Review of the Early Carboniferous source facies of the North Atlantic

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New Brunswick Basins

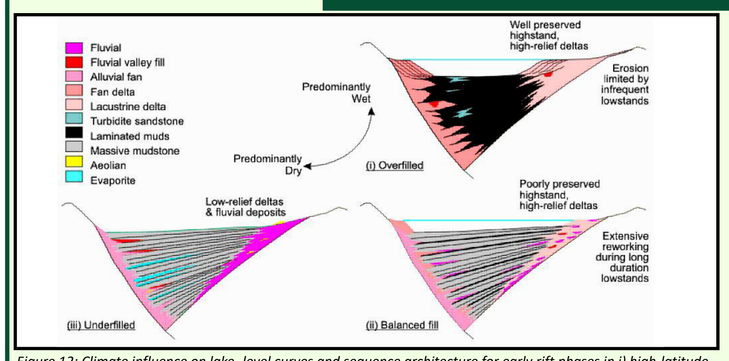

Figure 12: Climate influence on lake -level curves and sequence architecture for early rift phases in i) high-latitude, persistently wet (overfilled) systems; ii) tropical (balanced) systems; and iii) sub-tropical, semi-arid climate (underfilled) systems (Keighley and Brown 2005, after Olsen (1990).

Figure 12 is the Keithley and Brown (2005) representation of lacustrine systems with the development of potential source facies represented by laminated muds. These figures may be contrasted with those developed by Lung-Chuan (1994) (Figure 3). Keithley and Brown suggest that principal source development would occur in overfilled lakes whereas Lung-Chuan argues that sources in this setting may have organic matter accumulation more diluted than in the balanced lake setting. The amount and intensity of organic matter accumulation is probably also controlled by aspects such as lake depth and amount of turnover due to water throughout. So, this could account for the disparity in these two interpretation schemes. Geochemical data have been taken from the Geological Survey of Canada (GSC) Open File report 1497 (Macauley and Bell, 1987) and has been reappraised and assessed using more up-to-date interpretations of the Moncton Basin (e.g. Keighley and St. Peter, 2015).

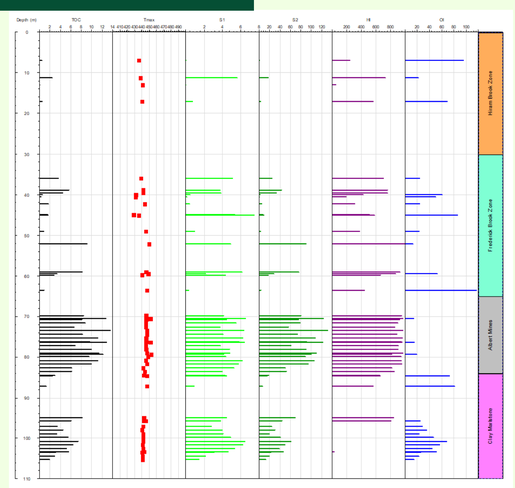

Figure 13: Geochemical log of Total Organic Carbon and Pyrolysis data for the Cartago Dover#1 well (data from Macauley and Bell, 1987).

The five wells that have the highest number of analyses have been used in this exercise. In each case the wells were extensively cored. Analyses were conducted over a very tight sampling range that builds a detailed picture of the fluctuations in organic richness. The log of Cartago Dover#1 well perhaps best expresses the distribution of organic richness within the Albert Formation with the best quality sources being located within the Albert Mines Member of the formation.

Marine Basins

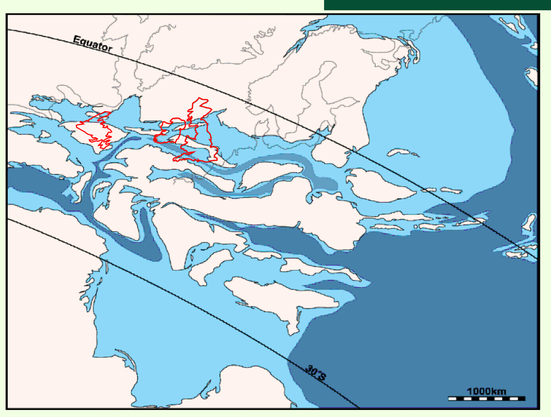

Figure 14. Palaeogeographical map of NW Europe during the Early Carbonaceous. Tan colours represent emergent land, whilst blue areas represent marine bodies and darker blue colours indicate increasing depth (modified from Blakey, 2011).

During the Early Carboniferous (Mississippisian 359 – 318 Ma) a relatively shallow epicontinental seaway extended across the Laurussian/Avalonian continent (Figures 14 and 17A). These manifest as a series of interconnected basins between emergent land areas. It is the land area that is now the Present Day Southern Uplands of Scotland that separated these marine basins from the pull-apart strike-slip basins that lie immediately to the north. A number of marine organic facies that are proven sources of commercial oil (East Irish Sea Basin, East Midlands Basin) developed at this time. There is also the possibility of similar source facies having developed in offshore basins that have only been lightly explored.

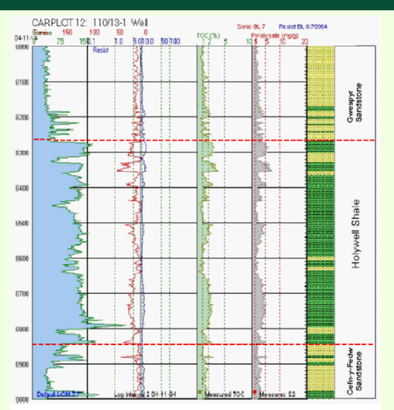

Figure 15: "CARPLOT" log of the 8000 - 9000 feet section of the 110/13-1 well (modified from Armstrong et al. 1997).

Figure 15 shows the approximate extent of the Holywell Shales (8270 to 8850 feet – 580 feet (175m) thickness). Using the methodology of Passey et al, 1990, relative source rock richness levels are estimated from the resultant TOC and Pyrolysis and S2 responses. The calculation suggests 220 feet or 66m (38%) of the Holywell Shales at this location is rated as having very good (2-3% TOC) to rich (>3% TOC) source potential (Armstrong et al, 1997).

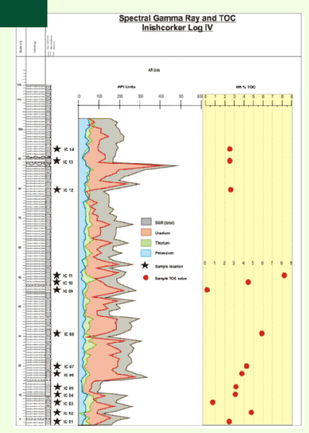

Figure 16: Inishcorker log with spectral gamma ray and TOC content (Nolan, 2012).

The Clare Shale section at Inishcorker logged and analysed by Nolan, 2012, (Figure 16). This is one of the most extensive logged sections of Clare Shale for which geochemical data are available. Nolan notes TOC values up to 8% TOC however, there is variation in organic richness, a constant feature of all of these Early Carboniferous marine source facies.

Analogue Basins

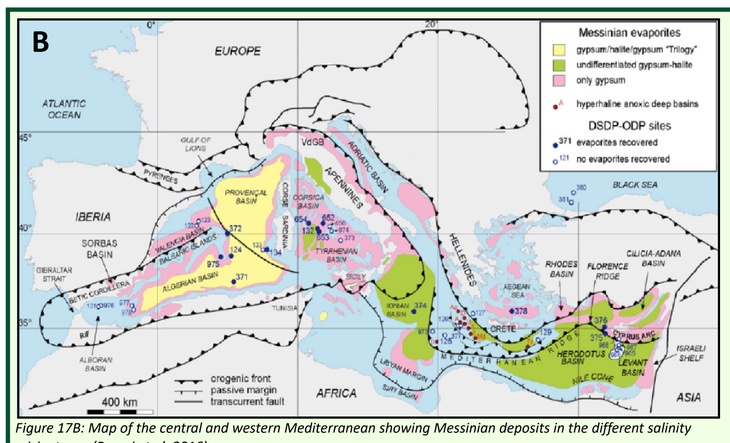

Figure 17B: Map of the central and western Mediterranean showing Messinian deposits in the different salinity crisis stages (Roveri et al, 2016).

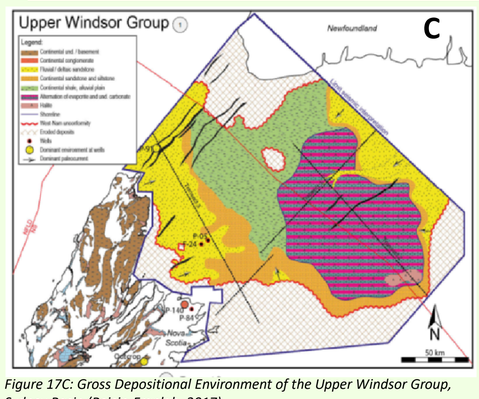

Figure 17C: Gross Depositional Environment of the Upper Windsor Group, Sydney Basin (Beicip-Franlab, 2017).

Figure 17A summarises the majority of the basins that were the subject of this study and shows the tectonic relationships across the Atlantic divide. The Early Carboniferous lacustrine facies are found primarily to the north of the Iapetus Suture whereas the marine facies lie to the south. In both facies high quality hydrocarbons sources have developed but, unlike some of the analogue basins noted here, commercial discoveries are more limited. The analogue basins noted are those related to the the Sumatran and Mediterranean closings. The latter, Present Day is similar in size to marine basin that occupied north-west Europe and into eastern Canada in Early Carboniferous times. One of the features of the Mediterranean is the Messinian Salinity Crisis (Figure 17B) that resulted in widespread desiccation and also potentially some rich oil-prone facies. Unlike much of the Early Carboniferous marine basin the Sydney Basin also experienced a similar period of desiccation (Figure 17C) thus marine sources that did develop in that basin as a result will be different from the remaining marine facies. Further investigation into the development of hypersaline marine sources in the Sydney Basin is a potential research topic.

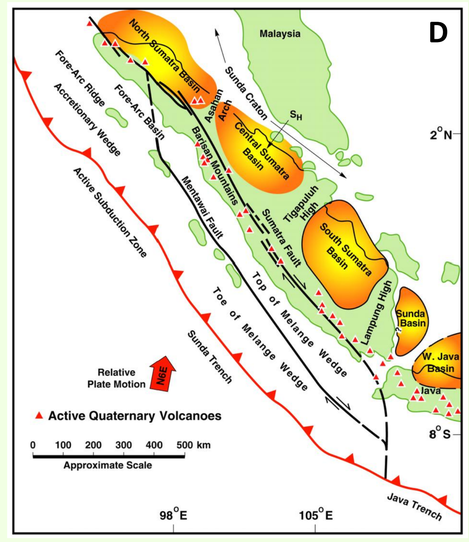

Figure 17D. Map of northwestern Sunda Shelf showing Tertiary Sumatran basins (modified from Heidrick and Aulia, 1993)

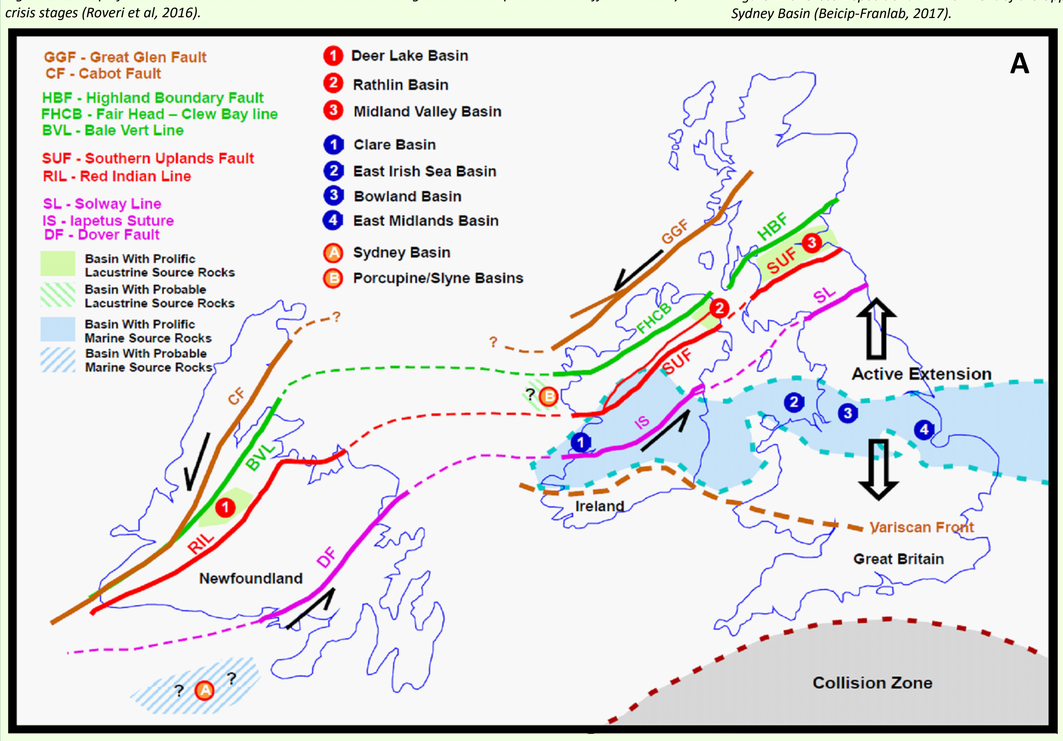

Figure 17A: A Palaeogeographical reconstruction of the Early Carboniferous from the UK to Newfoundland. The principal basins reviewed in this study are annotated. (developed from multiple sources).

The Sumatra basin complex (Figure 17D) is made of several separate synrift grabens with superimposed post-rift sequences (Doust and Noble, 2008). Of these basins, the Central Sumatran Basin is the most prolific yielding 13,210 MMBO of oil to date. The oil is of algal origin (Type I kerogen) with sources developing in the early syn-rift phase of the basin, in fresh to brackish water lakes. The setting of the Sumatran basins in terms of both magnitude and source type is similar to those of the study area. The principal difference is in thermal maturity. Most of the study area basins are of low maturity despite being significantly older than those of Sumatra. Thermal history and the development of a significant post-source overburden has aided hydrocarbon generation in Sumatra.

Figures 17E and 17F allow a comparison between the Early Carboniferous marine basins of northern England/Irish Sea and the Late Cretaceous marine setting in the Gabes Basin and adjacent basins. The two settings are of similar tectonic setting and magnitude but, as with the Sumatran Basins noted above, the younger basin is more prolific in commercial discoveries. In both settings, basin margins are marked by large carbonate platforms with deep offshore troughs allowing the development of basinal shales that form major source facies (Type II)

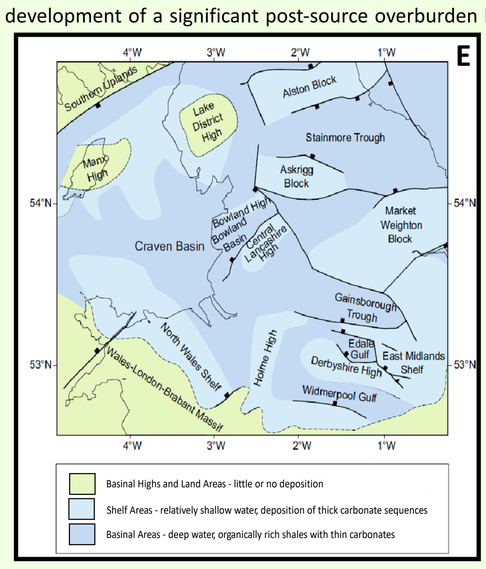

Figure 17E. Mississippian paleography of northern England (UK) with outline of Present Day coastline (modified after Newport et al. 2019).

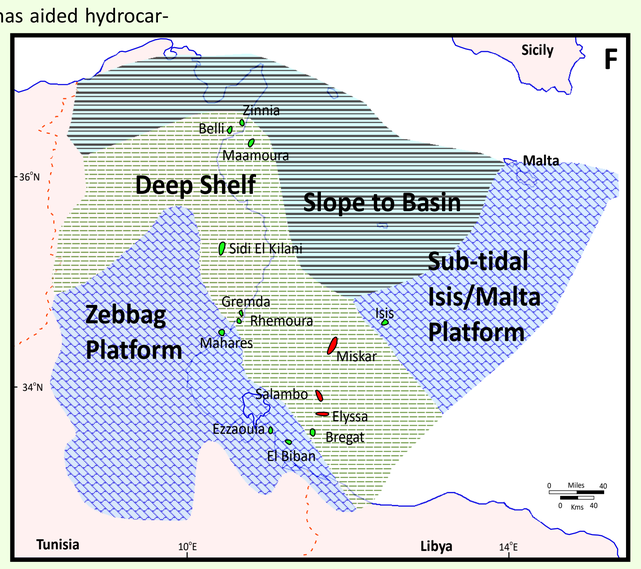

Figure 17F: Upper Cretaceous Petroleum System, Djeffara Trough, Gabes and Hammamet basins, Southern Mediterranean (modified after Zappaterra, 1995).

Conclusions

• There are at least two phases of major tectonic movement in the Early Carboniferous resulting in pull-apart basins in which lacustrine sources develop.

• First phase is in the (early to mid) Tournaisian and the resultant sources apparently only developed in the Canadian basins (Moncton, Sydney, Bay St. George, Deer Lake). The Tournaisian Inverclyde Group of the Midland Valley of Scotland consists primarily of (semi-arid) alluvial plain, fluvial plain and aeolian dune sediments.

• The second phase of widespread lacustrine development occurs in the Late Visean and sees the development of lacustrine sources in Scotland, Northern Ireland and Canada (Deer Lake Basin and Sydney Basin).

• The Early Carboniferous marine sources that developed primarily in Britain and Ireland result from the opening of a narrow seaway that evolved during a local extension phase that occurred simultaneous to the Late Visean tectonics responsible for the pull-apart basins in Scotland, Northern Ireland and Canada.

• Initially, carbonate platforms were widespread across this seaway with deeper water conditions suitable for marine source development first being established in the Bowland Basin (contemporaneous with the Late Visean Oil Shales of the Midland Valley of Scotland) and becoming more widespread (East Irish Sea, Clare Basin) at time of maximum extension in the Namurian.

• The closing of the Iapetus/Rheic ocean is tectonically similar to the Sumatran and Mediterranean closing. The Sumatra and Gulf of Gabes basins both have proven developed oil-prone facies and therefore, provide an insight on the possibility for similar development in basins affected by the Iapetus/Rheic ocean closing.

• Unlike the New Bunswick and the Midland Valley of Scotland, the extraction of hydrocarbons from lacustrine Carboniferous strata in Newfoundland and Rathlin Basin is in its infancy; few wells have been drilled and no commercial activity has been initiated.

• The East Irish Sea and East Midlands Basin of England have commercial developments for oil that are sourced by Early Carboniferous marine sources

• The Sydney Basin has both lacustrine (Horton Group) and marine (Windsor Group) Early Carboniferous sources. Unlike the other marine sources the development of such facies in this basin was affected by a "saline crisis" similar to that of the Messinian event in the Mediterranean thus source rock types may be different from other marine source rocks.

Acknowledgments

LF undertook this study as part fulfillment of a Masters degree in Petroleum Geoscience at the University of Derby. In doing so, she wishes to thank her family and friends, in particular her partner, Rogan Purewal, for their support. LF would also like to thank all her lecturers for passing on their knowledge during this course, particularly Dorothy Satterfield and Ian Billing.

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