Petroleum Systems in Oceanic-Transitional Crust: an example from the SW Africa Margin

by Tiago Cunha

INTRODUCTION: It is generally accepted that a lack of charge hinders the development of petroleum systems in oceanic basement. Although organic-rich sediments have often accumulated in anoxic oceanic basins, for example during the early stages of accretion, as documented off west Africa (USGS, 2006; Bray *et al.,* 1998; Lawrence *et al*., 2017), the sediment coverage is in most places thin, and the oceanic lithosphere reaches its cooled, steady-state equilibrium 40-60 Myr after break-up (Parsons and Sclater, 1977; Mckenzie *et al.*, 2005).

On the other hand, the discovery of very large oil and gas reserves in deep water rifted margins over the last decade (e.g. South Atlantic, Gulf of Mexico, Indian Ocean), the availability of high quality seismic data enabling the imaging of the complex ocean-continent transitional zones (e.g. Peron-Pivindic *et al.*, 2017), and borehole data indicating pervasive high geothermal gradients in stretched continental-transitional basement (potentially also old oceanic crust) long after break-up offshore SW Africa (e.g. Jackson *et al*., 2005; Doran and Manatschal, 2017), have triggered a renewed interest in the area.

A quick assessment of the oceanic charge model is performed here using the recently revised stratigraphy of DSDP Site 361, offshore South Africa (Lawrence *et al.*, 2017). The site is located in the proximity of the ocean-continent boundary (e.g. Heine *et al.*, 2013), at a water depth of 4549 m, probably in a complex transition zone where the basement may be heavily intruded and/or underplated (Hirsh *et al*., 2008; Mayestrenko, 2013; Figure 1). The available heat flow data show considerable scatter along the ocean-continental transition, but with higher values than expected over old oceanic or highly stretched continental crust (Stein and Stein, 1992; Watts, 2012).

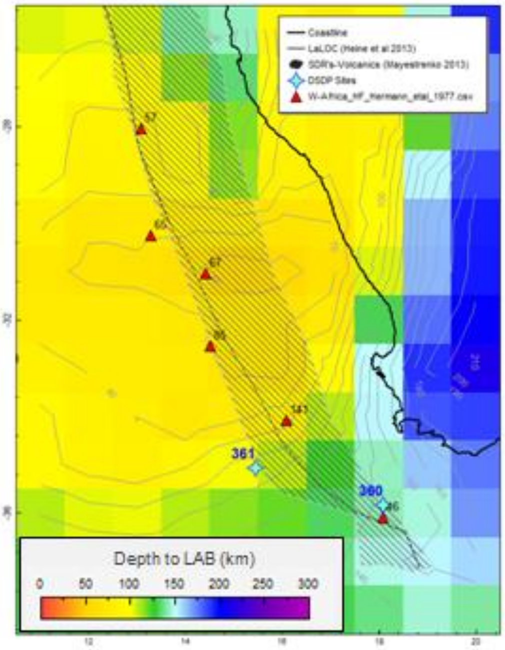

Figure 1: Surface wave dispersion global seismic model for the lithosphere (LITHO-1; *Pasyanos et al., 2014*; LAB is the Lithosphere-Asthenosphere Boundary).

Blue stars show the location of DSDP drill sites and red triangles are the heat flow values compiled by Hermann *et al.* (1977). The solid black line depicts the coastline, the dashed line the Landward Limit of Oceanic Crust (LaLOC *in* Heine *et al.,* 2013), and the stippled area corresponds to the extrusive/underplated volcanic bodies in Mayestrenko *et al.* (2013).

Organic-rich Aptian shales (up to 10% total organic carbon - TOC) were recovered in the lower section of the borehole, between 1000 and 1300 m below seafloor (Figure 2A), and petrographic data show a high liptinite content (Figure 2B), indicating a Type B (*sensu* Pepper and Corvi, 1995), marine oil-prone source rock.

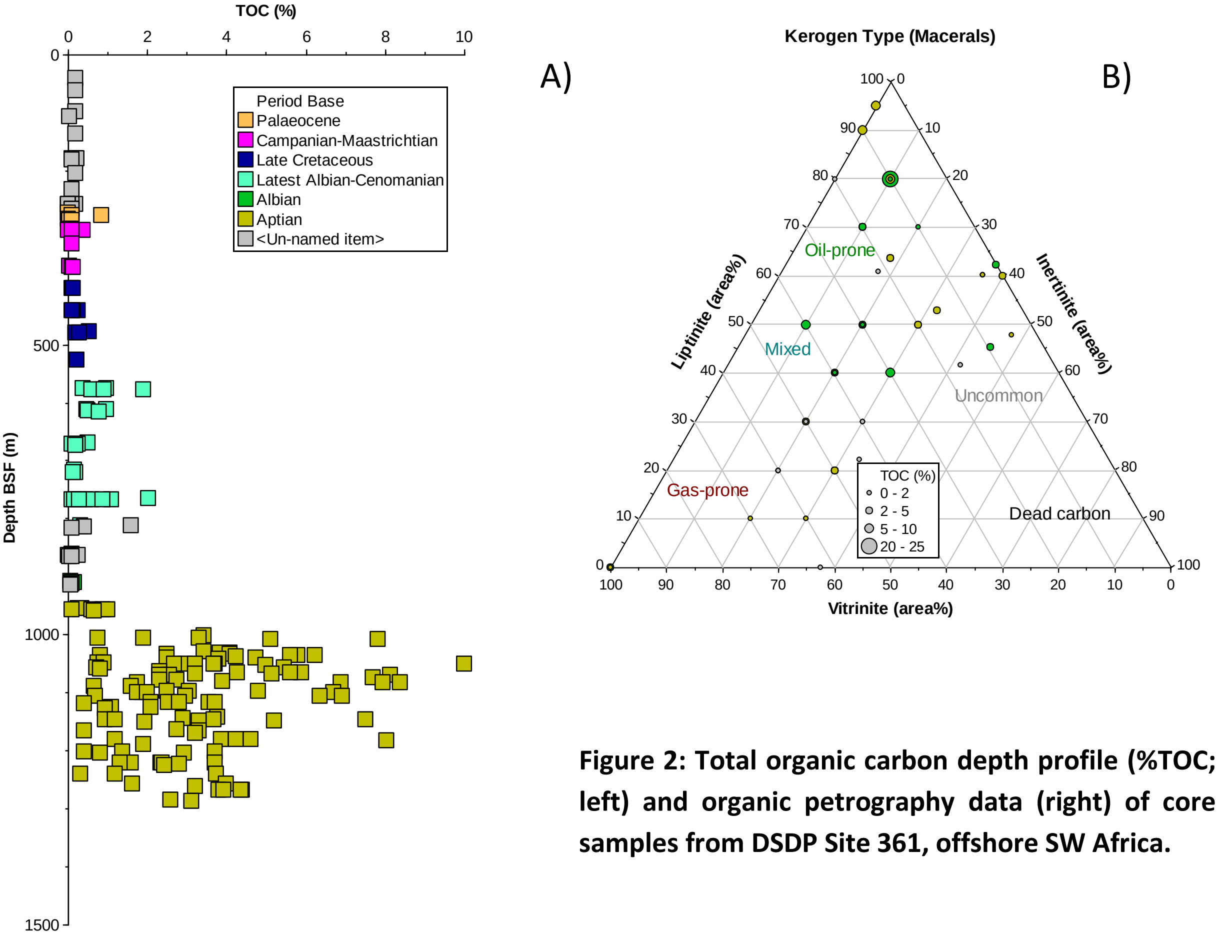

Figure 2: Total organic carbon depth profile (%TOC; left) and organic petrography data (right) of core samples from DSDP Site 361, offshore SW Africa.

THERMAL MODEL SETUP AND CALIBRATION: A rift-type model is used to simulate the thermal structure of the basin through time and predict source rock maturity, by setting a sudden rift event at the approximate time of break-up (125-130 Ma; Moulin *et al.*, 2009), with high lithosphere stretching but negligible crustal thinning (Figure 3A). The thermal model assumes 1350°C at the base of the lithosphere, as boundary condition, and accounts for a variable surface temperature as a result of subsidence and the increase in paleo-water depths following rifting. Three alternative lithosphere scenarios are tested, bounded by the range of observed heat flow values along the ocean continent transition (Figure 3B):

Reference (oceanic lithosphere) model – 8 km thick oceanic crust (4 km basaltic Layer-2 + 4 km gabbroic Layer-3) underlain by 72 km mantle lithosphere. The model predicts a present day surface heat flow of ~66 $mW.m^{-2}$, which is approximately the average along the ocean-continent transition (OCT) after excluding the two most extreme values (see Figure 1).

Cold (oceanic lithosphere) model – 8 km thick oceanic crust (4 km basaltic Layer-2 + 4 km gabbroic Layer-3) underlain by 102 km mantle lithosphere. The model predicts a present day surface heat flow of ~52 $mW.m^{-2}$.

Hot (continental lithosphere) model – 10 km thick continental crust (5 km granitic upper crust + 5 km mafic lower crust) underlain by 65 km mantle lithosphere. The model predicts a present day surface heat flow of ~80 mW.m^{-2}.

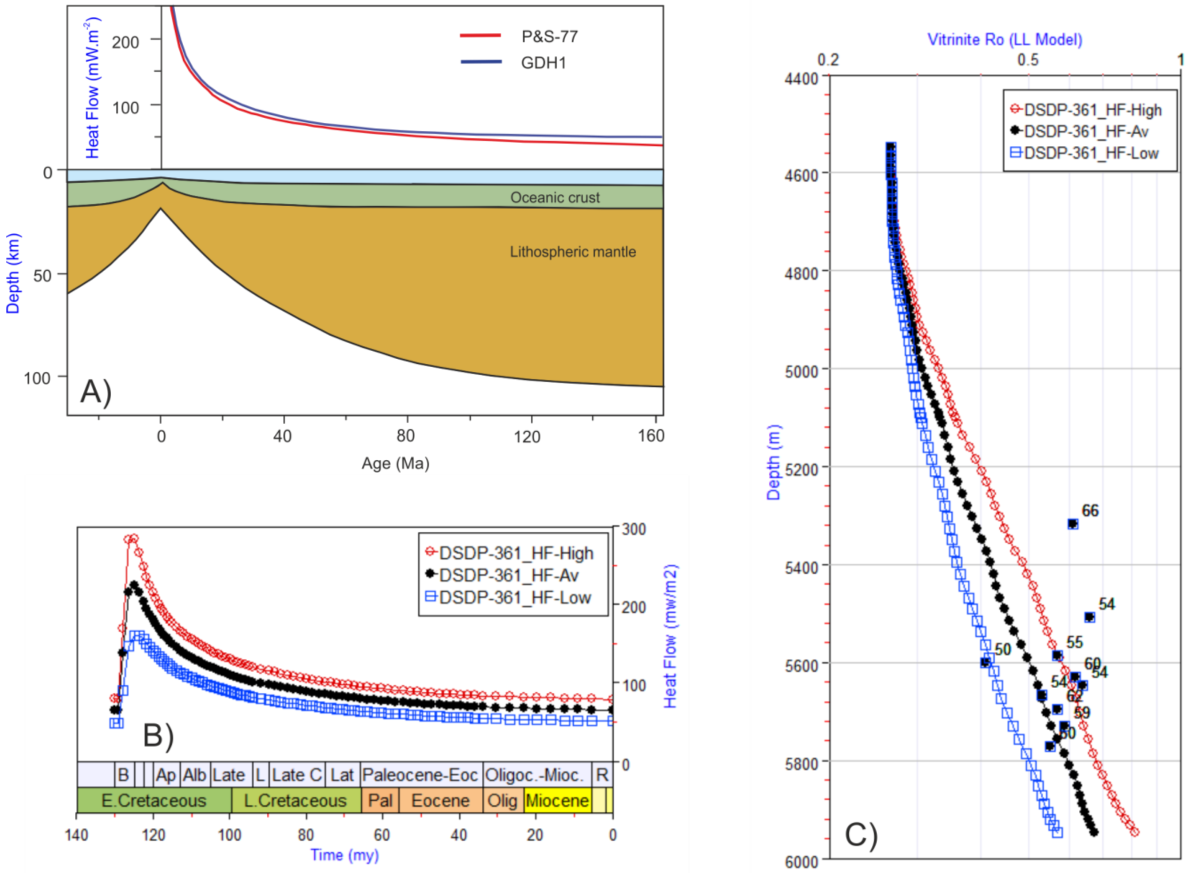

Figure 3: A) Schematic representation of the oceanic cooling plate model and predicted heat flow through time following Parsons and Sclater (1977; P&S-77) and Stein and Stein (1992; GDH1). B) Predicted heat flow through time for the reference, cold and hot models (see text for description). C) Comparison between measured (dots - numbers are number of measurements) and predicted vitrinite reflectance (LLNL %Ro model) for the three tested models.

The implied variations in the thickness of the lithosphere, between 75 and 110 km, are consistent with the LITHO-1 global seismic model (*Pasyanos et al.,* 2014) to the north of DSDP Site 361 (Figure 1). Other events which could have an impact on the predicted source rock (SR) maturity, such as underplating, or an increased heat flow during the late Early Cretaceous associated with a residual track of the Tristan plume (e.g. Maystrenko *et al*., 2013), were not considered here, for simplicity.

As depicted in Figure 3C, the modelled vitrinite reflectance (VR) depth trends cover broadly the range of available measurements. In fact, if the outliers are disregarded as unreliable/erroneous, the reference model appears to adjust to the lower trend of VR values and the hotter model to the higher one. This supports the models which predict a present day heat flow > 60 mW.m^{-2}, in agreement with the heat flow values in Herman *et al*. (1977).

PREDICTED EARLY CRETACEOUS SOURCE ROCK MATURITY:

Three SR levels were defined, assuming a marine oil-prone SR (Type B *sensu* Pepper and Corvi, 1995 - Figure 4): (1) In the uppermost Aptian where the measured TOC contents are higher (up to 10% - Figure 2); (2) In the lower Aptian, near the well TD, where measured TOC's are up to 4%; and (3) between the well TD and the estimated depth of the acoustic basement (1350-1400 m below seafloor; *in* DSDP Leg 40, Shipboard Scientific Party), with a Barremian age.

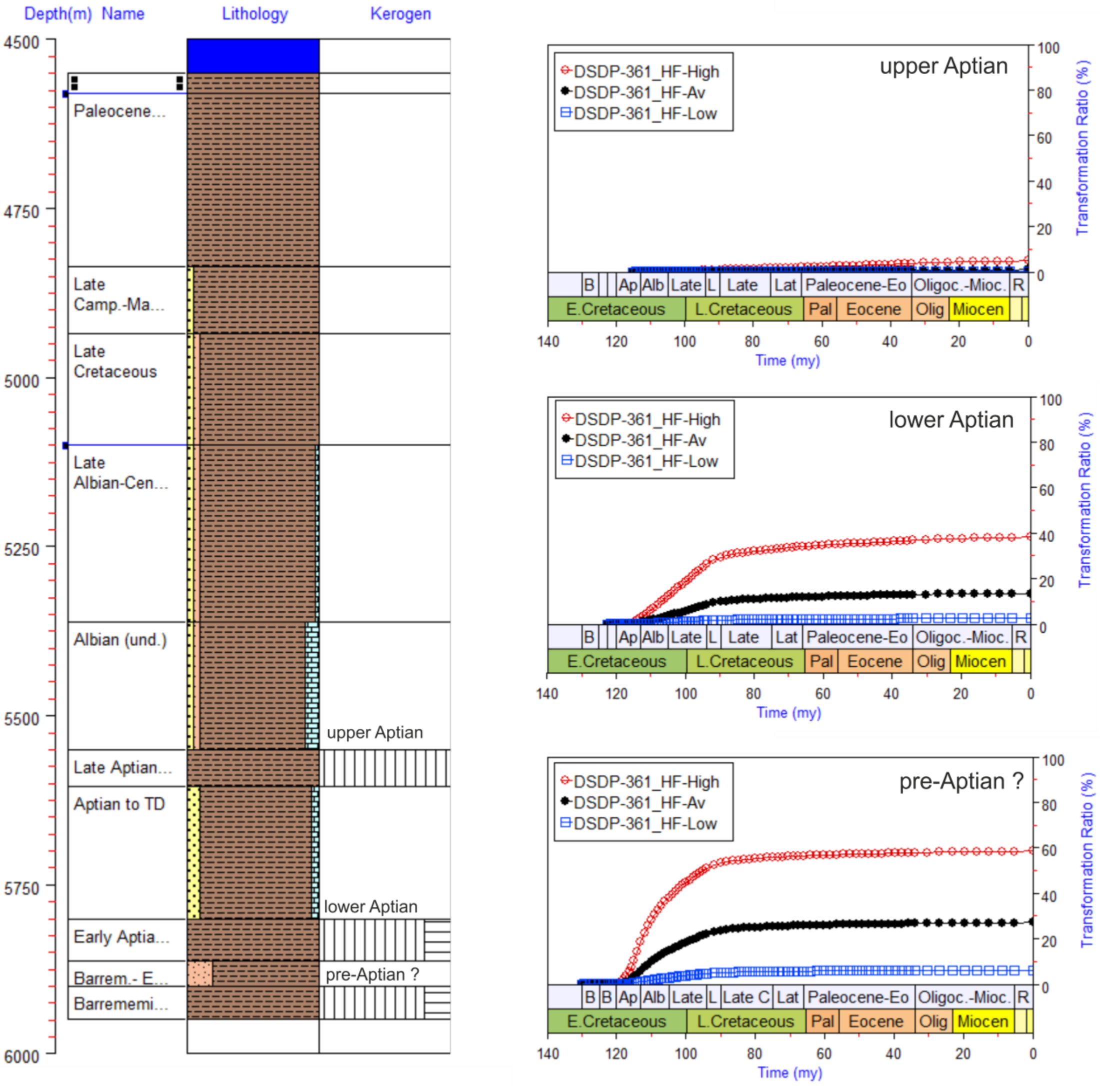

Figure 4: Predicted kerogen transformation in three source rock levels, defined in the upper and lower sections of Aptian, where the measured %TOC suggests excellent to good SR potential, respectively, and below the well TD, potentially in pre-Aptian sediments.

The model results suggest that the pre-Aptian? and lower Aptian SR levels may have reached oil-window maturity during the late Early-early Late Cretaceous, if the reference or hot models are favoured, as supported by the available heat flow and VR data. On the other hand, all models predict an immature, very organic-rich upper Aptian source rock. It should be noted, however, that the potential effects of underplating (e.g. Mayestrenko *et al.,* 2013), and/or recently (Oligocene onwards) elevated geothermal gradients, as inferred along the Angola and Namibia margins, have not been modelled (e.g. Hudec and Jackson, 2004; Jackson *et al.*, 2005).

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