# Geodynamic Evolution of the Atlantic Ocean: Constraints from Potential Field Data

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## ABSTRACT

The implications of some new developments in geodynamics and plate tectonics that are important in the exploration for hydrocarbons on continental margins are explored. To do this the relationship of potential field data signatures to structural and tectonic elements is shown and used to extend our understanding of these elements.

The development of basins during initial break up of continents is controlled by the location of zones of weakness that exist in the continental crust before rifting begins. The initial direction of rifting and spreading appears to depend upon the direction of the controlling zones of weakness. There are multiple orientations for zones of weakness in most areas of continental crust. The zones which are chosen are those that align most closely with the preferred direction of spreading. This direction is related to the direction of convection in the upper mantle or possibly to hotspot plume orientation.

Zones of weakness may not align exactly with the preferred direction of spreading. During rifting and for some period of time thereafter, the interaction of the various continental fragments also may not be well defined. These two factors, and others, may contribute to a period after rifting and prior to the drift phase where the direction of spreading may be somewhat chaotic. During this phase parts of the continental crust may be fragmented and intermingled with volcanic material produced from the embryonic ridge system. Possibly other types of volcanism than mid-ocean ridge basalts may occur. These factors are the basis for the formation of the "proto-oceanic" crust described by Dickson and Odegard (2000) and Odegard (2002). This crust undergoes further modification as it descends from its formation at or near sea level to deeper ocean depths.

After the onset of the drift phase and the formation of normal oceanic crust, the near linear zones of weakness in the continental crust appear to reactivate and propagate into the extended continental, proto oceanic and oceanic crust. The cracks appear to be the locus of volcanism associated with epidural warm spots. These warm spots elevate the heat flow and affect the maturation of hydrocarbons. They also segment the basins forming on the continental margins. This segmentation may compartmentalize oils of different composition and maturity (Fryklund, et al., 2001).

This paper describes in greater detail the observation and characteristics of the processes described above. Observations are shown for various areas of the Atlantic Ocean shown with some additional observations for Brazil.

## The New Plate Tectonics

The plate tectonic model, developed in the 1960's, accounted for many of the major tectonic features on the Earth. It also accounted for much of the volcanism on the Earth's surface, which is at plate boundaries. It did not, however, account for "mid-plate" volcanism such as Hawai'i, Iceland and Yellowstone. In 1971 Morgan proposed a "mantle plume" model, another form of convection in the mantle, to account for this type of volcanism. The plume or hotspot model seemed to account nicely for this type of volcanism and was eventually proposed as the model for over 5,000 volcanic centers. Recently, however, different types of mechanism have been proposed for most of these centers.

### *Hotspots – To be or not to be*

A strong debate is raging in the scientific community as to which volcanic centers are related to mantle plumes, or even if mantle plumes exist at al. See, for example, papers by Courtillot, et al., 2003, Anderson (2000), and Fairhead and Wilson (2003).

Based upon the work by Courtillot, et al., the number of significant hotspots has been reduced to about forty. These are shown in Figure 1. Because the level of heat flow is important to the generation of hydrocarbons, it is important to understand how these various types of hot or warm spots affect the heat flow in an area.

The mantle plume type of hotspot, for which Hawai'i is a model, may not have a significant heat flow signature. In measurements over the Hawai'ian ridge (Stein and Stein, 1993) there appears to be no significant heat flow anomaly associated with the hot spot. This may be for one or more reasons. First, the plume causing the volcanism may be narrow as shown in Figure 2, so that no significant energy is imparted to the surrounding rock. All the excess heat could be dissipated by the cooling of the volcanic edifice. Second, the heat flow anomaly could be so broad that the heat flow is only slightly elevated as is seen over the Hawai'ian swell

Because the level of heat flow is important to the generation of hydrocarbons, it is important to understand how the hotspots and warm spots described above interact with basin development along continental margins. Because many of the warm spots are related to zones of weakness in the lithosphere, it is important to understand the

## The Cracked Earth

To understand how paleo-structural features may affect today's tectonic development, we look at the continent of Africa. The African continent has been relatively stable over much of its existence. Thus, if we are to see older features that may be related to recent features, this would be a good place to begin.

To do this we look at the gravity field over the African n plate. Gravity records variations in the density of the Earth. These density variations are produced by the geological processes that we wish to investigate. Looking at enhancements or special visualizations of the gravity field allows us to highlight different types of geological processes. We also can use magnetic, and topographic and bathymetric data for similar purposes. In our investigations we integrate these data with other available data that will be seen later in this paper.

### *Extended Gravity*

Gravity data over the African continent was compiled by GETECH over fifteen years ago (Fairhead et. al., 1988). Using modern topographic and bathymetric data these gravity data have been reprocessed. During this reprocessing the Free Air Gravity grid was in filled in areas of no data using the gridding algorithm from Smith and Wessel (1990). After adding corrections for the complete Bouguer and for Isostatic compensation these data show a gravity "image" that extends into areas not covered by gravity measurements. Thus the use of the term "Extended Gravity". This extended gravity image can be used to investigate the location and extent of tectonic features in the Earth's crust. Other enhancements are then done to these images to highlight a variety of structural and tectonic features.

Offshore Africa, because of developments in satellite derived gravity, the coverage is nearly complete. In this study we use the data from Sandwell and Smith (1997). New processing methods are being developed, however, that will extend the coverage, accuracy and resolution of satellite derived gravity. See Odegard and Fairhead (2003) and Fairhead, et al. (2002) for details.

## African Tectonic and Structural Features

When the extended gravity over the African plate is displayed as shown in Figure 3, many features are seen that are associated with known plate tectonic elements. Other features, however, are associated with tectonic/geological elements that appear to violate plate tectonics. Others are related to non tectonic sources.

### *Possible Impact Structures*

One of the striking features that is easily seen in the images is the appearance of a large circular structure in west central Africa with a diameter of about 780 kilometers. This structure begs to be correlated with the postulated Bangui impact structure (Girdler, et al., 1992) as shown in Figure 4. Other larger and smaller structures are also seen that may correspond to impacts. Several of these appear to be associated with other tectonic structures. Other circular structures could be interpreted, but those shown are limited to those that are most obvious.

### *Linear Structural Features*

Also seen are features that are associated with known plate tectonic elements like fracture zones. Other features, however, are associated with tectonic/geological elements that appear to violate plate tectonics. Some of these are indicated in the interpretation in Figure 5. In particular those associated with the Benguella volcanic line of southern Angola (Danforth, 1998). Possible mechanisms for emplacement of these features may be deeper tectonic processes or extension of zones of weakness from the continent into the oceanic plate.

There appears to be an interesting correlation between the impact structures and at least some of the major linear features. The "rims" of many of the "impact" structures appear to correlate to the location of the linear features. This may affect the location of the rifting that occurred in Gondwana/Pangea.

### *Stresses cracks and heat flow*

The linear features that have been identified in Figure 5 have interesting consequences with respect to the identification of areas with hot or warm spots in the upper mantle. Shown in Figure 6 is the gravity field over the North Atlantic reconstructed to an age of 135 MYBP. For information on the method see: http://www.getech.com/ptm.htm. The image is of the gravity field with an enhancement for the total horizontal derivative applied. This tends to show volcanic centers as doughnuts or sinuous features.

In this image it becomes obvious that the New England seamounts and the Canary Islands have some common feature that relates them genetically. It appears that this is the major linear feature seen in the northwest part of Africa and offshore in Figure 5. The New England seamounts appear to be related to a similar feature starting in onshore New England, USA.

Two interesting facts about these two seamount chains is their differing ages and the age range for a seamount site. Radiometric ages for the New England seamounts indicate that the formed from 70 to 100 MYBP with volcanism of significantly different ages for the same location (McHone, 1996). The Canary Islands on the other hand are currently active with volcanism beginning about 20 to 25 MYBP (Carracedo, 1994). Similarly the volcanism extends over most of this period at the volcanic sites with a somewhat younger progression to the west. Both of these lines trend near to the spreading direction, but are slightly oblique. Other volcanic chains such the Cameroon line, the Guinea seamounts and the Benquella line appear to have similar characteristics and are highly oblique to the spreading direction.

An interesting feature of the Canary Islands is their association with a hotspot of the secondary type as shown in Figure 1. This type is formed at the base of the upper mantle and has seamounts derived from it. From heat flow measurements we know that the area to the north and locally around the Canary Islands has an elevated heat flow. The arrival of the heat flow anomaly in this area and part of onshore Morocco can thus be correlated with the advent of volcanism along the Canary chain. The volcanism is manifest along cracks in the lithosphere at two angles. One is parallel to the Moroccan coast and another along the onshore-offshore lineament. This observation gives us a predictive model for the variation of heat flow in a developing basin, and could be used in a basin maturation model.

## Effects of Geodynamic Processes on Basin Development

The geodynamic processes described in the previous sections have important consequences for the development of basins during and after rifting.

### *Crustal Segmentation*

The segmentation of the developing and thinning crust, during and after rifting appears to be controlled by two factors. First some zones of weakness in the continental crust appear to influence the initial direction of opening of the rift system. During the initial rifting and perhaps for some time before the beginning of formation of true oceanic crust (the drift phase), different local rift systems “fight” for control of the final spreading direction. Even after the spreading direction is set changes in the overall spreading direction can change, although probably at a slower pace.

Second, during and probably even after rifting has stopped, zones of weakness in continent and/or upper mantle can segment the developing basins by propagating “cracks” into the lithosphere at angles oblique to spreading. Both of these types of segmentation are important to basin development. They also appear to be important to the geochemical development of a basin.

### *Crustal Thinning*

It is reasonably clear that the segmentation of the crust during rifting is controlled by zones of weakness in the continental crust. Oblique zones of weakness may also have an effect on how, and to what extent crust is thinned in a particular area. How this occurs should be investigated in the future.

### *Proto Oeanic Crust*

Areas of apparent oceanic crust, which have characteristics that are not those of pure oceanic crust, have been mapped in the North and South Atlantic Ocean basins. Neither are they extended continental crust. This crust has been described as "Proto Oceanic Crust" (POC) by Dickson and Odegard (2000), and others.

Seismic, well, gravity, magnetic and topographic data were merged into a Geological Information System (GIS). Results of this integration have shown that the POC has a distinctive gravity and/or magnetic signature. As described by Odegard and Dickson (2001), on seismic sections POC typically shows an architecture of tilted fault blocks and on lapping fill. Depending upon the area, POC appears to be either volcanic material, abducted mantle, separated continental fragments, or a combination of these materials. Emplacement can occur at or near sea level, in regions of restricted lacustrine to oceanic circulation, or open marine environments. The type of material, timing, emplacement mechanism, and depositional environment determines how prospective these areas are for hydrocarbon exploration. This is particularly true in deep and ultra-deep water areas. Of particular importance is the magnitude of heat flow during and after emplacement.

As an example of the difference between proto and pure oceanic crust, the east coast of North America is shown. In Figure 7 the magnetic field over part of northeastern North America can be seen. An area north of the linear feature associated with the New England Seamounts shows little apparent magnetic signature, while to the south magnetic anomalies associated with spreading can be seen. In Figure 8, which shows the dip-azimuth of the magnetic field, the spreading anomalies can be clearly seen, while to the north these anomalies appear to be possibly present, but with a chaotic signature.

This area of chaotic signature would be characterized as an area of proto-oceanic crust. The chaotic nature of would be attributed to the “fighting” which occurred during the period when the spreading direction was being set. The signature also appears to be seen in seismic profiles. Heat flow appears to be somewhat higher in areas of proto-oceanic crust and thus important to hydrocarbon exploration.

The division between the proto and pure oceanic crust indicated by the seamount chain is interesting. Why there is a division is not clear, but it appears to be obvious. The mechanism for the exact method of proto-oceanic crust formation is left to future research.

## Discussion

A number of new developments in plate tectonics and geodynamics have been shown and discussed. I started with a somewhat outrageous proposition that impact structures might be associated with the future breakup patterns of continental rifting. Then the importance of new plate tectonic theory was indicted. Finally the possible occurrence of proto-oceanic crust and its influence on basin development was described. These new development are clearly important in understanding the development of basins from the initial rifting through drift phase, and even into the more passive development of the basins. Through application of these developments we should be able to develop a predictive model for basin development, segmentation and maturation.

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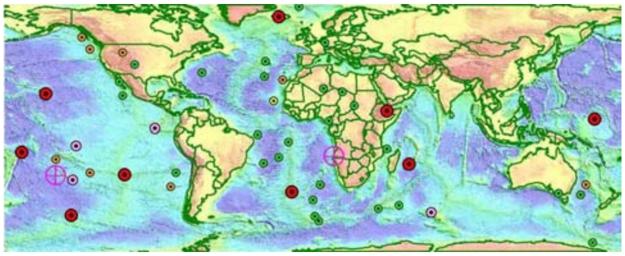

Figure 1

Three types of hotspots from Courtillot, et al., 2003. The colors of the three types are red and pink: primary and possible primary; yellow: secondary; and green: tertiary. Also shown are super swells as magenta circles with a cross. The genesis of the three types is shown in Figure 2.

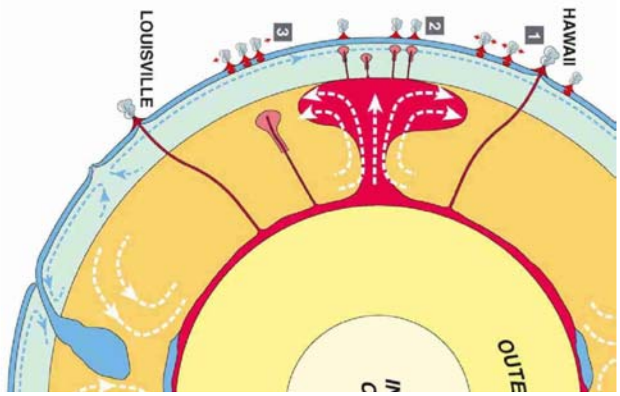

Figure 2

Earth dynamics from Courtillot, et al., 2003. Primary hotspots come from the core mantle boundary. Secondary hotspots are generated at the boundary between lower and upper mantle above super plumes. Tertiary hotspots are generated by decompression melting at the base of the lithosphere below zones of weakness

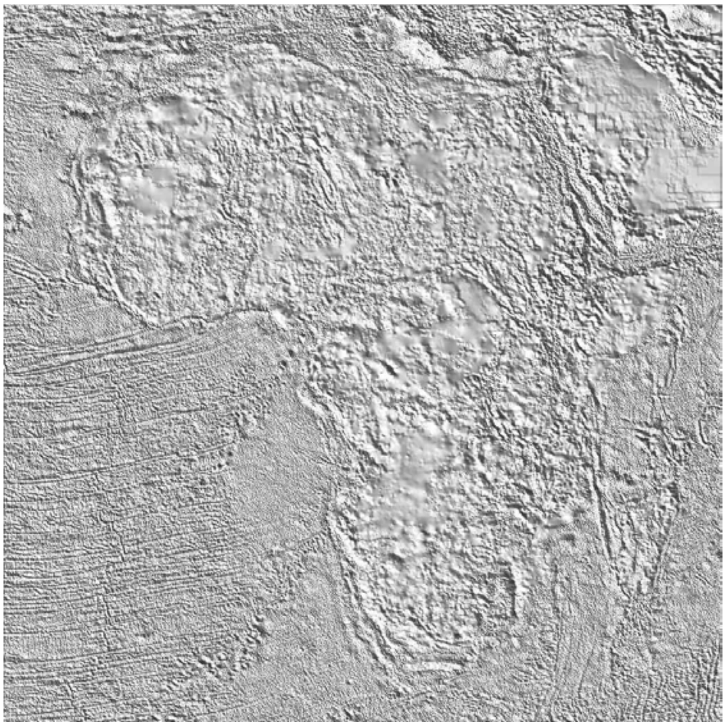

Figure 3

Extended and satellite gravity over the African plate displayed in gray shaded relief with a 45 degree shading azimuth.

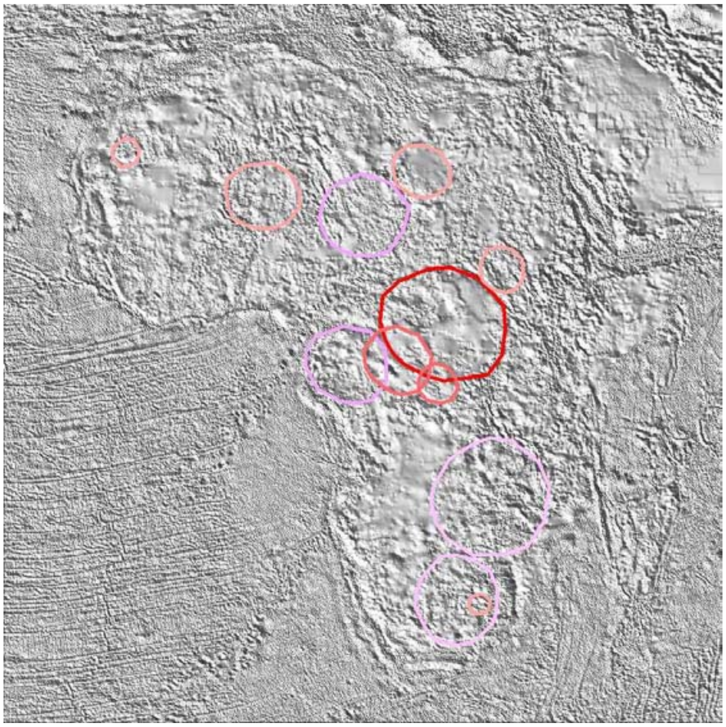

Figure 4

Extended gravity over the African plate with possible impact crater locations

Figure 5

Extended gravity over the African plate with possible major linear features oblique to plate tectonic flow.

Other linear features can be interpreted.

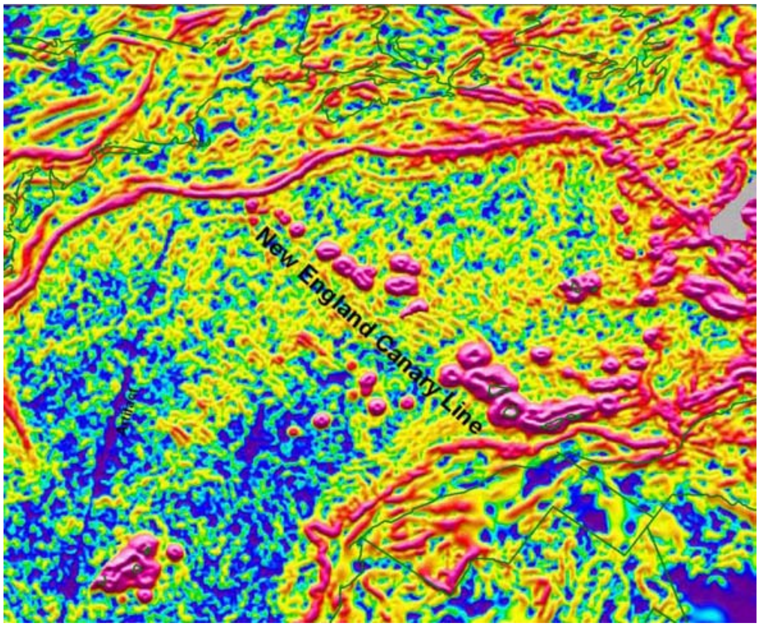

Figure 6

Total horizontal derivative of the Bouguer gravity reconstructed to 135 MYBP showing the collocation of the New England and Canary seamounts. Coastlines and country boundaries are show as green lines. The NNE-SSW linear feature on the left is an artifact.

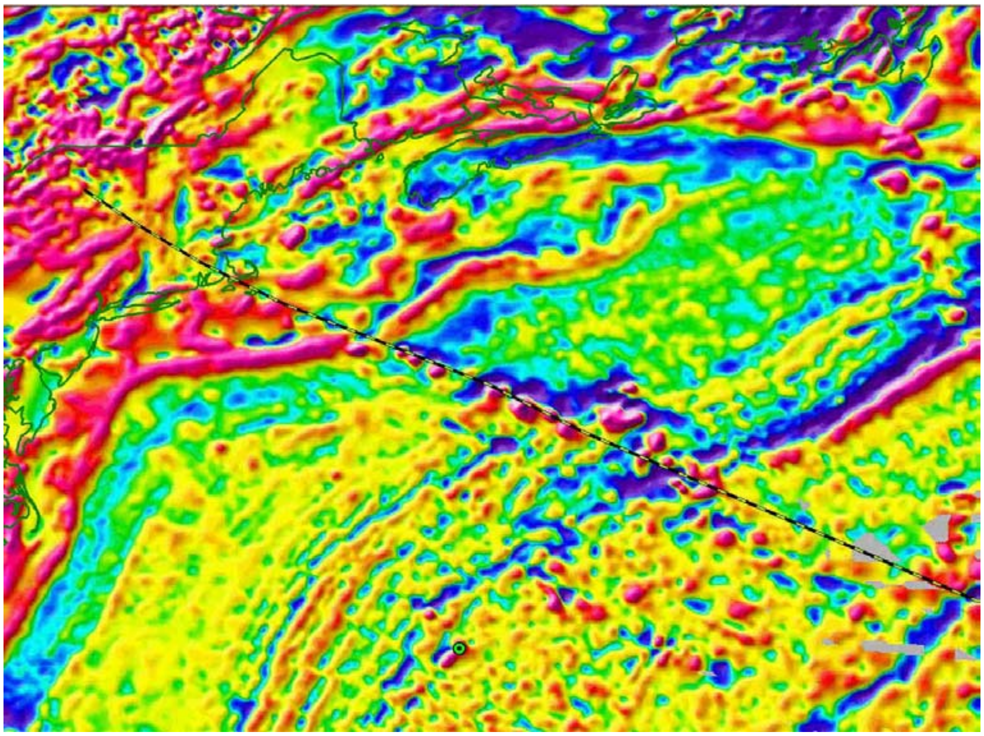

Figure 7

The total magnetic intensity field over part of northeaster North America. The linear feature is the New England Seamount chain and possible landward and seaward extensions of the linear zone of weakness. An area north of the chain appears to have little magnetic signature. To the south spreading anomalies can be clearly seen.

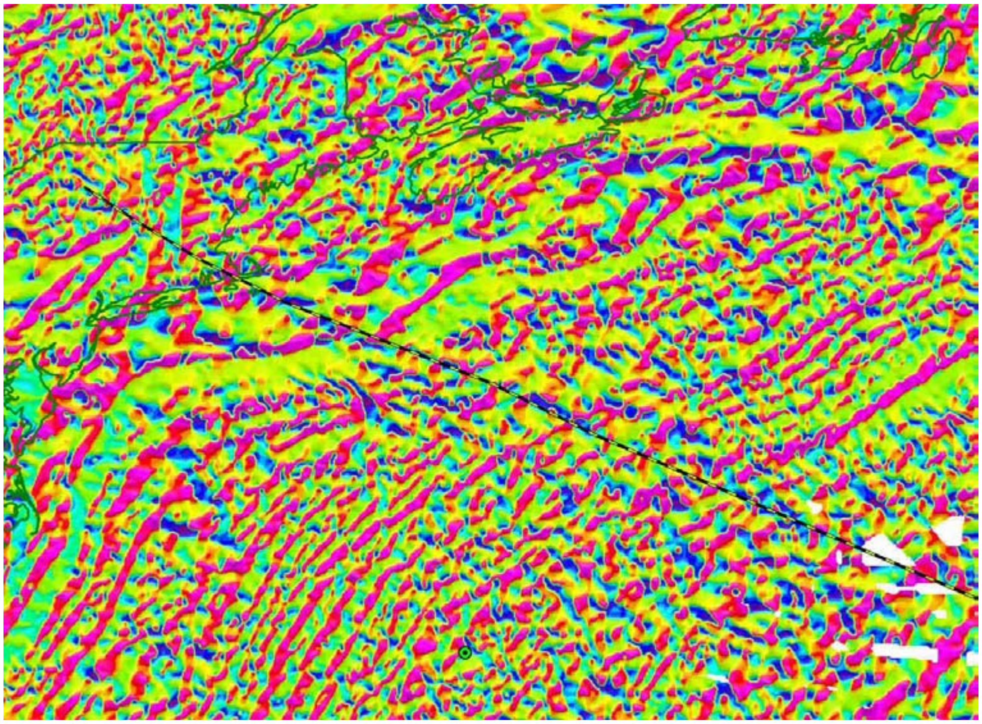

Figure 8

The dip-azimuth total magnetic intensity field over part of northeaster North America. The spreading anomalies can be seen to the south while the northern area of the previous figure show a signature of spreading anomalies with a chaotic signature.