Tracing the West and Central African Rift and Shear Systems offshore onto oceanic crust: a ‘rolling’ triple junction

William Dickson (DIGs), and James W. Granath, PhD, (Granath & Associates)

Abstract

Compared to the understood kinematics of its continental margins and adjacent ocean basins, the African continent is unevenly or even poorly known. Consequently, the connections from onshore fault systems into offshore spreading centers and ridges are inaccurately positioned and inadequately understood. This work considers a set of triple junctions and the related oceanic fracture systems within the Gulf of Guinea from Nigeria to Liberia. Our effort redefines the greater Benue Trough, onshore Nigeria, and reframes WCARS (West and Central African Rift and Shear Systems) as it traces beneath the onshore Niger Delta and across the Cameroon Volcanic Line (CVL), Figure 1. We thus join onshore architecture to oceanic fracture systems, forming a kinematically sound whole. This required updating basin outlines and relocating mis-positioned features, marrying illustrations from the literature to imagery suitable for basin to sub-basin mapping. The resulting application of systems structural geology explains intraplate deformation in terms of known structural styles and interplay of their elements. Across the Benue Trough and along WCARS, we infer variations in both structural setting and thermal controls that require further interpretation of their petroleum systems.

Introduction

Excellent work has defined Africa's onshore geology and the evolution and driving mechanisms of the adjacent (particularly the circum-Atlantic) ocean basins. However, understanding of the oceanic realm has outpaced that of the continent of Africa. This paper briefly reviews onshore work. We then discuss theoretical geometry of tectonic boundaries (including triple junctions) and our data (sources and compilation methods). Additional sections discuss application of theory and data to the Gulf of Guinea system; and illustrate an updated interpretation of connecting elements along WCARS via our remapped Benue Trough into the Gulf of Guinea fracture system (Figure 1). We conclude by summarizing our efforts and suggest avenues to reassess hydrocarbon exploration along these features.

Africa: Prior and New 'Big Pictures'

Following mapping by the colonial surveys, a generation of regional geologists applied 'Big Picture' integrative thinking in Africa *per* the seminal work of, *inter alia*, Bosworth, Burke, Fairhead, Genik, Guiraud, and co-authors, establishing the basin-and-craton framework. The Ed Purdy Memorial GIS project (Exploration Fabric of Africa or EFA) then offered a continent-scale view derived from a 1:5MM scale compilation. Although EFA included key structural features such as faults and basin outlines, they were often generalized and mostly divorced from underlying genetic linkages. Our synthesis (Tectonic Fabric of Africa, or TFA) uses more advanced data to build upon EFA, connecting adjacent oceanic realms across the continent in a kinematically sound fashion to suggest and define missing tectonic elements. We previously discussed that work (Granath & Dickson, 2016a, b; 2017) for both WCARS and a less-recognized 'Trans-Southern Africa Rift & Shear System' (STARSS), seen in eastern Africa as the Karoo system.

Theoretical Geometries

Triple junctions, while integral to the kinematics of plate tectonics, also illustrate any geology where the relative motion of blocks is involved. Motions are described by the interaction of block boundaries with simple vectors. Boundaries may involve a) ridges, rifts, or extensional margins (R); b) transforms or strike-slip fault systems (F); and c) trenches or convergent margins (T), Figure 2. Only some junctions are inherently stable, capable of simultaneously accumulating significant displacements (McKenzie & Morgan, 1969) while maintaining the same vector relationship and so surviving for substantial geologic time. When survival of a triple junction is limited, it usually fragments into two separate triple junctions or one arm is essentially abandoned.

Plate divergence, as in the case of Atlantic opening, produced a series of rift segments that evolved into an ocean spreading system composed of spreading-ridge segments linked by transforms. Beyond the neighboring ridge segment limits, transforms became dormant as fracture zones (FZ). At initiation of continental breakup, transform/FZ locations often corresponded to pre-existing features within the marginal continental block, suggesting some (usually minor and rift-restricted) reactivation. Nascent spreading segments may, however, link with a transform that actively extends into the continent, thus forming a triple junction composed of a transform, the spreading ridge/rift, and an intra-continental fault system. Unless two ocean basins develop between the continental blocks, the situation decays to a transform and a rift segment with abandonment of the third element. The spreading system then drifts away from the two separated continental crustal blocks (e.g. Dewey & Burke, 1974). If the third element is a rift or a trough, at its outset this system forms an *aulacogen, sensu* Shatsky (1946). The Gulf of Guinea provides a good example with the West African Transform Margin (WATM) connected to the ridge (or rift) segment running south and in which WCARS was the abandoned arm. The Benue Trough is then likened to Shatsky's aulacogen.

Development of such a system is illustrated by Figure 3, a stability diagram *a la* McKenzie & Morgan (1969), drawn for the Gulf of Guinea system. Figure 3a shows a typical map relationship between FZ precursor in blue, an onshore fault system in red, and the continental margin rift in black. A connected string of these forms a sweep from, *i. e.* the West African southern extensional margin to the West African Transform Margin.

Figures 3b&c are in ‘velocity space’ with arrows showing displacement vectors between blocks and dotted lines showing orientations of boundaries between blocks. Symbol AvB signifies the vector motion of block A relative to block B (shown by the arrow). For WCARS, we do not know exact angular relationships between elements during the Cretaceous nor the displacement rates on the faults involved, so these vectors are generalized to represent all the component triple “junctionettes”. Viewing the triple junction region in this way offers a twofold observation:

1. For small displacements and low displacement rates (Fig 3b), there is great latitude in configurations that retain stability, *i.e.* a rift can connect to two divergent transform segments with a wide angular relationship. If deformation is concentrated at the intersection, internal accommodation can accommodate orientation mismatches, as for example, within the Benue Trough.
2. At higher displacements or displacement velocities (Fig 3c), CvA and AvB become collinear. As the rift widens and oceanic spreading begins, CvA dominates and AvB becomes irrelevant. A triple junction may fit the initiation of these tectonic elements but with time it decays to a rift and a transform, with spreading carrying the relationship away to the west. Blocks A and B are left behind, as C links with its counterpart in the next (adjacent) triple junction, and ocean spreading fills the gap.

This implies that motion in and around the triple junction on African crust in the A or B block evolved with time, imparting interesting structural relationships. Rotation of displacement vectors between A and B may cause inversion of early structure in the triple junction. Indeed the Abakaliki Anticlinorium onshore Niger Delta (Reijers *et al.*, 1997) demonstrates such inversion.

The second implication is that multiple triple "junctionettes" may evolve to a simpler geometry. The Yola and Doba Basins (Figure 1) may effect a connection between the CARS and WARS/Benue systems, so de-emphasizing or abandoning the lower (southerly) CARS faults in western Cameroon. This reduces complexity towards the simpler triple junction idea.

Data

Modern densely sampled data from ships (2D and 3D seismic especially) and satellites have driven forward the understanding of passive margin evolution and development of ocean basins and continental margins (Dickson *et al.* 2016 and references therein). From want of regional tectonically-focused data and lack of incentive from big oil & gas discoveries, this progress has lagged onshore. Still, adequate spatial resolution (to sub-basin or better scales) continent-wide grids have been compiled of potential field data (Odegard *et al.*, 2007b). These in turn constrained inversions for sediment and crustal thicknesses (*i.e.*, MARIMBA project depths to basement, Moho and Curie surfaces). This provided scaffolding for GIS-based geo-locating and mosaicing of published material.

Along the West African margin, the edge of magnetically striped oceanic crust is defined on our magnetic imagery (TMI-THD or total horizontal derivative of total magnetic intensity; not shown), along with a narrow bordering strip of 'transitional crust', be it exposed upper mantle and/or hyperextended continental crust. However, the gravity isostatic residual anomaly (GI) and its total horizontal derivative (GI-THD) have been most-used to locate, revise, and connect known and interpreted tectono-structural features both on- and near-shore.

The tectonic connection between the Bight spreading system and WCARS has lacked clarity, being obscured by twenty-some km of Niger Delta sediments. A multi-disciplinary approach, combining geophysical and geochemical methods concluded that crustal features could be well-imaged and accurately positioned (Dickson & Schiefelbein, 2015), identifying and connecting offshore fracture zones (FZ) beneath the delta both off- and onshore. A proprietary reprocessed compilation of gravity data provided primary control for tectono-structural interpretation, augmented by similarly compiled magnetics, depth, and thickness grids to define the deep rift-phase structure (Odegard *et al.*, 2007a & b described compilation and processing steps). Active hydrocarbon exploration meant that broad coverages of detailed 3D seismic and surface geochemical exploration (SGE) programs had been presented in cited papers. From a non-exclusive study (used by permission), characteristic oil geochemistry of the Niger Delta was matched to SGE results. Our correlations from basement features up across intra-sedimentary structuring through inferred hydrocarbon leakage pathways terminating at the surface demonstrated both precision and accuracy in defining the deeply-buried crustal architecture (Figure 4).

Gulf of Guinea System

A simple triple junction underlying the Niger Delta is usually pictured as having evolved into the Mid-Atlantic Ridge, receding from the divergent African margin and abandoning the Benue Trough (onshore Nigeria) in its wake. With most of the lower Benue Trough hidden beneath the Niger Delta, this evolution had largely been assumed. Our imagery indicated that the triple junction was not a simple three-armed system as theory suggested, but rather a west-stepped, progressive sweep in which a N-S trending extensional system converted to the E-W trending transform (trans-tensional) margin in discrete segments that accommodated the overall larger 'triple region' (Figure 2b). The serrated transform margin continued westward as strike-slip segments connected extensional segment step-wise to extensional segment along the length of the coast across present-day Nigeria to Liberia. One segment ran from Benin and Cote D’Ivoire along the Romanche FZ, which keys off the Akwapim Fault system bordering Ghana's Neoproterozoic Voltaian Basin. The next step to the north connects to the St. Paul FZ, which keys off major Precambrian basement faults in Cote d’Ivoire at the southern end of the Liberia coast.

As described above, the oceanic FZs can now be traced nearly one-to-one to discrete onshore tectonic elements that were significantly active during birth of the continental margin (Figure 1). Some FZs connect to African tectonic elements and some to Brazilian (Krueger *et al.*, 2018, this conference). The Charcot FZ connects beneath the Niger Delta to the southern boundary of the Anambra Basin and Benue Trough. Hence extension in the Chad-Niger Rifts is transferred to spreading between the Romanche and Charcot FZs (including the Benin, Chain, and Benue) which last is continuous with the northern bounding margin of the Benue Trough. The Ngaoundere FZ connects to the main strand of the Central African shear zone across the Cameroon Volcanic Line (CVL). The Paraíba FZ connects to South American features discussed by Krueger *et al.*, 2018, this conference.

Southwards along the West African margin from Douala to Cape Town, fracture zones often lie opposite tectonic features in the African continental crust, but they were not reactivated within the continent itself at breakup and are not further discussed in this paper.

Niger Delta - CARS (Central African Rift System)

Work by Weber & Daukoru 1975 (citing Murat 1970) shows main tectonic features of the Niger Delta floor. Genik, 1993 remains the key reference defining WCARS basins and shears of Chad, Niger, and Sudan. PGW flew Nigeria-wide aero-geophysics surveys and published a depth-to-magnetic-basement initial interpretation (Reford *et al.*, 2010) particularly illustrating the greater Benue Trough, and associated sub-basins. Dou *et al.*, 2014 illustrated the CARS shear system using an uncited rectilinear representation of the affected basins & sub-basins to emphasize directional control via shear on the basin shapes.

Our work refines these features and provides estimates of the crustal deformation involved. We observe that crustal thinning is not a function of feature amplitude on our gravity imagery (not shown). Prominent narrow, high-amplitude GI-THD anomalies associated with north-west and south-west flanks of the Termit / Tenere Basin resulted from shallow depth to the main sediment-basement density contrast. The much deeper (c. 14 km) basin center has a subdued gravity response as sediments have compacted, reducing the density contrast at the interface whose gravity signature at depth is also strongly attenuated by the inverse square law.

Across our interpretation region, the cumulative ne-sw width of the Bida (Benue SW), Yola (Benue NE), and Termit basins is about 500 km which implies ne-sw stretch of perhaps one-third of that. Published gravity inversion models across these basins & sub-basins indicate crustal thinning of about one-third, from a normal continental 30 - 35 km thickness to about 22 - 26 km.

The ne-sw-trending Benue Trough present-day varies in width from about 140 - 260 km. It contains, as stated earlier, the inverted Abakaliki Anticlinorium, within the Anambra Basin, lower Benue Trough (Reijers *et al.*, 1997) plus the Onitsha High and the Benue Folded Belt, implying a greater pre-inversion width. Adjacent to the southwest, the onshore Niger Delta contains three deeply-buried sub-basins, from northwest to southeast being the Benue SW; the Awaizombe Low (squeezed between the southwest ends of the Onitsha High and the Abakaliki Anticlinorium); and the two-part Afikpo Low. Roughly rhomboidal, the steep flanks of the Benue SW and Afikpo are formed by vertical offsets along the Benue and Charcot FZs. Prior to burial by the drift-age delta, they may have formed as early pull-aparts floored by highly-thinned continental crust. Because we need first to undo observed Santonian inversion and restore the effect of Apto-Albian extension, our interpretation thus far has no estimate for the amount of crustal thinning caused by Barremian nw-se extension.

To the north-east, the Yola and Doba Basins appear to have formed a connection between the Doseo pull apart Basin in CARS and the WARS/Benue system (Figure 5). This would transfer upper (northern) CARS motion directly into the Benue Trough, thus de-emphasizing or abandoning the lower (southern) CARS faults in western Cameroon. The timing would correspond to opening of the adjacent ocean as the “junctionettes” are de-emphasized or even abandoned in western Cameroon. The rectangular shape and substantial depths of the Benue internal sub-basins (Benue SW and Afikpo Low) are consistent with such a history.

Our interpretation confidence is lowest carrying these features across the CVL with its thermal and volcanic activity masking the density changes so easily traced both east and west of the CVL. We rely more on principles of structural geology and less on the weaker expressions in the potential field data in this area to infer that early in the evolution of the passive margin the lower CARS and perhaps also the Sanaga Fault made a connection through to the fracture zones.

We suggest that the Benue SW and Afikpo sub-basins initially filled with restricted lacustrine sediments, offering source potential that may augment the well-known terrestrial and marine sources (Haack *et al.*, 2000; Schiefelbein *et al.*, 2000) of the Niger Delta.

Conclusions

Triple junctions have interesting origins and histories, developing for example within oceanic crust of the Gulf of Guinea as a stepping series of "rolling triple junctions". Linked triple “junctionettes” may have evolved to a simpler geometry, reducing complexity towards the simpler, classic triple junction.

Evolving motions in and around the initial Gulf of Guinea triple junction on African crust imparted varied structural relationships. Inversion resulting from rotation of the angular relationship required by the breakdown of initial displacements would explain the Abakaliki Anticlinorium, within the Benue Trough, onshore Nigeria.

Our kinematically-constrained structural interpretation of the West and Central African Rift System (WCARS) is consistent with our current understanding of the evolution of the adjacent oceanic crust. The Yola and Doba Basins may have effected a connection between the CARS and WARS/Benue systems, and the previously obscured Benue architecture provides the key linkage between continental and oceanic systems.

Deep pull-aparts beneath the onshore Niger Delta, likely of Barremian to Albian age, would initially have been lacustrine rather than marine, with implications for source rock deposition.

Basins belonging to the WCARS system can be re-evaluated based on their revised shapes, deformation history, and relationships to sources of thermal and sedimentary inputs with an eye to their hydrocarbon potential.

Acknowledgements

The Purdy Project (Exploration Fabric of Africa or EFA, www.efafrica.com) is now available from AAPG's Datapages subsidiary as a non-exclusive adjunct to other DEO (Datapages Exploration Objects) material.

MARIMBA (Margins of the Atlantic Region Integrated Multidisciplinary Basin Analysis) and **TFA** (Tectonic Fabric of Africa) are non-exclusive studies referenced with permission; more at www.digsgeo.com

Map-based figures in this paper were generated as screen exports from ArcGIS$^{(TM)}$ 10 and annotated using PaintShopPro 9. Maps are in unprojected geographic coordinates (lat-longs) using the WGS84 datum.

An extended set of citations is available from the authors

References

Dewey, J.F., & K. Burke (1974) Hot spots and continental breakup: implications for collisional orogeny. Geology 2, p. 57-60.

Dickson, William & Schiefelbein, Craig (2015) Searching High and Low: Correlating shallow (drift phase) and deep (rift phase) structural trends with surface and subsurface geochemistry in the Niger Delta, West Africa. GCS-SEPM Perkins-Rosen Research Conference, Houston

Dickson, W., Schiefelbein, C.F., Odegard, M. E., & Zumberge, J. E. (2016) Petroleum Systems Asymmetry across the South Atlantic Equatorial Margins. Geological Society, London, Special Publications, 431, ch.13, pp15.

Dou, L., Shrivastava, C., Dai, C., Wang, J., Hammond, N., Anakwe, C., Siddick, M., & Xu, B. (2014) Deciphering an Unconventional African Reservoir: Geological Characterization of Granitic Basement from Bongor Basin, Chad, AAPG Search and Discovery Article 10673

Genik, G.J., 1993. Petroleum Geology of Cretaceous–Tertiary rift basins in Niger, Chad, and Central African Republic. AAPG Bulletin v77, 1405–1434.

Granath, James W. & Dickson, William (2016a), Cross-Africa shear zones and their kinematic relationship to rift basins. HGS/PESGB Africa Conference Sept. 2016.

Granath, James W. & Dickson, William (2016b), Regionally connected structural systems: the power of the big (continental-scale) picture. AAPG Search & Discovery paper 2571578.

Granath, James W. & Dickson, William (2018), Organization of African Intra-Plate Tectonics, AAPG Search & Discovery 30555 from AAPG ICE, London Oct. 2017.

Haack, R.C., Sundararaman, P., Diedjomahor, J.O., Xiao, H., Gant, N.J., & May, E.D. (2000) Niger Delta Petroleum Systems, Nigeria. AAPG Memoir 73, Ch.16, p. 213-231.

Krueger, A., Murphy, M., Norton, I., Casey, K., de Matos, R. D. (2018) Influence of Proterozoic Heritage on development of rift segments in the Equatorial Atlantic, HGS/PESGB Africa Conference Sept. 2018

McKenzie, D.P. & W.J. Morgan (1969), Evolution of Triple Junctions. Nature 224, p. 125-133.

Odegard, M. E., Dickson, W. G., & Schiefelbein C. F. (2007a) The Application of New Developments in Geodynamics and Plate Tectonics to Hydrocarbon Exploration: Development of Predictive Methods, COAS Marine Heat Flow Workshop, Oregon State U, September

Odegard, M. E., Dickson, W. G., & Schiefelbein C. F. (2007b) Structural and Lithological Inversion Using Gravity and Magnetic Data Integrated with Geological Information, 10th International Congress, SBGf, Rio de Janeiro, Brazil, 19-22 November

Reford, S. W., Misener, D. J., Ugalde, H. A., Gana, J. S., & Oladele, O. (2010), Nigeria's Nationwide High-resolution Airborne Geophysical Surveys *in* SEG Annual Meeting Abstracts, p1835-1839

Reijers, T.J.A., Petters, S.W., & Nwajida, C.S. (1997) The Niger Delta Basin, *in Sedimentary Basins of the World, V. 3 African Basins* (R.C. Selley, ed), ch.7, p. 151-172.

Schiefelbein, C.F., J.E. Zumberge, N.C. Cameron, and S.W. Brown (2000) Geochemical comparison of crude oil along the South Atlantic margins, in M.R. Mello and B.J. Katz, eds., Petroleum systems of South Atlantic margins: AAPG Memoir 73, p. 15-26

Shatsky, Nicolas (1946), The Great Donets Basin and the Wichita System, comparative tectonics of ancient platforms. Geology Series, #6 Akademiia Nauk SSSR Doklady, pp. 57-90.

Weber & Daukoru (1975), Petroleum Geology of the Niger Delta, 9th World Petroleum Congress, vol 2, p209-221.

Figures

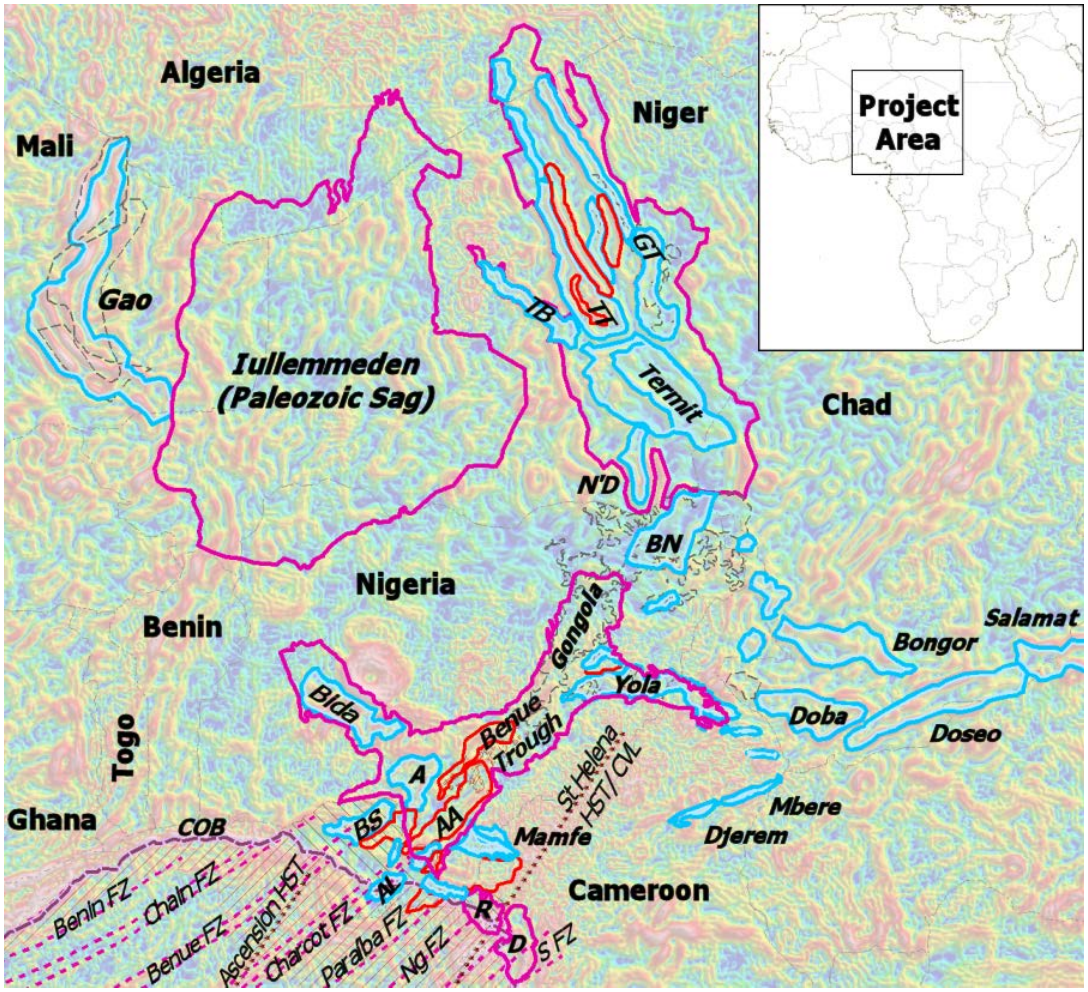
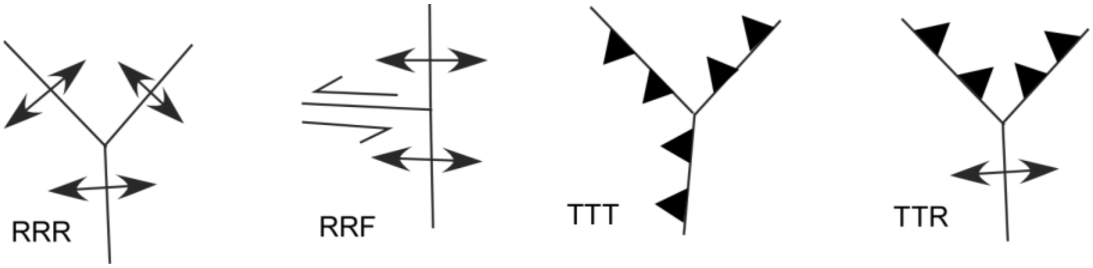


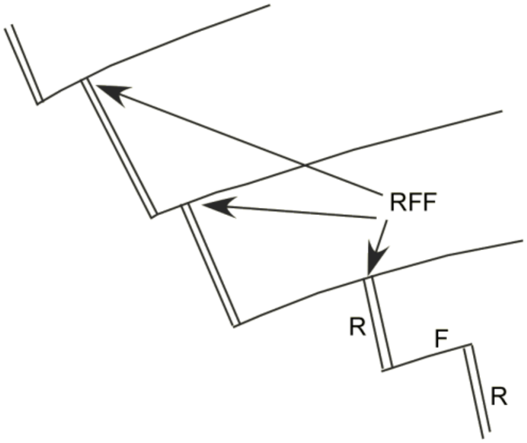
Figure 1. WCARS features. a) General location map (inset). b) Country names (bold); basins (bold italics), oceanic fracture zones (FZ, italics), hot spot tracks (HST). Main basins outlined in mauve; sub-basins in blue; intra-basin highs in red; possible sub-basins in grey dashes. COB = Continental-Oceanic Crust boundary. Basin abbreviations: A: Anambra Basin; AA: Abakaliki Anticlinorium; BN: Benue NE (sub-basin); BS: Benue SW (sub-basin); D: Douala; GT: Grein

Trough (Termit Basin); N'D: N'Dgel Edgi; R: Rio del Rey; TB: Tefidet Basin (Termit Basin); TT: Tenere Trough (Termit Basin). FZ abbreviations: Ng FZ: Ngaoundere FZ; S FZ: Sanaga FZ. Backdrop is the total horizontal derivative of the gravity isostatic residual (GI-THD).

Figure 2.



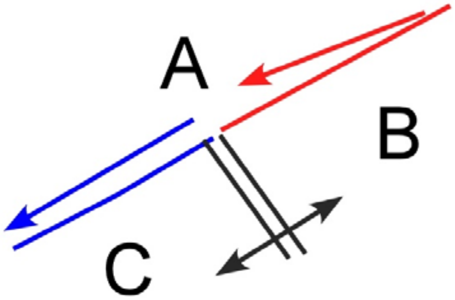
a) Simple representation of four triple junctions with different stability relationships. Rift-Rift-Rift (RRR) is stable under all circumstances. Rift-Rift-Transform (RRF) is inherently unstable unless the boundaries are perpendicular and certain rate balances are met. Trench-Trench-Trench (TTT) is stable under certain balanced rates of plate motion. Trench-Trench-Rift (TTR) can be stable if rate balances or equal angles are met.



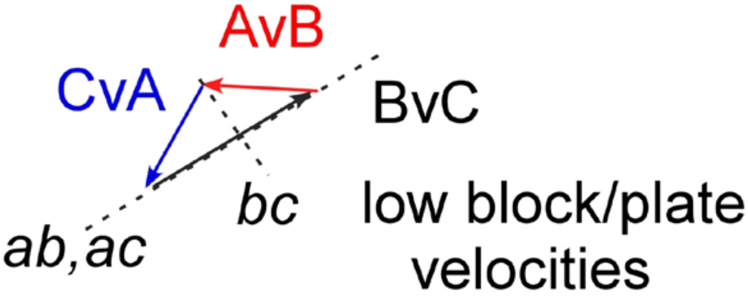
b) Left-stepping arrangement of three RFF triple junctions along a generalized extensional plate margin. The triple junctions are formed from by three transform fault systems that penetrate into the right hand plate well beyond the tips of their respective rifts. This is a generalization of the analysis of the Gulf of Guinea triple junction region in this paper.

Figure 3. Stability relationships for the Gulf of Guinea complex triple junction. Elements of the triple junction: on the west side the fracture zones in blue, rift segments to south (or equivalently north) in black, and onshore African fault systems in red.

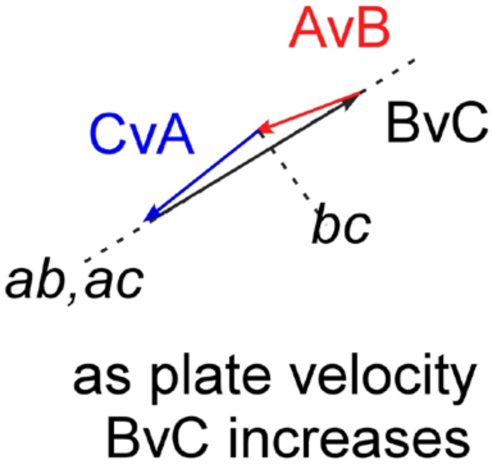
a) Map topology as three blocks: the north side of triple junction A, and the two sides B and C of the extensional basin. C will evolve into oceanic crust. Relative displacements between blocks are shown by arrows (e.g. AvB).



b) While displacement rates between the three elements are relatively low and similar (upper right), the system can evolve if the rift segment is allowed to propagate, despite different relative directions of displacement.



c) As oceanic crust is born, and fast plate divergence rates (which usually exceed intraplate rates) begin to apply to the BvC relationship, the triple junction stays stable if AvB and CvB are collinear. Otherwise the triple junction becomes unstable and is abandoned or replaced with a different configuration. One replacement is the introduction of another rift segment, the mechanism by which the rift system propagates along the continental margin and negotiates the plate margin bend in the Gulf of Guinea.



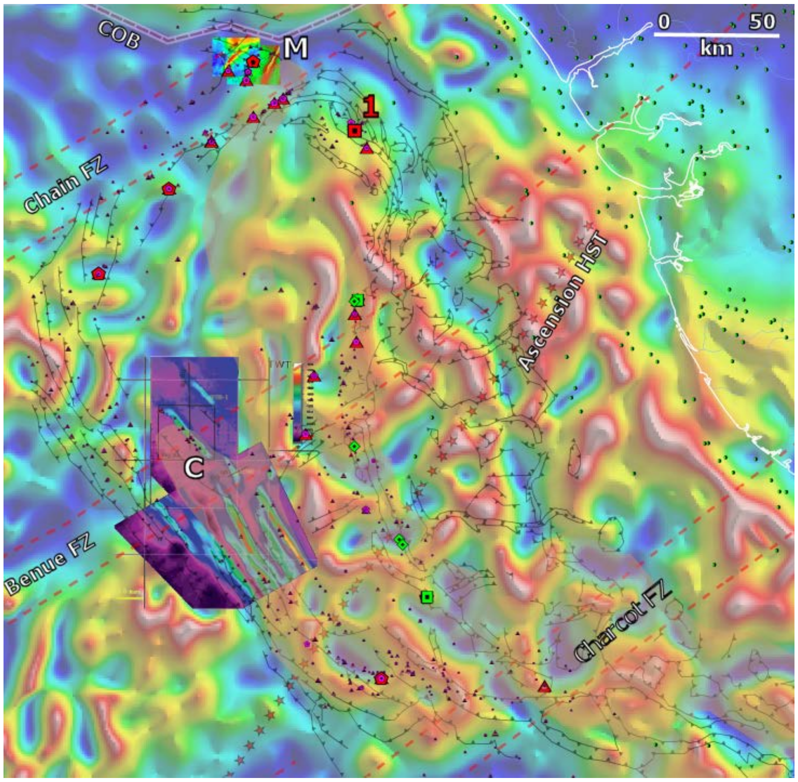


Figure 4. Offshore Niger Delta feature correlations from basement to surface (after Dickson & Schiefelbein, 2015) demonstrate reliability and precision of data employed to interpret basin floor offsets and long-lived basement control on tectono-sedimentary evolution of the on- and offshore delta. Crustal features and gravity backdrop with overlays from Cobbold *et al.*, 2009 (C) and Matthews *et al.*, 2010 (M) of intra-Miocene structures on 3D seismic. Piston core (PC) data (red, green & purple points), toe-thrust-belt (TTB) subcrops (black) and BSR outlines (faint orange shading) represent at/near seafloor control. Note the density of PC samples along intra-Miocene anticlines (Cobbold), demonstrating accuracy of PC targeting (PC locations normally test potential leakage paths). PC anomalies lie between the Matthews *et al.* 2010 (M) Miocene anticlines, suggesting a registration error in the georeferencing. However, structural trends on overlays C and M align closely with PC and TTB trends and anticline offsets of overlay C fall across the trace of the Chain FZ which is mimicked by seafloor offsets in the TTBs.

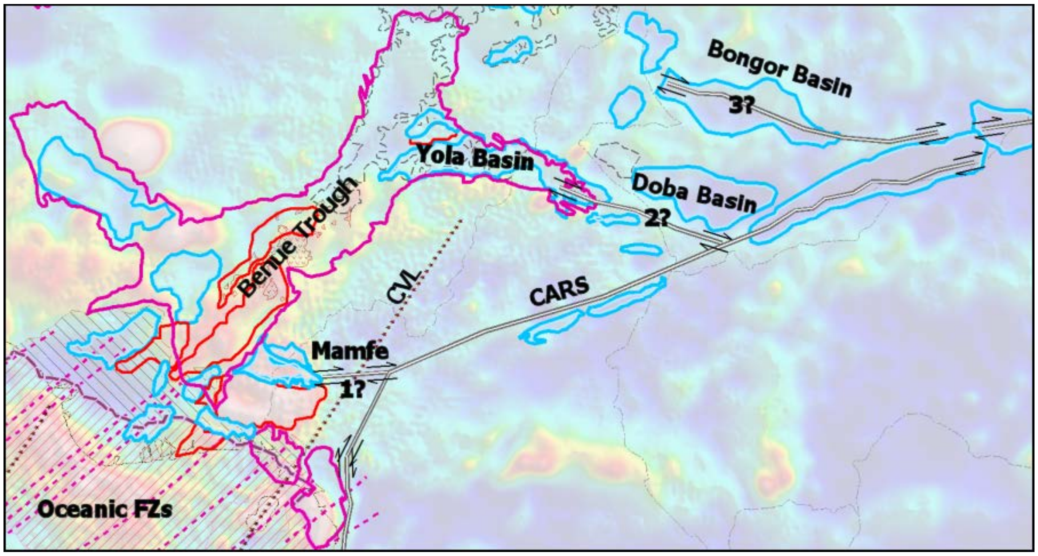


Figure 5. Gravity (GI) underlay with basin outlines. Representation of WCARS northern shears shows possible Benue Trough connections via Mamfe (1?), Yola-Doba (2?) and Bongor (3?) basins, or a combination of these paths, likely masked by younger CVL activity.