Assessing potential Cretaceous source facies within the Orphan Basin using analogue examples from the North Atlantic and 1D basin modelling.

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Source Rock Synthesis

The development and distribution of Cretaceous source facies across the North Atlantic region appears to have close relationships with Ocean Anoxic Events (OEAs). There are several OAEs suggested during the time of the development of the opening North Atlantic: (time-line details each OAE Figure 8). OAE 1 has up to four sub-divisions but, depending on locality within the North Atlantic area, these are not always all recognisable. OAE 1C (a Late Aptian event) in particular can be poorly represented in the region. The principal events are:

OAE 1
1A 120 Ma Early Aptian Anoxic Event
1B 110Ma Early Albian Anoxic Event
1D 100Ma Late Albian Anoxic Event
OAE 2
95Ma Cenomanian-Turonian Anoxic Event
OAE 3
85Ma Santonian Anoxic Event

Using the analogues of Jeanne D'Arc, Flemish Pass, offshore Iberian and Moroccan basins an understanding of source rock development related to these OAE events can be developed. Furthermore, the array of data obtained over several decades from the Deep Sea Drilling Project (DSDP) and the subsequent Ocean Drilling Program (ODP) is readily accessible and forms a cornerstone of this synthesis.

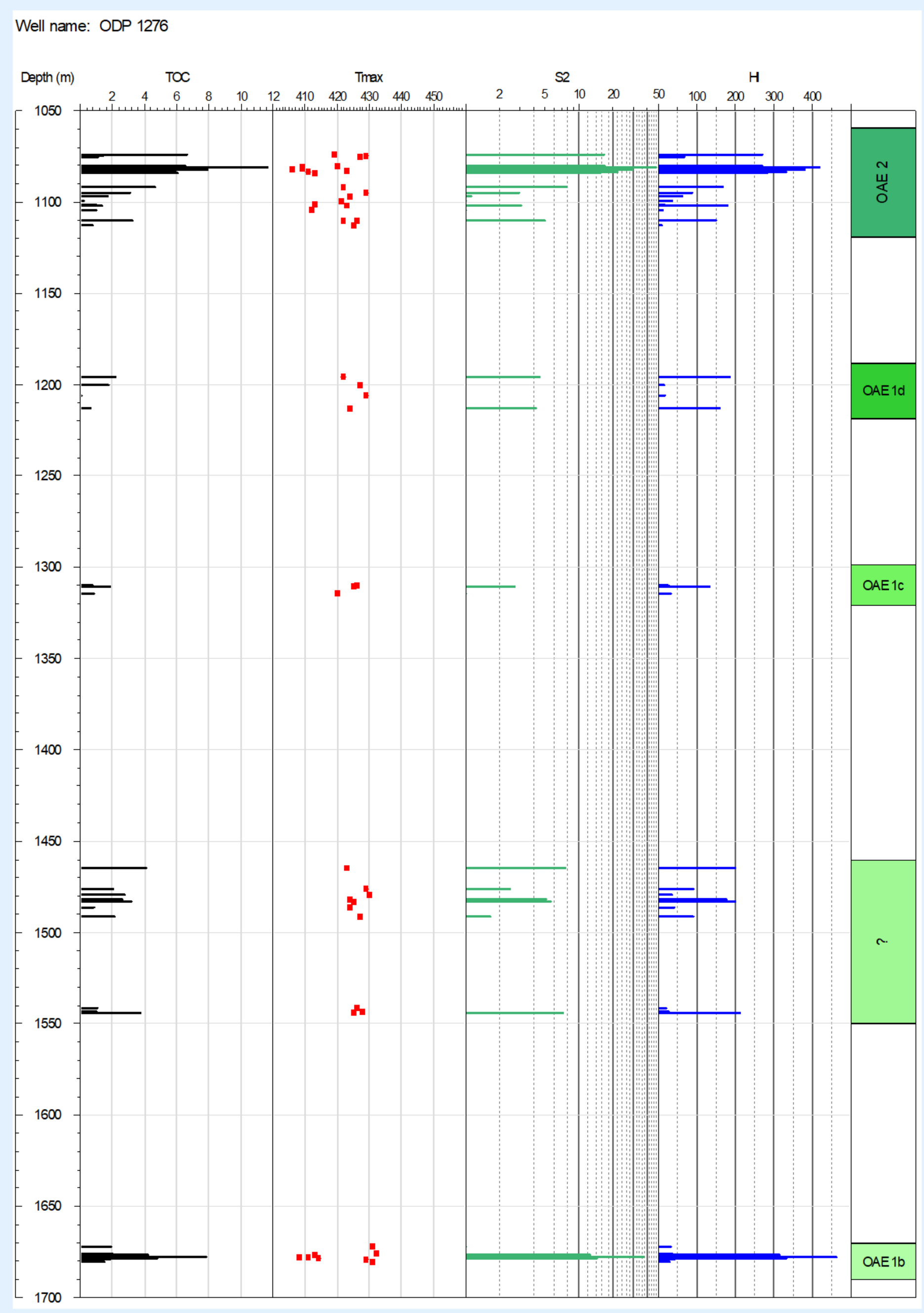


Figure 9: Using the data from Arnaboldi and Meyers 2005, the different OAEs time-frames with TOC, Tmax, S2 and HI of the source rocks at site 1276.

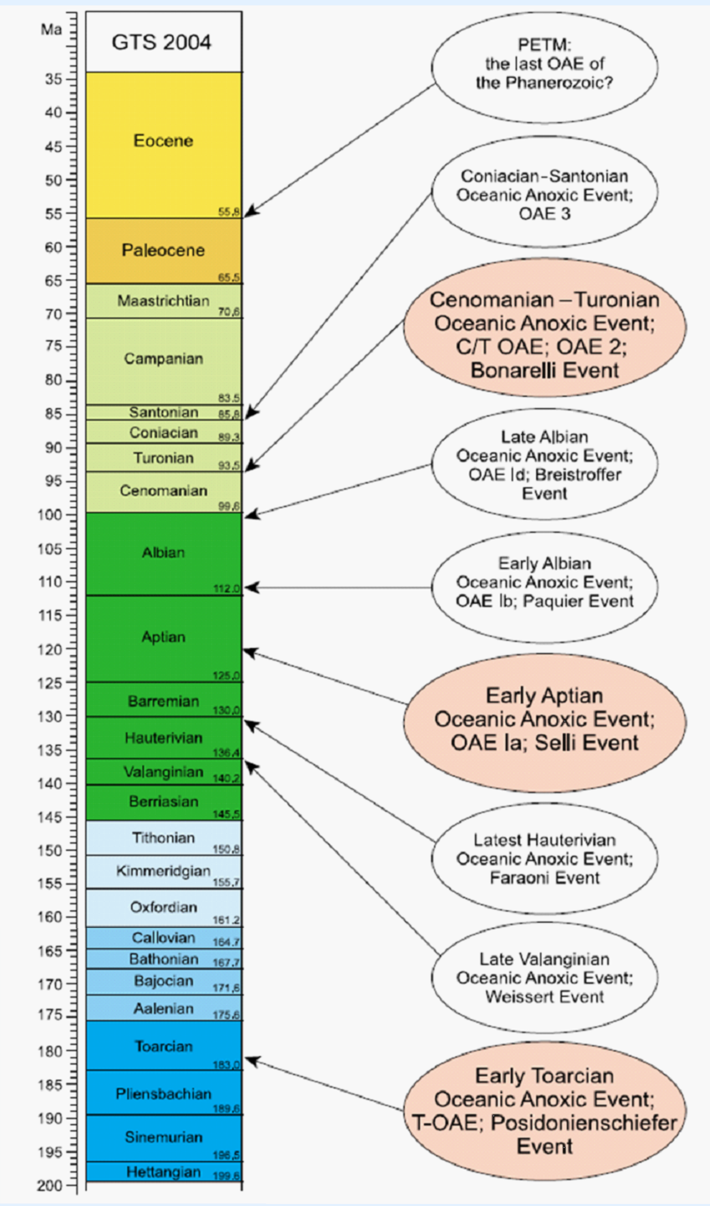


Figure 8: Time-line of OAE events (Jenkyns, 2010).

DSDP 1276 is the closest such site to the Orphan Basin, lies East of the basin. The graphic log (Figure 9) details that the OAE 2 (Cenomanian-Turonian) and OAE 1b (Early Albian/Late Aptian) have the highest recorded values of organic richness. Although these two events have the highest TOC, Tmax, S2 and HI values the data have considerable fluctuations particularly of pyrolysis S2 yield and Hydrogen Indices. These demonstrate that the source accumulation events were not constant across time. Although OAE 1b and 2 show the highest values in the data relating to good source rock the Tmax values (<435ºC) suggest these sources are immature and possibly early mature at best.

A review of geochemical datasets from all of the DSDP reports pertaining to the North Atlantic has been undertaken. It must be remembered that these data were acquired over more than three decades. During that time geochemical analyses made considerable advances so focus has been made on Total Organic Carbon (TOC) and Pyrolysis data. These data give a basic overview of source potential. OAE 1b (Late Aptian/Early Albian) shows the most extensive distribution of source facies across the North Atlantic (Figure 10) however the generative potential of these sources is mixed, that of DSDP 1276 is one the more promising. Better quality, oil-prone sources are consistently associated with OAE 2 (Cenomanian - Turonian).

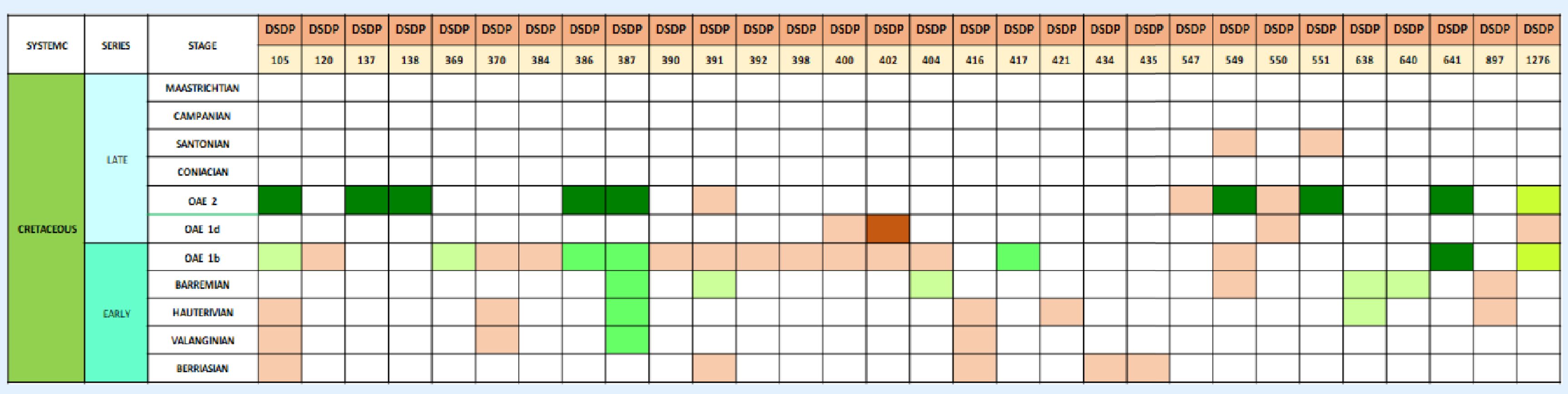


Figure 10: Summary of Cretaceous source potential in North Atlantic DSDP sites

Modelling Summary

Figures 1a and 1b show the broad and more detailed location of the two Pseudo Wells (nominally labelled PW#1 and PW#2) in the Orphan Basin. These two locations address two differing structural settings in which accumulation of Cretaceous sources could occur and where there is sufficient overburden to facilitate maturation of such source to a level where generation and expulsion of hydrocarbons may be possible. Tops for the two locations as determined from seismic interpretation are recorded in Table 1.

		Cretaceous Fairway PW#1	Jurassic Mini Basin PW#2
Marker	**Age**	**Depth (m SS)**	**Depth (m SS)**
Sea Floor	Neogene	-2598.77	-2370.48
C10	Mid Neogene	-2872.18	-2870.86
C24	Top Oligocene	-3531.92	-3722.16
C45	Top Middle Eocene	-3812.02	-4118.69
C54	Top Palaeocene	-4267.24	-4542.06
C65	Top Cretaceous	-4627.91	-4927.88
K100	Top Albian	-5418.57	-5159.07
K114	Top Middle Aptian	-5978.8	-5233.03
K135	Top Valanginian	-6611.52	-5412.75
Top Jurassic		-7381.11	-5721.48
Top Kimmeridgian		-8337.92	-7853.47
Basement		-10854.91	-10386.92

Table 1: Tops for two Pseudo Well horizons as determined from seismic interpretation by Nalcor.

Pseudo Well #1 is within the laterally extensive Cretaceous Fairway whereas Pseudo Well #2 lies in a more restricted Jurassic Mini Sub-Basin. Both localities have extensive developments of Cretaceous and Tertiary sediments. The accumulation of sediments can be compared with those of the adjacent highs where the Cretaceous in particular is often eroded or condensed. These high areas are often the target of drilling activity (e.g. Lona O-55) which partially explains the lack of data on Cretaceous sediments particularly source rock information. Figure 12 shows the projected locations of these three locations.

There are no kerogen kinetics for the Cretaceous source rocks in the Orphan Basin so kerogen analogues from Burwood, 1999 (Figure 2) have been employed. These relate to similar tectonic settings together with equivalent palaeogeographies to those of the Cretaceous Orphan Basin. The four kerogen types selected are Iabe - lacustrine/terrestrial/marine facies, (Albian) Micrite - marine carbonate rich facies, Chela - transgressive shallow marine and Teba - deeper water marine.

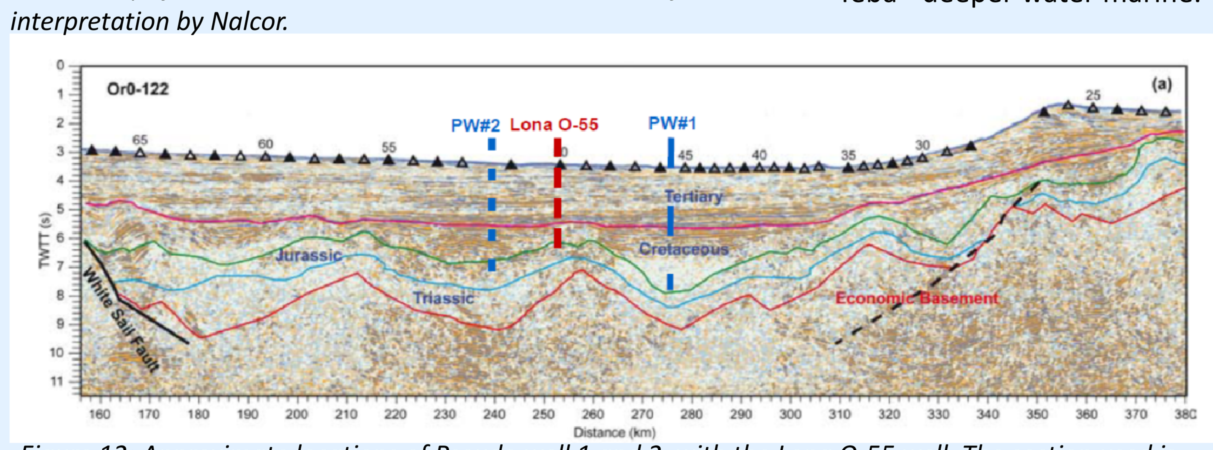
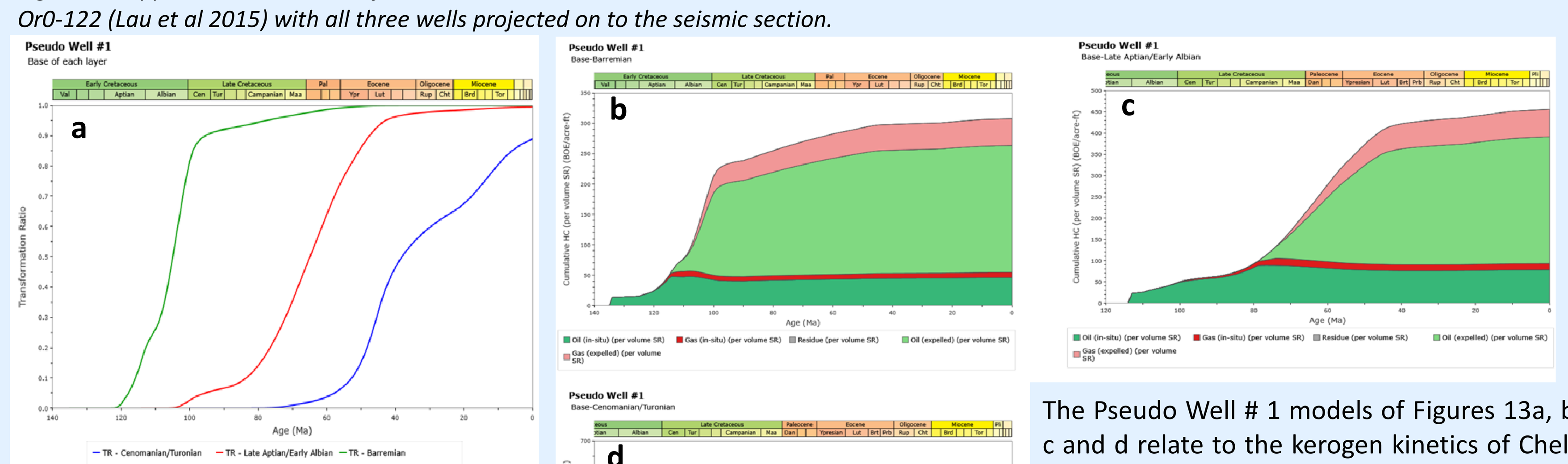
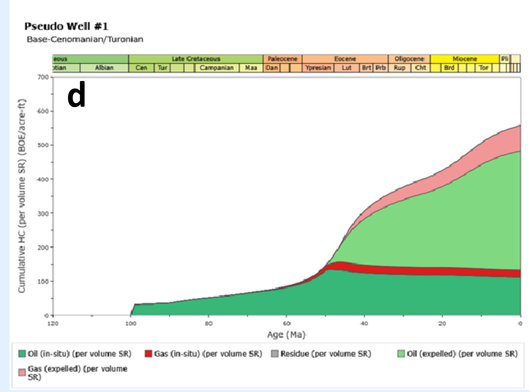


Figure 12: Approximate locations of Pseudo well 1 and 2 with the Lona O-55 well. The section used is Or0-122 (Lau et al 2015) with all three wells projected on to the seismic section.

These kerogen types have been applied to three potential source horizons delineated in the two pseudo-wells. This was done as follows:

Source	First Run Kinetics	Second Run Kinetics
OAE2	Chela	Albian Micrite
OAE1b	Chela	Teba
Barremian	Iabe	Teba





Source Rock	Total Transformation	Main Transformation	50% Transformation (peak generation)
Barremian	100% Middle Eocene	Albian	105Ma Albian
OAE 1b (Late Aptian/Early Albian)	100% Late Miocene	Late Cretaceous to Eocene	66Ma Late Maastrichtian
OAE 2 (Cenomanian/Turonian)	87%	Eocene to Present Day	38Ma Late Eocene

Figure 13a-d: Models detailing transformation, generation and expulsion of source rocks modelled with high heat flow using analogue Iabe and Chela kerogen kinetics.

The Pseudo Well # 1 models of Figures 13a, b, c and d relate to the kerogen kinetics of Chela and Iabe (Figure 2) combined with a high heat-flow regime. This is used as an example of the output from the software. The amount of transition (Figure 13a) combined with timing of generation and expulsion for each source rock has been used sytematically for all iterations considered for PW#1 and PW#2 and sumarised in Tables 2A and 2B.

Pseudo Well #1	OAE2 - Chela	Albian Micrite	OAE2 - Chela	Albian Micrite
Kerogen Kinetics	OAE 1 - Chela	Teba	OAE 1 - Chela	Teba
	Barremian - Iabe	Teba	Barremian - Iabe	Teba
Source Horizon	High Heat Flow	High Heat Flow	Low Heat Flow	Low Heat Flow
Ceno-Tur OAE 2				
Start expulsion:	50Ma	48Ma	27Ma	12Ma
Amount expelled:	347 BOE/acre ft	560 BOE/acre ft	135 BOE/acre ft	75 BOE/acre ft
Alb-Apt OAE 1b				
Start expulsion:	79Ma	58Ma	58Ma	27Ma
Amount expelled:	298 BOE/acre ft	237BOE/acre ft	254 BOE/acre ft	72 BOE/acre ft
Barremian				
Start expulsion:	114Ma	105Ma	105Ma	71Ma
Amount expelled:	210 BOE/acre ft	160 BOE/acre ft	202 BOE/acre ft	140 BOE/acre ft

Table 2A: Start and amount of expulsion for Cretaceous source horizons using differing kerogen kinetics – Pseudo Well #1

Pseudo Well #2	OAE2 - Chela	Albian Micrite	OAE2 - Chela	Albian Micrite
Kerogen Kinetics	OAE 1 - Chela	Teba	OAE 1 - Chela	Teba
	Barremian - Iabe	Teba	Barremian - Iabe	Teba
Source Horizon	High Heat Flow	High Heat Flow	Low Heat Flow	Low Heat Flow
Ceno-Tur OAE 2				
Start expulsion:	8.5Ma	3Ma	0Ma	0Ma
Amount expelled:	84 BOE/acre ft	31 BOE/acre ft	0 BOE/acre ft	0 BOE/acre ft
Alb-Apt OAE 1b				
Start expulsion:	11Ma	0Ma	0Ma	0Ma
Amount expelled:	86 BOE/acre ft	0 BOE/acre ft	0 BOE/acre ft	0 BOE/acre ft
Barremian				
Start expulsion:	22Ma	0Ma	0Ma	0Ma
Amount expelled:	68 BOE/acre ft	0 BOE/acre ft	0 BOE/acre ft	0 BOE/acre ft

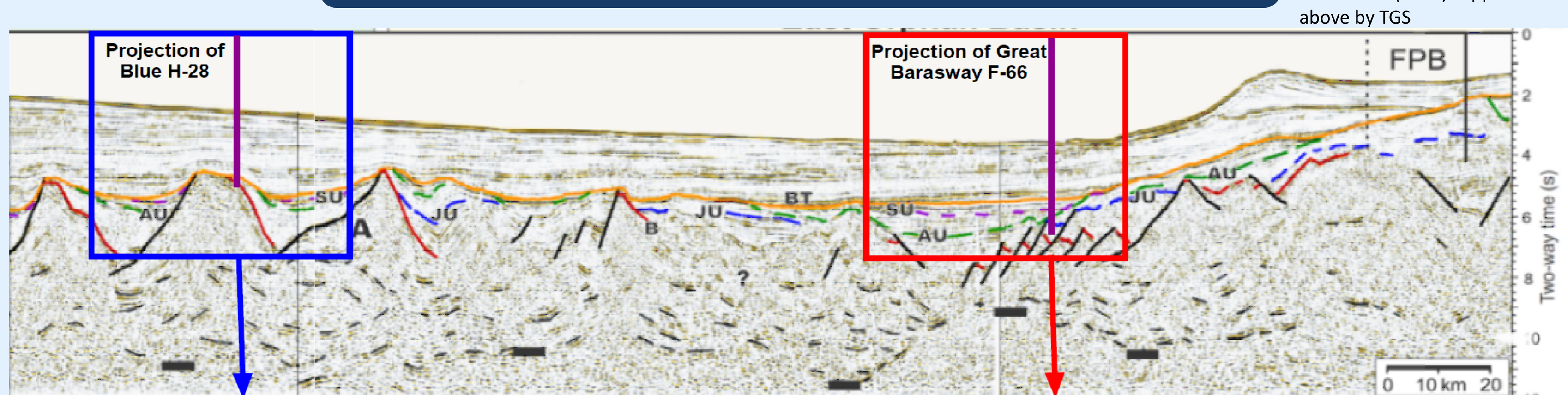
Table 2B: Start and amount of expulsion for Cretaceous source horizons using differing kerogen kinetics – Pseudo Well #2

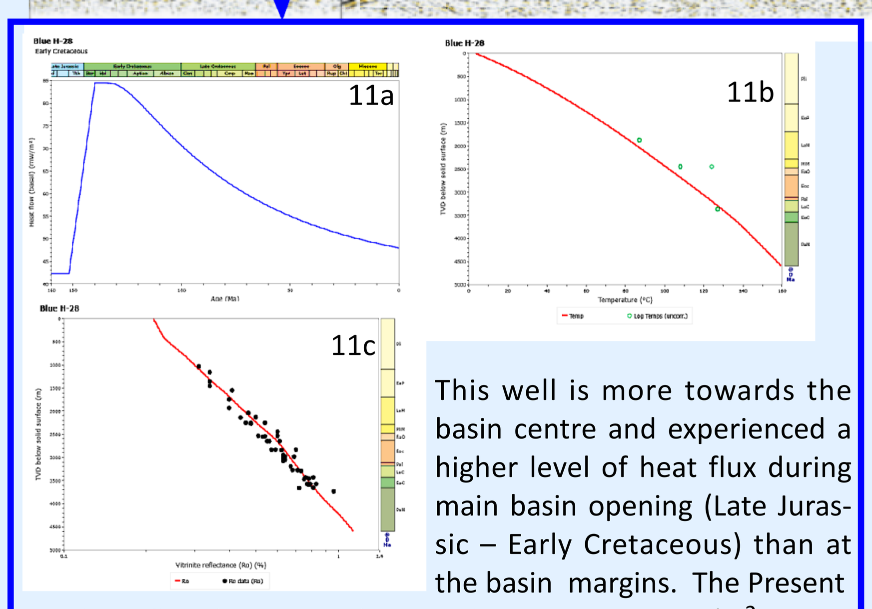
Tables 2A and 2B summarise the timing and amount of expulsion calculated by the modelling of three Cretaceous source horizons within Pseudo Well #1 (Cretaceous Fairway) and Pseudo Well #2 (Jurassic Mini Basin). In both cases differing kerogen types and heat flow histories have been applied. There is considerable variation in the timing and amount of expulsion between Pseudo Well #1 and Pseudo Well #2. There are no differences in the initial parameters applied to equivalent settings (e.g. OAE 2, High Heat Flow, Chela Kinetics, in both PW#1 and PW#2 an initial TOC value of 7% with a Hydrogen Index of 400 was applied). As is evident from the output gained from modelling, in the Fairway setting there is potentially prolific expulsion indicated. Here the key risk indicated may be timing. In the Jurassic Mini Basin setting, the amounts of transformation indicated are lower resulting in lower amounts of expulsion which occur later in the geological history of the basin and indeed, in the lower heat-flow regime, expulsion appears completely retarded.

Model Calibration

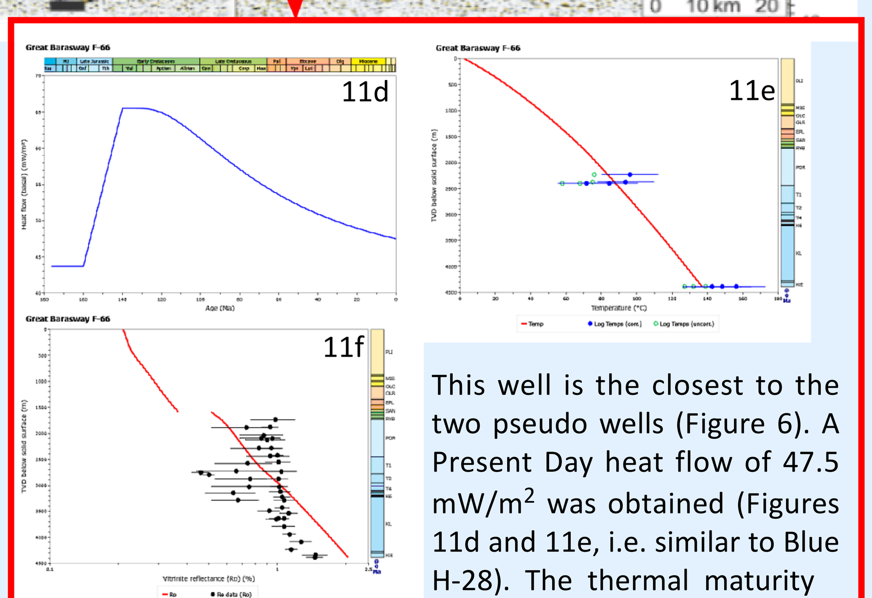
Figure 11 Model Calibration

Seismic section adapted from Dafoe et al (2017) supplied to above by TGS





This well is more towards the basin centre and experienced a higher level of heat flux during main basin opening (Late Jurassic – Early Cretaceous) than at the basin margins. The present Day heat-flow (Figure 11a) is calculated to be 48mW/m^2. This is higher than the values used in the Beicip-Franlab study (see Figure 7). In Figure 6 the estimated stretching factor for Blue H-28 is 3 to 3.5 but best data calibration (Figure 11c) a β factor of 2.5.



This well is the closest to the two pseudo wells (Figure 6). A Present Day heat flow of 47.5 mW/m^2 was obtained (Figures 11d and 11e, i.e. similar to Blue H-28). The thermal maturity data in this well is more difficult to assess (Figure 11f). This may result from drilling fluid contamination or overpressure. As with the Blue H-28 well a final heat-flow history was established using a stretching factor of 2.5 rather than 3 to 3.5.

Principal Conclusions

- The main phase of Orphan Basin opening occurred during the Late Jurassic-Early Cretaceous
- A connection between the East and West Orphan Basin was established by the Early Cretaceous and possibly earlier.
- A variety of stretching factors are noted across the basin, these will impact heat-flow at time of rifting and subsequently.
- During the Cretaceous environmental conditions were generally shallow marine but in some grabens deep marine conditions persisted.
- Tectonics resulted in the abundance of horst and graben structures where deep marine sediments were deposited during the Cretaceous.
- Previous wells drilled across the basin targeted Jurassic source rocks similar to the Jeanne D'Arc Kimmeridgian unit.
- Data from ODP 1276 identifies OAE 2 Cenomanian-Turonian and OAE 1b Aptian-Albian as potentially the best Cretaceous source units
- The possibility of a good quality Barremian source is also considered in addition to these two OAE sources.
- The Cumberland B-55, Blue H-28 and Great Barasway F-66 wells have been modelled using a simple McKenzie heat flow model.
- This enabled calibration of heat-flow history and understanding of variations in this linked to stretching factors.
- Two Pseudo Wells relating to the Cretaceous Fairway (PW#1) and Jurassic Mini Basins (PW#2) have been subsequently modelled.
- These two Pseudo Wells were modelled using the differing sources and keogen kinetics resulting in a variety of generation histories.
- As well as different kerogen kinetics, a high and low heat-flow history was applied to each Pseudo Well which also affected outcomes.
- In Pseudo Well #1, there was good prospectivity for generation and expulsion from potential sources of the Barremian, OAE 1b and OAE2.
- Pseudo Well #2 proved to be more problematical, particularly for generation and expulsion.
- With the high heat flow model, some limited expulsion was indicated but in the low heat flow model there was little prospect generation.
- The study suggests that the presence of mature, generative Cretaceous source rocks in the Orphan Basin is a viable possibility.

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