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EAThermal Anomalies Across Africa: Causes and Effects on Petroleum Systems*

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Abstract

A database of some 2000 geothermal gradient and 'quicklook' heat flow calculations is being assembled across the African plate. The data and calculations to date show major variations in these measurements both between and within basins, suggesting that most predictive maturity models we apply in exploration are too simplistic. Geothermal gradients in excess of 40° C/km are surprisingly common, not only in active regimes such as the East African Rift and Red Sea, but also in passive margin settings and in intracratonic settings such as the Paleozoic basins of Algeria. These positive thermal anomalies help to explain recent discovery trends, including several basins which turned out to be oil bearing where immaturity had once been predicted and others where more gas has been found than oil. On the other hand, some other basins show negative thermal anomalies and have very deep resulting oil windows or are prone to biogenic gas.

There are a number of explanations that can be put forward for the anomalies recognized, including thermal conductivity variations within sediments, heating and cooling effects related to timing of active rifting or spreading, and the influences of shallow crustal type and deep-seated mantle convection. All such explanations can be proposed for different thermal anomalies within this dataset, with type cases being illustrated. The mantle convention model is shown to be a particularly strong influence, responsible for the largest anomalies. The data assembled here indicates that wider and generally higher ranges of heat flow should be applied in basin models across most African basins and petroleum systems

Introduction

From an academic viewpoint, the African plate provides an ideal laboratory for testing relationships between heat flow and tectonics. This is particularly true on the plate margins, where timing of break-up ranges from Triassic to Pliocene. The presence of a complicated Basement substrate and of mantle convention cells below Africa also allows study of relationships between heat flow, crustal type and dynamic mantle tectonics.

From a petroleum perspective, there has, particularly in West Africa, been a historic tendency to underestimate source rock maturity. This has led to the discovery of oil where some did not expect it, for instance Tullow have been quoted as saying that on their entry to Ghana, they believed there was no mature kitchen in the Jubilee area. More recently, more gas has been found than oil, with geothermal gradients in areas of new discoveries such as the Tortue-Teranga area in Mauritania-Senegal being found to be extremely high. The aim of this article is to attempt to combine the academic and petroleum perspectives to help try to predict thermal maturity more accurately.

Methodology

Thermal anomaly mapping is being undertaken in three parts:

1) Collation of reported geothermal gradient measurements across the continental portion of the African plate.

2) Manipulation of the dataset to obtain greater consistency and an easier comparison between the data, particularly in the corrections applied to bottom hole temperatures.

3) Compilation of a thermal conductivity dataset and conversion of selected geothermal gradient points to calculate ‘quicklook’ heat flows. This part of the project is approximately 60% complete as shown by the comparison of data points in Figure 1 and Figure 2.

Figure 1 shows the gradients reported in public domain datasets for some 2000 deep wells. In general, in order to reduce errors, only sections over 1000 m deep are included here and shallow core data is not being included. There is a contrast between dense coverage and corrected datasets in North Africa, with more sporadic and sometimes uncorrected data over much of Sub-Saharan Africa. For instance, detailed analyses are available over Algeria, Tunisia and the Western Desert of Egypt, based on temperatures corrected by Horner Plots and a further calibration to DST flowing temperatures, whereas the wide spread of values shown in Mozambique are mainly taken from the highest temperatures recorded during logging, without any corrections applied. It is thought from the North Africa calibrations that the Mozambique data may be reading 12-16% low relative to true geothermal gradient.

Once such corrections have been made, the next stage is to assess which apparent thermal anomalies are due to variations in lithology and thermal conductivity. The best known such effects are those attributable to the high thermal conductivity of salt, which creates negative anomalies. Geothermal gradients generally decrease with overburden due to increasing compaction and thermal conductivity. To obtain accurate heat flows, which would be the ideal manner of making this assessment, a detailed analysis is required based on electric logs and good datasets on thermal conductivity variations with lithology, porosity and temperature. This is not achievable in a study on this scale, though has been achieved by some authors within the bounds of a single country (e.g. Takherist, 1990). The approach taken here has been to calibrate to the best datasets in north Africa, particularly against published thermal conductivity, porosity and depth relationships in Morocco (Rimi and Lucazeau, 1987) and Algeria (Takherist, 1990). Matrix thermal conductivities used are in broad agreement with the published thermal conductivity datasets of Sekugchi (1984) and Vasseur (1984). These relationships are then applied to lithological columns in other basins and the corrected geothermal gradients are then multiplied by averaged thermal conductivities for the sections concerned to obtain ‘quicklook’ heat flow figures. Differences observed between these basins in these ‘quicklook’ heat flows between basins are more credible than the actual numbers and care should be taken in comparing these against radically different datasets such as those from oceanic cores. These estimates (Figure 2) can then be compared against the anomalies seen on Figure 1 to see which anomalies may be due to lithological variations in the sediment pile and which require more deep-seated explanations.

Anomalies Related to Thermal Conductivity Variations in Sediments

These can be identified by comparison of Figure 1 and Figure 2. Examples of altered perceptions on the anomalies defined by geothermal gradient alone include:

- On continental margins, many of the apparent positive anomalies are removed or reduced in their contrast to background values and to anomalies elsewhere. Examples include increasing geothermal gradients as one moves offshore Lower Congo Basin and Ghana/Côte D'Ivoire. Much of this change, though not all, is due to lateral changes in thermal conductivity, particularly the influence of thick sections of undercompacted Tertiary mud.

- On continental margins including thick salt, the opposite happens: geothermal gradients fall below the thick salt sections. In the Kwanza Basin (Figure 4), geothermal gradient falls below salt to 19^{o} C/km. When conversion is made to quicklook heat flow, similar figures are obtained for salt-bearing and salt-free sections.

- The thermal anomalies in the Sahara Basins of Algeria are accentuated due to high thermal conductivities in compact Paleozoic strata, making these the ones which stand out most in the dataset.

- A high geothermal gradient in one Eritrean well in the Red Sea (Figure 4) of 55^{o} C/km, converts to a quicklook heat flow of 214 mW/m^{2}, the highest seen in this study, because most of the well section is salt.

Anomalies Related to Basin Formation and Thermal Cooling

Most basins are expected to be hottest at the time of rifting or spreading, following which a period of exponential cooling is predicted during a period of thermal subsidence (e.g. Hantschel and Kauerauf, 2009). We would thus expect the youngest margins to the African to be the hottest and the oldest to be the coolest. As shown on Figure 3, specific observations include:

- The youngest margin (the Red Sea) has the highest quicklook heat flows.

- In contrast, the oldest margin, namely the Eastern Mediterranean/Levantine Basin (a rift of Triassic age), has, with the exception of the Niger Delta, the lowest quicklook heat flow.

- While there are some wide spreads within the margins considered, particularly in the maxima seen, averages seem to support theories of exponential thermal decay, following the curve of Hantschel and Kauerauf (2009), for Beta=4, assuming exponential thermal decline from underlying thinned crust. Similar thermal decay curves have been interpreted from modelling of Cretaceous margins – an example is shown from the deepwater Kwanza Basin (Baudino et al., 2018).

- There remains a series of anomalies off the trend, both negative and positive, particularly the red circles marking the maxima seen on individual margins, most noteably in parts of the Niger Delta close to the Cameroon line and in parts of Mauritania-Senegal.

Anomalies Related to Shallow Crustal Type

Most modellers assume a major component of basal heat flow is derived from the decay of radioactive minerals in granitic portions of the crust. With reference to Figure 2 and Figure 3, the following observations can be made on this African dataset.

- Cratonic areas (e.g. the Taoudenni Basin on the West African craton) are generally, as expected, cold. The same is observed over the Kaapvaal Craton in South Africa. Because these are the regions of thickest crust, there is not therefore a good relationship between total crustal thickness and thermal gradients.

- Figure 3 suggests that volcanic margins (with thick series of seabed dipping reflectors) are hot at the time of their inception but cool rapidly to give negative thermal anomalies. Central and Southern Mozambique appears to be the best illustration of this, being significantly cooler than margins of similar age elsewhere in East Africa.

- The Algerian anomalies do not seem to follow the complex fabric of cratons and intervening mobile zones that form the Basement here. In fact, these seem to trend east-west, perpendicular to the basement trends, suggesting a deeper control on them.

Anomalies Related to Upper Mantle Convection

Africa is thought to be underlain by active mantle convection cells, mapped through variations in S wave velocities. The distribution of seismic receivers recording such data is sporadic outside of East Africa, but most studies suggest a similar distribution of low velocity anomalies centred around 100 km deep (Figure 2). These are interpreted as indicating raised asthenosphere and thinned lithosphere (Fishwick and Bastow, 2011). These correspond to regions of Miocene-Recent uplift and intrusion or extrusion of alkaline mantle-derived igneous material. The distribution of such volcanics across Africa in time and space would suggest that the Miocene was the peak of such activity. Given the degree of definition of the velocity anomalies, there appears to be a good regional correlation with high quicklook heat flows, suggesting this is a major control. Specific observations include:

- With the exception of two points in the East African rift, all figures in excess of 100 mW/m^2 lie in regions of interpreted lithosphere less than 100 km thick.

- This is the most obvious control on the Algerian anomalies, as thermal gradients and quicklook heat flows increase towards the Ahaggar Massif, an uplift thought to be caused by mantle convention (Lesquer et al., 1990). Ayadi et al. (2000) have separately shown that the highest heat flows in the hottest basin (Ahnet) directly overly a region of hot mantle not shown on Figure 2.

- This also appears to be the most likely model applicable to the anomalies in the gas province around northern Senegal and southern Mauritania (Tortue-Teranga area). The volcanics known from Cap Vert are similar in age and composition to these on the Ahaggar and on the Cape Verde islands, which has also been proposed to be underlain by a mantle convection cell (Lodhia et al., 2016).

- Proximity to mantle convection cells can explain the rise in thermal gradients in the Gulf of Guinea towards the Cameroon Line and also why the Melut Basin in Sudan, with a tectonic history similar to the adjoining Muglad Basin, is significantly hotter.

Other Causes and Effects

There are a number of other potential more localised effects on thermal anomalies. Examples include:

- The lowest heat flows in the Niger Delta are likely related to the thermal blanketing effects of Pliocene sedimentation rates in excess of 500 m/Ma.

- Not all systems are at thermal equilibrium. Movement of hot waters, particularly at shallow depths and the recent uplift of hot aquifers, can create apparent anomalies. These are likely explanations for high geothermal gradients seen in the Victoria Nile portion of Lake Albert, Uganda

Influences on Petroleum Systems

Oil and gas windows are known to vary widely in Africa, with oil generation thresholds for instance in northeast Africa varying from around 1500 m in the Eritrean Red Sea (Figure 4) to 4500 m in the Levantine Basin. These extremes, which are consequences of the different ages of initiation of these basins and their relative positions with respect to mantle convection cells, tie to extremes in the petroleum products of these two basins, which are dominated by thermogenic and biogenic gas respectively. This study also indicates that the generally applied methodology of applying a ‘flat’ OGT or uniform heat flow across a basin is likely to be wrong in all except the least dynamic settings.

Furthermore, we need to consider the past – was heat flow higher (or lower) then? There is growing evidence that much of the pre-salt petroleum system of West Africa suffered high heat flows close to the time of first spreading, with petroleum having been generated at that time. An extreme example is the deep water Kwanza Basin (Figure 4), which appears to have suffered paleo-heat flows up to three times the Present Day figure (Baudino et al., 2018), driving much of the syn-rift system into gas and carbon dioxide. It is notable that the paleo-heat flows predicted there are similar to those seen today in the Red Sea at a similar point in both basins’ tectonic history. On the other hand, the lesser incidence of pre-Neogene alkaline volcanics suggests past heat flows could have been lower in the African interior.

In order to improve the predictability of thermal anomalies, both at Present Day and in the past, we need therefore to:

- Consider the plate tectonic setting and igneous history throughout the basin’s history.

- Use data on modern analogues to predict the past.

- Consider the relationship to volcanics, which involves understanding the chemistry and origin of these volcanics.

- Understand the heat contribution from the Basement and how it may have changed through time.

- Model mantle dynamics in the past as well as control them better in the future.

- Apply ranges of possible thermal histories, not a single model.

Conclusions

While this work continues, the indicated broad conclusions arrived at to date include:

- Africa is a dynamic continent, both in terms of crustal and mantle tectonics. This is reflected in wide variations in geothermal gradient and heat flow that follow the development of features such as the Basin and Swell structure.

- Lithology/thermal conductivity variations themselves cause significant anomalies. Some high geothermal gradients in low conductivity deepwater strata may not be true thermal anomalies.

- Most African margins follow a standard ‘McKenzie’ cooling model. Many of these were consequently hotter in the past, with heat flows possibly as high as the Red Sea today.

- Large parts of Africa are experiencing a high thermal regime related to mantle convection cells, with the peak of this probably in the Miocene. The Senegal and Ahaggar anomalies are examples.

- Wider and generally higher ranges of heat flow should be applied in basin models, not only at Present Day but also during the times of break-up or other peaks of igneous activity.

- The anomalies mapped here help to explain recent petroleum discovery trends, including several basins which turned out to be oil bearing where immaturity had once been predicted, and others where more gas has been found than the predicted oil.

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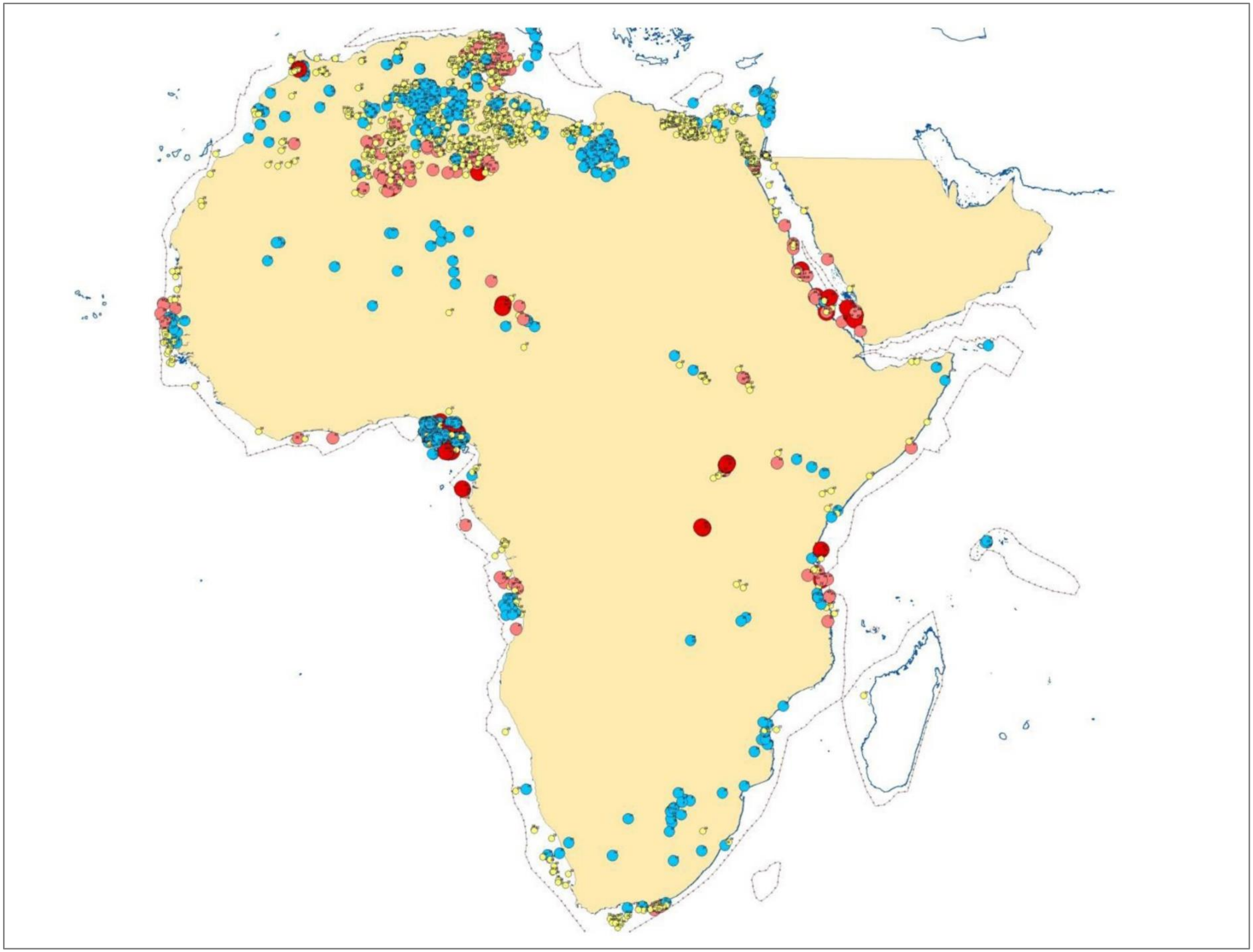


Figure 1. Geothermal Gradient in deep wells in Africa, corrected where necessary for borehole cooling effects. Blue = GG under 25^o C/km, Yellow = 25^o - 40^o C/km, Pink = 40^o - 50^o C/km, Red = above 50^o/km.

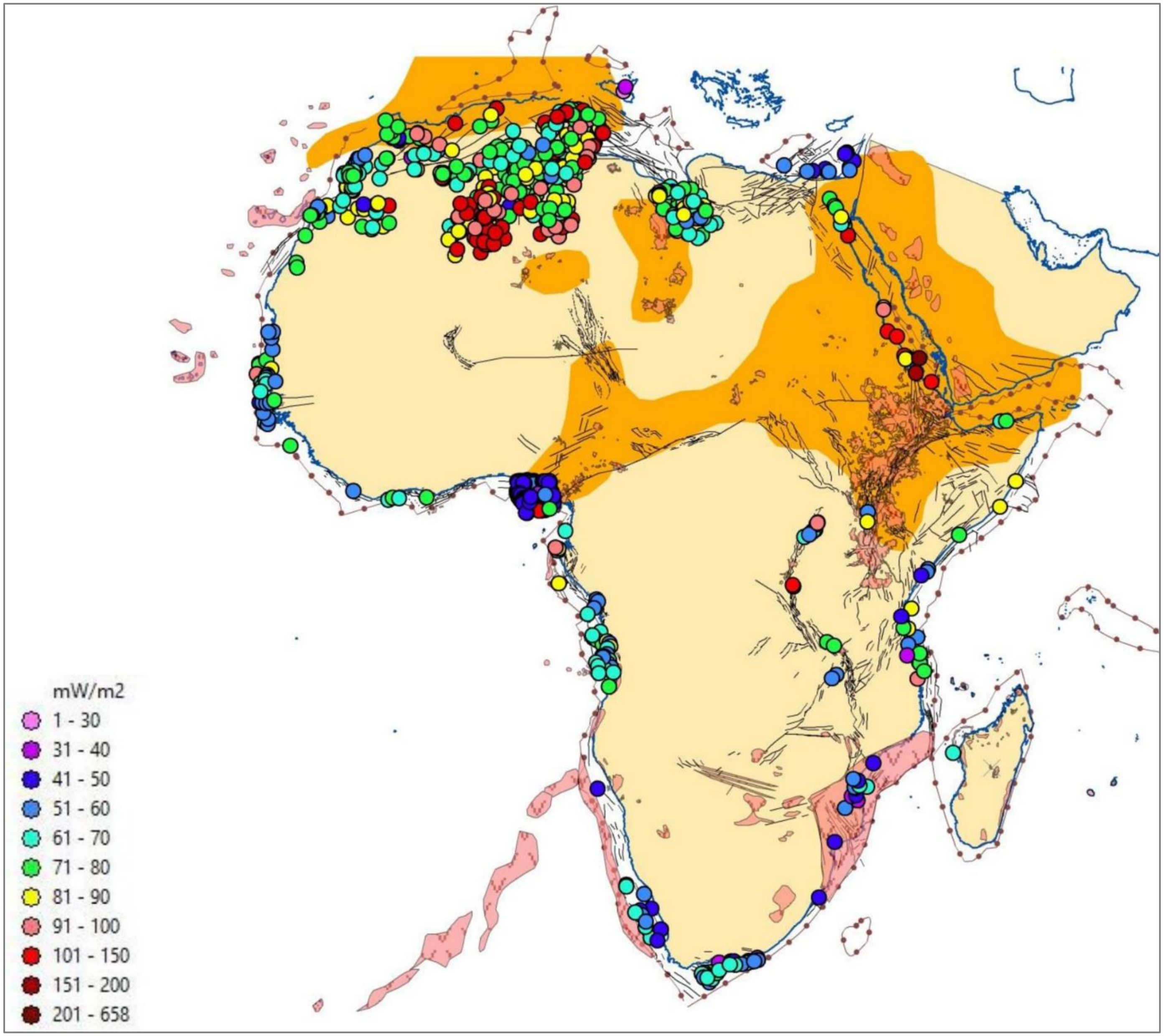


Figure 2. Quicklook Heat Flow map of Africa, constructed using thermal conductivity/age/depth relationships calibrated to Moroccan and Algerian datasets. Volcanics of various ages in pink. Orange polygon represents regions of interpreted lithosphere under 100 km thick, interpreted by Fishwick and Bastow (2011).

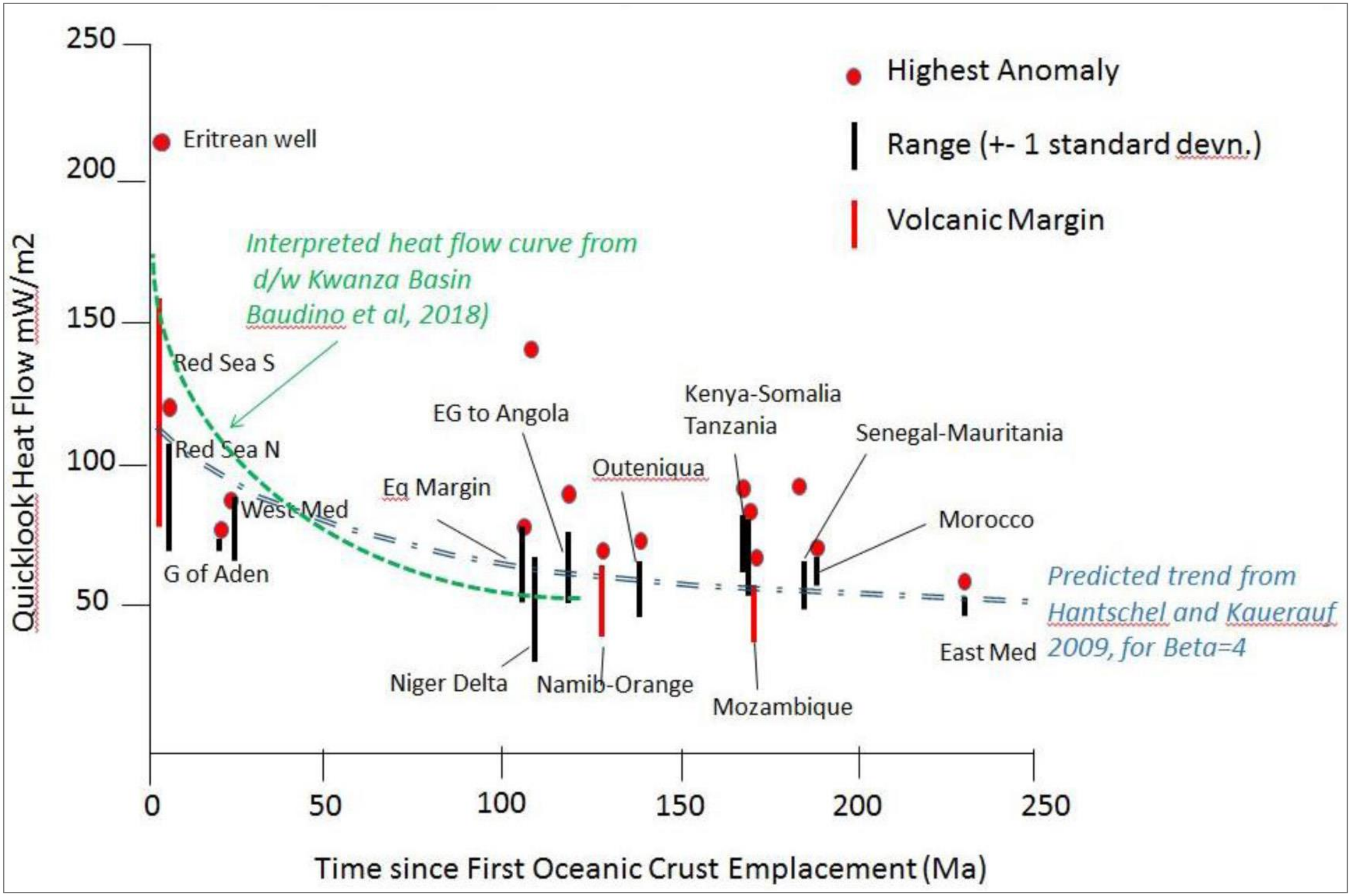
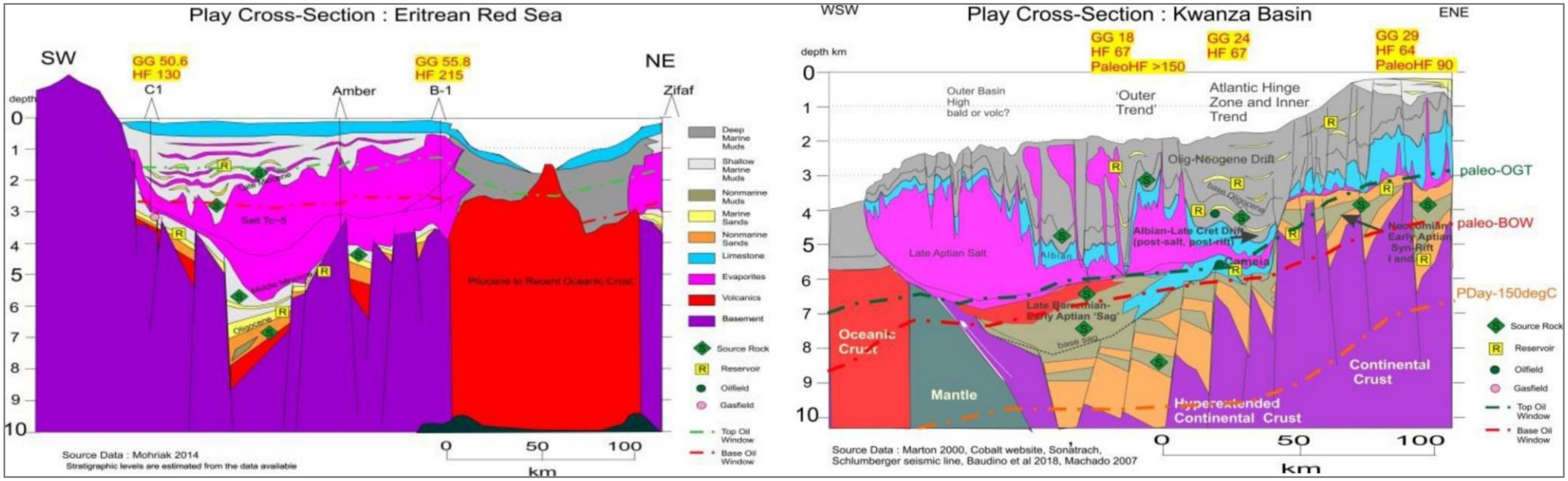


Figure 3. Quicklook Heat Flow for African plate margins plotted against time since onset of drift, when heat flow was likely highest. This is compared with heat flow vs time curves predicted for Beta=4 and interpreted from modelling in the deepwater Kwanza Basin.



Play Cross-Section : Eritrean Red Sea

Source Data : Mohriak 2014

Stratigraphic levels are estimated from the data available

Play Cross-Section : Kwanza Basin

Source Data : Marton 2000, Cobalt website, Sonatrach, Schlumberger seismic line, Baudino et al 2018, Machado 2007

Figure 4. Comparison of a basin in which spreading has just been initiated (Red Sea) with one which suffered a high heat pulse at an equivalent time in its spreading history (Kwanza) but has since cooled. In both cases the high heat flow during late rift and early drift has driven syn-rift source rocks into the gas window or beyond. A very narrow paleo-oil window results in deep water Kwanza. Kwanza interpretations largely after Baudino et al, 2018.