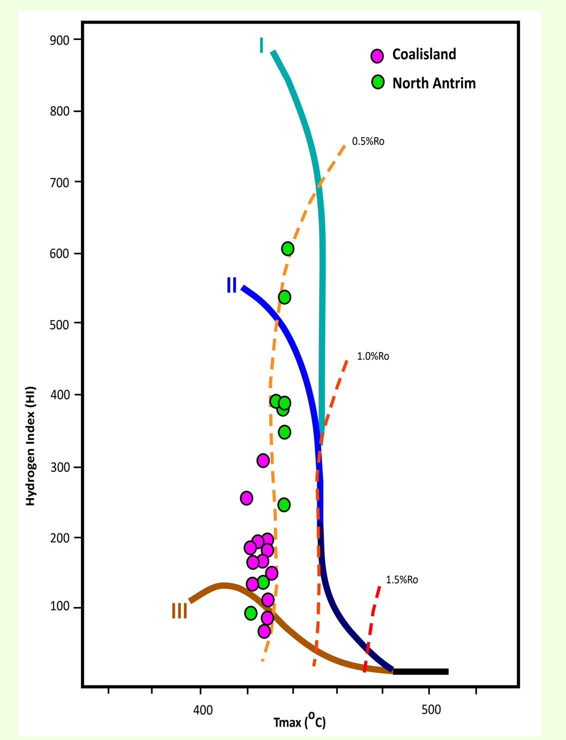
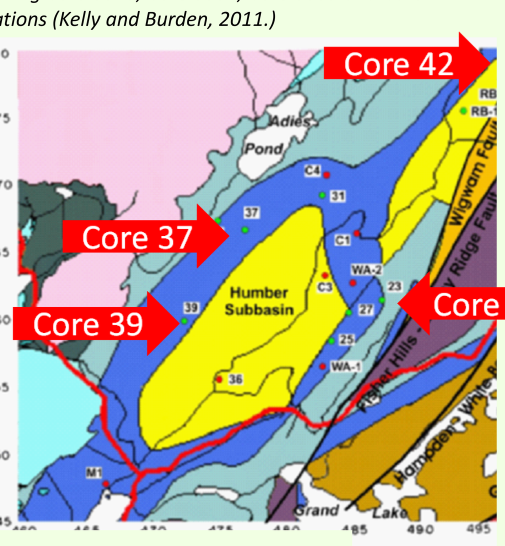


Figure 8. Cross-plot of Hydrogen Index (HI) and pyrolysis (Tmax) temperatures for samples in Figure 7 and those of Coalisland (modified from Parnell, 1991).

Early Carboniferous organic-rich coals and lacustrine oil shales (Figures 7 and 8) as well as Late Carboniferous coal are the most likely source rocks for plays in the Rathlin Basin (Mitchell, 2004; Providence, 2016). Such Carboniferous successions need to have been buried to depths required for hydrocarbon generation (Parnell, 1991) and its is generally held that generation has occurred in the deeper basinal settings of the Rathlin Basin. This notion is upheld by oil having recovered from the Carboniferous in Ballinlea-1 well within the basin.

Deer Lake Basin

Figure 9: Tectonic and geology of the Deer Lake area showing Core 0023, Core 0037, Core 0039 and Core 42 locations (Kelly and Burden, 2011.)



In the Deer Lake Basin, the principal lacustrine source horizon is the Asbian Rocky Brook Formation. In this formation there are two members that contain high quality source rocks, the Squires Park and the Spillway members. Both members have many thin horizons containing significant Type I source rocks. Such accumulations are characteristic of Balanced-fill Lakes where input of sediment keeps step with basin subsidence and thus, water levels (Figure 3). Kalkreuth and Macauley (1989) indicate that the source facies of the Rocky Brook Formation is dominated by lamalginite and sporonite. This is very similar to that recorded for the Albert Formation in New Brunswick.

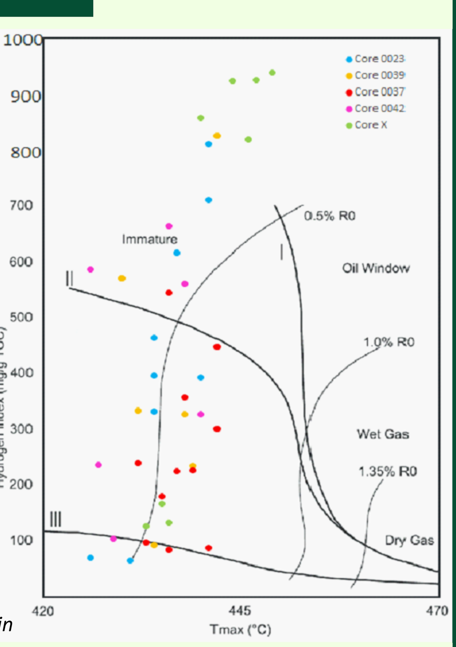


Figure 11. Cross-plot of Hydrogen Index (HI) and pyrolysis (Tmax) temperatures for Deer Lake Basin core samples (data from Hamblin, 1997).

Figure 10: Geochemical log of Total Organic Carbon and Pyrolysis data for samples from Deer Lake core samples (data from Hamblin, 1997).

There is also a second, older sequence of lacustrine source facies noted in the Deer Lake area. This is the Stillwater Cove Member which is part of the Anguille Formation (Tournaisian). An equivalent facies of the same age, the Snake's Bight Member, is found in the Bay St. George Basin which is a southern extension of the Deer Lake Basin. The core samples (Figures 9,10 and 11) have wide ranging organic carbon contents, pyrolysis S2 yields and pyrolysis derived HI values. In the Midland Valley of Scotland such ranges are often a response to localised igneous intrusions as in the Dodhead and Spouthead examples (Figures 4,5,6). In the Deer Lake Basin these fluctuations are more probably a response to the cyclicity of the lacustrine conditions in which sediments accumulated resulting in a series of thin organically enriched layers.