DEFORMATIONAL STYLES OF THE WEST AFRICAN MARGIN

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Abstract

Reprocessing of the PROBE Study seismic data set indicates that the continental margin between Cameroon and Southern Gabon is separated into the North Douala and Gabon Basins by the Kribi Fracture Zone. This is a 75 km-wide transform fault that trends NE-SW and intersects the coastline between 2-3^0 N. Much of the margin off Equatorial Guinea is influenced or controlled by fracture zone tectonics. North of the Kribi Fracture Zone, oceanic crust extends to the coastline and floors a narrow shelf off Cameroon. Little rift margin exists in the North Douala Basin. Reflection Moho beneath oceanic crust is relatively weak but continuous throughout the North Douala Basin and oceanic crustal thickness is extremely uniform, averaging about 1.75 s in two-way travel time. South of the Kribi Fracture Zone, oceanic crust is offset about 350 km to the southwest, creating a broad rift margin off Gabon. Rifting of the margin here seems to involve brittle, upper continental crustal sheets overlying a series of ductile lenses that generally dip southeasterly. The ductile lenses may unroof toward outer highs, which mark the boundary between oceanic and continental lithosphere. Strong reflection events are often associated with the ductile shear zones that define the lenses, but a single, continuous event representing reflection Moho cannot be mapped. The concept of a regional reflection Moho beneath rifted continental crust may be flawed in this area. The tectonic and rheological models presented here may be useful in framing hydrocarbon exploration tactics and strategies along this passive margin.

INTRODUCTION

The sedimentary basinal architecture of the passive continental margins bordering the South Atlantic is steadily being revealed as more and more multichannel seismic (MCS) data bases are acquired and analyzed. Although the sum total of the knowledge remains somewhat fragmented by the proprietary nature of the data bases, and informational gaps and imaging problems still exist, it is fair to state that much progress has been made over the past four decades in the sedimentary realm. The same cannot said of the deep structure of these passive margins, which has proven to be very difficult to resolve except in the broadest contexts. Thus, the expressions of the rifting processes below the basement remain poorly constrained and subject to a diverse range of possible models. There are several reasons for this situation. Foremost is the comparatively limited amount of deep-imaging MCS data that has been collected across these margins. Secondly are the acquisitional and processing differences between and within the deep-imaging MCS data sets that do exist. These differences hamper comparisons and the problem is further compounded by a lack of "rules" or guidelines in regard to interpreting reflections and reflector patterns below the basement. These intrepretive difficulties are exacerbated by the diversity in crustal types that are encountered across these margins. These can range from relatively unrifted continental crust to highly stretched and possibly intruded "transitional" crust to normal oceanic crust. The occurrence of fracture zones complicates matters even more. The fact that the existing deep-imaging MCS data across these margins cannot be ground-truthed with well information at the deeper levels imaged adds another degree of interpretative freedom.

One of the more extensive deep-imaging MCS data sets in the South Atlantic is the PROBE Study collection off Cameroon, Equatorial Guinea, and Gabon (Rosendahl et al., 1991, 1992). Much of this collection has now been reprocessed and the resulting images offer the possibility to constrain the deep structure of this margin segment to a greater degree than previously possible. In so doing, some of the problems listed above can be addressed more rigorously than was possible with the original PROBE collection. The results of the reprocessing are presented comprehensively in Rosendahl and Groschel-Becker (in press). This extended abstract highlights and builds on some of these results.

TECTONIC SETTING

The reprocessed PROBE data depict a 75 km-wide transform fault margin (Kribi Fracture Zone – KFZ) that trends approximately NE-SW and intersects the coast at the position of Equatorial Guinea. North of the KFZ, oceanic crust

(OC) extends essentially to the coast of Cameroon. Consequently, the narrow continental shelf here is built on OC and there is little rift margin per se. South of the KFZ, the OC is offset about 350 km to the southwest, resulting in the broad rift margin off Gabon. The boundary between this rift margin and OC is marked by an outer high (OH) at the level of basement. No major-offset fracture zones are mapped south of the KFZ within the region covered by the PROBE lines.

MAJOR REFLECTIONS, REFLECTOR PATTERNS, AND CRUSTAL TYPES

Oceanic crustal basement (top of layer 2) is generally clearly imaged and easily recognized both in terms of reflection character and stacking velocity. The reflection Moho (RM) is a relatively weak reflector couplet, but it is very continuous throughout the oceanic sector and line ties are usually excellent in spite of the weak reflectivity of oceanic RM. The parallelism of the oceanic basement and RM is so close that the resulting seismic thickness of OC, 1.75 s in two-way travel-time (TWTT), rarely varies by more than about 5% in the area north of the KFZ. The mean thickness in nominal depth is about 5.63 km. The nearly constant thickness of OC suggests that either oceanic crustal genesis was extremely uniform in the Gulf of Guinea, or oceanic basement and RM are coupled in some dynamic way. The total depth to oceanic basement (or to RM) depends mainly on the amount of overburden, suggesting that basement and RM are mechanically coupled and that both respond dynamically to loading. A choppy, discontinuous reflection pattern is sometimes observed in the upper OC, but there is little indication of any layered, coherent, and mappable reflection events within the OC. Occasional, obliquely-trending reflections are observed dissecting OC, but rarely if ever do such events correlate to offsets in basement and RM away from the KFZ. In fact, there are few instances in which offsets of basement and RM can be confidently connected except within the KFZ, implying that through-going faulting of OC may be relatively rare.

Crust within the KFZ tends to be thicker than normal OC, although there is a high degree of structural variability both within the fracture zone and along its length. Through-going faulting is common within the KFZ, creating large tilt blocks that tend to be inclined toward the oceanic side. This gives some profile crossings of the KFZ a distinctly rift-block appearance. Volcanic or intrusive highs also are common within the zone. The reflectivity of apparent RM tends to be markedly greater within the KFZ than the reflectivity of normal oceanic RM, at least on some profile crossings. The southern edge of the KFZ (i.e., the continental side) is difficult to constrain and map accurately, which is not surprising given that the KFZ is a continent-bounding transform fault. The KFZ is probably the eastern end of the Ascension Fracture Zone and may be the West African conjugate equivalent of the Pernambuco-Paraiba Fracture Zone of Mohriak et al. (1995).

South of the KFZ and landward of the OH, there are many major reflections at various levels below the post-rift succession. How these reflections group into events and packages and what they signify geologically are key to understanding the rifting history of the broad margin off Gabon. Initial interpretative efforts tended to center around identifying and mapping continental reflection Moho in a similar vein to what was achieved in the oceanic crustal sector. It was felt that this would be the surest way to provide an intepretative reference frame across the stretched continental sector of the study area. Various attempts to do so were unsuccessful. The reasons for this are instructive and deserve to be highlighted here. Unless otherwise indicated, the subsequent discussion refers to the part of the continental margin that lies landward of the OH and inboard of the KFZ.

There are long segments of individual lines (100 km or more) over which a consistently strong and coherent *apparent* RM could be identified. These reflection events generally occurred within the depth interval from 7-11 s (TWTT). Conversely, there also are areas that display almost no coherent reflection events in this depth range. Multiple possible RM events appear along some line segments, any, all, or none of which could represent RM. Events picked as apparent RM along one line segment sometimes mis-tied with apparent RM on crossing lines, as long as consistent intrepretational criteria were employed. Yet, almost always apparent RM on one line could be tied to a reliable, albeit lesser reflection event (or package) on a crossing line. There were even places in the deep section where apparently real reflection events seemly merged and crossed each other in ways that would violate the interpretational rules used in sedimentarry regimes. Reasonable RM-computed Moho depths along one line segment became unreasonable computed Moho depths at other positions along the same line, or along some tied line. In some places, apparent RM relief bobbed up and down by up to 12 km over lateral distances of 80 km or less. Some of these difficulties undoubtedly derive from differences in the quality of the pre-stack processing, ray focusing and defocusing, and out-of-plane reflection phenomena. Nonetheless, in the final analyses a consistent, reliable, repeatable, and intellectually honest set of interpretations could not be achieved using the premise that a singular, regional RM event (or package) could be mapped here. Attempts to force such an interpretation throughout the data set would inevitably result in misinterpretations, no matter how inadvertent. Accordingly, attention was defocused on trying to map RM across the Gabon margin, and instead we concentrated on defining and tying the major reflection packages. To those unfamiliar with interpreting MCS data, this may seem like an overly fine distinction. In fact, it represents a significant conceptual departure from the standard approach.

This interpretational approach resulted in an internally consistent model of the stretched continental margin off Gabon. The model consists of one or two upper sheets of crustal material overlying a series of interleaved lenses of lower crustal and upper mantle rocks. Extension in the upper sheets has mainly been accommodated by brittle deformation; extension in the interleaved lenses by ductile deformation between and within the lenses.

Reflection patterns and reflector packages in the upper sheets are consistent with the existence of both landward and seaward dipping faults that fragment the upper crust into large blocks rafted along on the ductilely stretched underlying lenses. The arrangement of the faults that define these blocks is uncertain, but there may be a prevailing northeasterly sense of orientation to the fracture fabric. Rarely if ever do the reflection images of the block-bounding faults penetrate to the level of the ductile lenses, although the projections of these faults often coincide with relief along the top surface of the lenses (see below). Either a direct mechanical linkage does not occur between these levels or the linkage cannot be seismically imaged in this data set.

The ductile lenses are defined by a very complex, anastomizing series of reflector patterns that generally dip southeasterly. It is assumed these patterns represent acoustic impedance contrasts derived along discrete zones of ductile shear. About 10 such lenses have been identified and tied with a reasonable degree of confidence. Some of the reflection-defined boundaries of these lenses can be followed to depths in excess of 14s (TWTT). These reflection boundaries tend to flatten and merge with each other in ways that create a successive series of bumps or noses along the upper level of the lenses. This level, or zone of flattening, is often highly reflective and laterally coherent over many tens of kilometers, but invariably the dominant reflection package switches back and forth between different ductile shear zones, or disappears entirely in some areas. This is why the notion of a single and laterally coherent RM was abandoned. There is a strong sense that the ductile lenses unroof toward the outer high, as if progressively greater stretching toward the OH has emplaced lower ductile lenses at successively shallower levels. This could explain how the locus of seafloor spreading ultimately materializes.

CONCLUDING COMMENTS

The rheological model presented above fits the major deep reflection events and patterns observed in the reprocessed PROBE data into a coherent, rationale, and generally mappable story. This does not mean the story is the only possible way to explain these deep reflections, but the alternatives tend to lead to less appealing explanations. For example, it is possible that deep MCS imagery across continental margins is intrinsically flawed (and hence uninterpretable) due to such problems as side-swipe and out-of-plane reflections. However, the ability to define and tie many (most) of the PROBE deep reflection events agrues otherwise. It could be argued that there is something intrinsically wrong or at least unique with the PROBE data base. However, the PROBE data agree very well with the MCS imagery reported in Wanneson et al. (1991) from the same general area. It is also possible the deep, southeasterly-dipping fabric we interpret as discrete ductile lenses is some ancient metamorphic grain that has little or nothing to do with rifting. However, reactivation of such a grain during extension would seem likely. In defense of the model presented here, it might be noted that we have made few assertions about what is continental crust and mantle, beyond the assumption that the upper sheets are brittlely deformed rifted continental crust. We do not base the model on the mapping of some arbitrary RM across the continental margin. Indeed, we do not think RM is a useful reference frame beneath the continental sector of this margin. Our most controversial assumption pertains to the ductile lenses of lower continental crustal and upper mantle material. But even this assertion is consistent with modern views of the rheology of the lower continental crust and upper mantle. The most troubling aspect of the rheological model proposed here may ultimately prove to be its apparent uniqueness in comparision to interpretations of deep MCS imagery from other passive margins, especially the conjugate Brazilian margin (e.g., Mohriak et al., 1995).

The tectonic setting depicted by the PROBE data is clearly applicable to hydrocarbon exploration in this region. This is especially true for offshore Equatorial Guinea, where the margin has been heavily influenced by transform fault tectonics associated with the KFZ. How the above rheological model aids the explorationist is less evident, but it could be noted there is ususally a crude correlation between large-scale relief along the upper surface of the ductile lenses and major basement topography. Given that the ductile sheets are often better-imaged than either the basement/syn-rift or syn-rift/post-rift horizons, it could be argued that the deep structure may yield useful clues about the shallower regime in frontier margin areas.

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