HGS/PESGB Africa Conference Sept. 2016

Cross-Africa shear zones and their kinematic relationship to rift basins

James W. Granath Consulting structural geologist, Highlands Ranch CO (jgranath@q.com)
William Dickson DIGS, Houston TX (billd@digsgeo.com)

Extended Abstract

Intra-plate deformation is a sideline of plate tectonic processes, but nevertheless is an important aspect of crustal architecture and a major habitat for important petroleum systems around the world. Arrays of fault blocks loosely aligned in belts often comprise the third, 'failed' arm of divergent plate triple junctions (such as the Central African Rift System [CARS]), or comprise fields of compressional uplifts in the deformed foreland of orogenic belts (such as the late Paleozoic Ancestral Rocky Mountains in the interior of western North America). Scattered extensional basins or block uplifts are common within cratonic interiors, and although they can occur as isolated features are probably more common in small clusters. Transfer faults occur within and between individual elements of such systems (as intra- and inter-basinal faults): they are fundamental, well recognized features and are necessary to facilitate the kinematic harmony of the system (e.g. Ebinger et al., 1987; and many others). At their extreme, transfer faults systems may be organized into inter-basin/uplift, regional 'mega-shear' systems that often are localized by pre-existing defects in the crystalline basement, such as the Precambrian sutures between various African cratons. The Central African Shear Zone (CASZ) is one of the most familiar examples. These mimic wrench faults in their overall geometry, but have some significantly different internal kinematic characteristics from true wrench faults. The similarities and differences between them can be exploited in terms of predicting missing elements of the system and devising exploration programs. This paper aims to describe these differences and to illustrate how they can be used.

Figure 1 compares and contrasts three typical but hypothetical systems. In all of them transfer faults connect individual faults within elements of the system, be that within a distinct rift basin or block uplift: these constitute so-called 'hard-linked fault' connections, i.e. ones in which faults physically connect to each other. One example is circled in blue in Figure 1a. Relationships wherein there are gaps between the tips of faults are called 'soft linkages' or ones that do not physically connect; these distribute deformation on smaller scales through fracturing and folding. In Figure 1a, two examples of these are circled in yellow. At a larger scale, separate basins or uplifts are connected similarly in hard or soft-linked transfers via elements of the mega-shear system. They accommodate the relative displacement directions on either side of the through-going fault system. Some of the relative offsets may be left lateral and some right lateral depending on the local situation, i.e. the magnitude of the extension involved in each element, how they sum on each side of the mega-shear, and where any pin or null points occur along the trace of the shear all govern the cumulative offset. In Figure 1 such differences are shown in green and red components of the through-going shear. That total offset actually is often minimized as cumulative displacement on one side can be balanced by oppositely directed extension on the other. Hence despite the possibility that the system connects to major plate margins at either end of the mega-shear, offset within and on the margins of the continent can be minimal

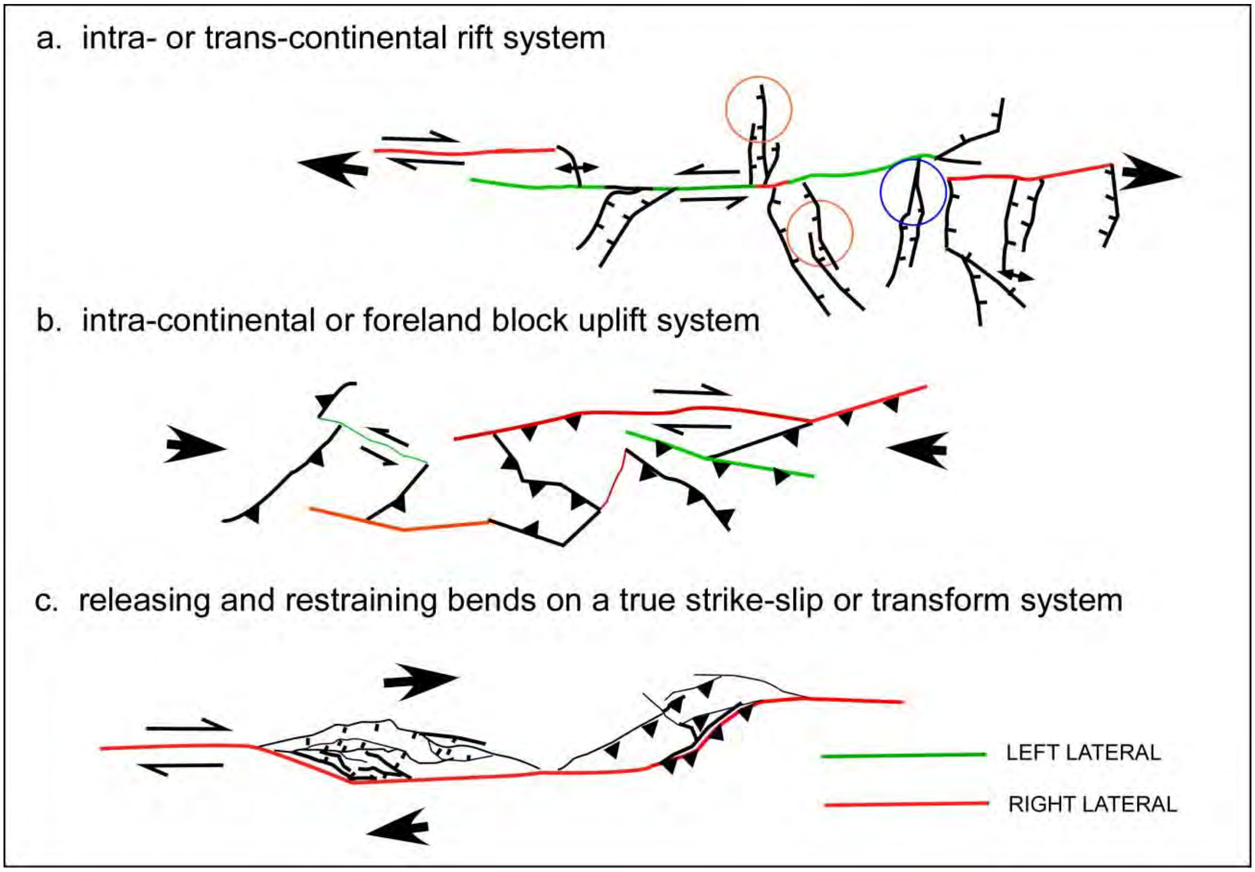

Figure 1. Three types of strike-slip related intra-cratonic deformation zones or mega-shears. (a) extensional field, yellow circles identify soft-linkages of intra-basin transfer faults, blue circle an example of a hard-linked one, (b) compressional field as might develop in the foreland of an orogenic belt, (c) true wrench zone, as might evolve as a transform plate margin. (a) and (b) can terminate within the craton, but (c) connects to two other major plate-related features if not plate boundaries themselves.

Figure 2 illustrates the point that the relative sense of offset can reverse along the length of the mega-shear. In this hypothetical situation three rifts have nucleated along opposite sides of a crustal weakness that is destined to form the mega-shear. In the southeast, 2 km of total extension have accumulated in Rift 1 (R1) on the edge of a stable block (represented by the blue pin point); block A remains fixed in this scenario. Two km of displacement shift block B to the west relative to block A and hence a right lateral offset develops as far west as R2. If R2 then opens with 15 km of extension, it shifts block C 15 km west relative to block A, and thus creates a left lateral offset between block B and C as far west as R3. If R3 opens 22 km offset between B and D, the western end of shear there becomes a right lateral shear between blocks C and D. The cumulative offset could be minimized by another rift opening on the north side. The assumption of course is that these offsets develop more or less synchronously. In addition, along the length of the mega-shear, left and right stepping bends may create restraining and releasing relationships, just as a wrench system might; the appropriate *en echelo*n strain-related deformation features may develop along the length of the mega-shear.

In the case of compression on the edges of the craton (Fig. 1b), a similar geometry may obtain, again so that there is minimal relative motion across the whole system. A good example would be the Southern Oklahoma Aulacogen/Ancestral Rockies uplift system in North America. These situations both contrast with true strike-slip dominated, plate-margin systems (Fig.1c) ---trans<u>form</u> faults--- in which there can be large relative offset between the two sides of the system. The amount of displacement on individual faults in transform systems is typically difficult to specify, and the relative plate motion is often distributed over several features, but the magnitudes of offset are all large. In the case of a system like the San Andreas transform in North America, only part of the ~650 km of Pacific/North America relative motion is resolved on the San Andreas fault itself: something like 195 +/- 15 km of net strike-slip offset is demonstrable (Darin & Dorsey, 2012). The rest is partitioned to other features within the transform zone. Extensional and compressional elements occur along the length of the overall transform to accommodate left and right bends and steps, but their extensional and compressional magnitude are typically an order of magnitude less than the total strike-slip offset. For example, it is not unusual for pull-apart basins to be translated considerable distances along the wrench to subsequently be deformed at a restraining bend, and vice versa.

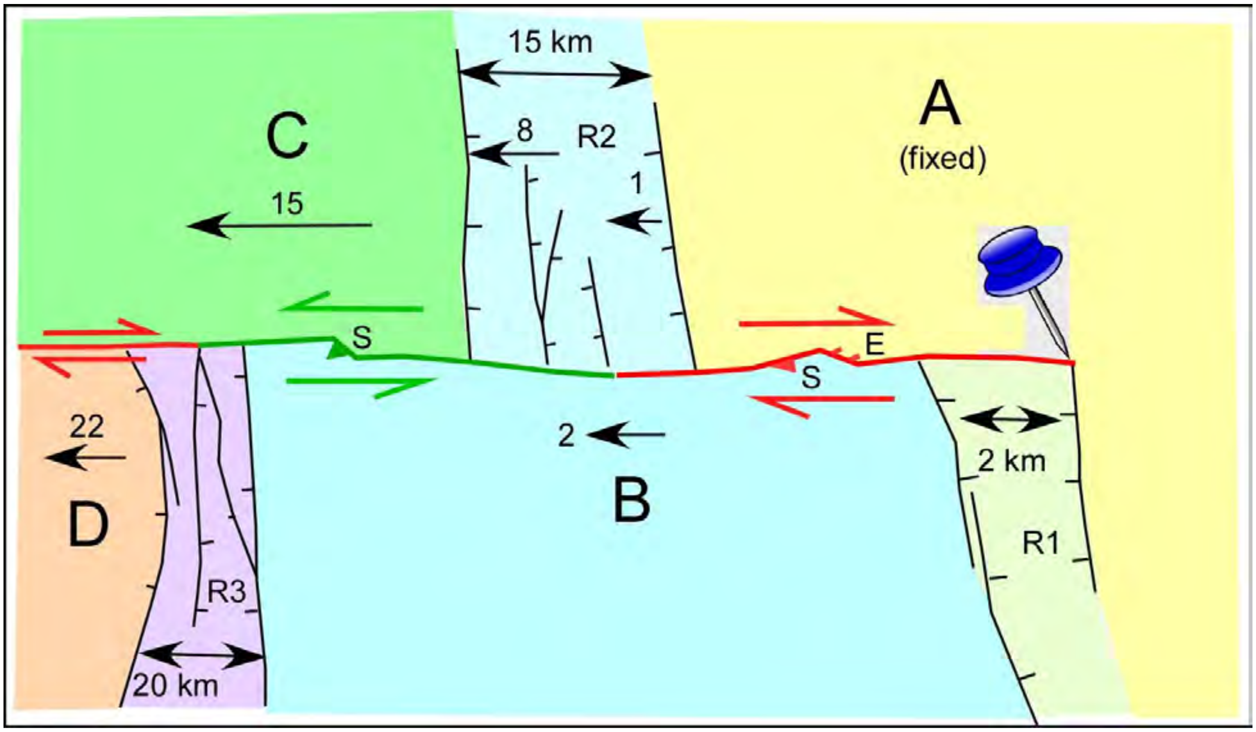

Figure 2. Hypothetical relationship among three rifts (R1, 2, & 3) and four crustal blocks (A. B. C, & D) illustrating the reversal of sense of relative offset along an intra-cratonic shear zone. E extensional strain, S shortening strain. See text for further discussion.

CARS/CASZ Example

The Central African Rift System (CARS) is a good example of an intra-plate extensional field in which a group of rift and pull apart basins are strung out along a continental shear zone, the Central African Shear Zone (CASZ), from essentially the Niger Delta to eastern Sudan. The basins dominantly developed during the Cretaceous, and very likely in many cases reactivated older features, although this is not universally evident. Cretaceous extensional basins exist to the east in Somalia and Yemen, but the CASZ does not seem to connect in the east to another major plate-scale feature. Displacement noticeably falls to zero in the area of the Atbara Rift, thus stopping short of connecting to the Red Sea (Fig. 3). It does connect to the southeast through rifts in South Sudan and Kenya, into the Indian Ocean part of the Gondwanaland breakup, into the Somali Basin. In the west it is coupled with the Benue trough, which strikes more northeasterly from the same region in Nigeria into Chad and southern Algeria. Timing wise, although not exactly coeval (Guiraud & Maurin, 1992) these two trends connect to the Gulf of Guinea (messy) triple junction developed during the opening of the Atlantic (Fairhead & Green, 1989; Binks & Fairhead, 1992). The extensional plate margin of the western African continental margin negotiates a change in trend to the transform margin of the Guinea coast at the tips of the Charcot, Chain, and Romansche fracture zones. CARS/CASZ represents the eastern, 'failed' arm of this triple junction, failed in the sense that it did not develop into a mature continent-ocean transition.

Figure 3 is a GIS compilation of the CARS features from an on-going project to develop a detailed tectonic overlay for the Exploration Fabric of Africa, the 'Purdy' project. Sources of the information are public data such as Genik (1993), Bosworth (1994), Dou et al. (2007), and others, original work (e.g. Granath, 2001), and published geological mapping, all supported by synoptic potential methods data sets from Marimba (DIGS, http://www.digsgeo.com/MARIMBA.html), and interpretation of those data sets. The backdrop of Figure 3 is a sediment thickness inversion from the potential methods compilations, an inversion of Free Air gravity to sedimentary thickness/depth-to-basement (D2B). The overall guiding philosophy in the compilation project is that kinematic patterns of the various structural styles as deformation systems can be used to fill out the tectonic map by formulating testable structural predictions.

A kinematic interpretation of the West African and Central African systems is shown in Figure 4. Extension in the Sudan rifts south of the CASZ set up a situation similar to Figure 2, in which extension on the south side of the shear in the east sets up a right lateral system that negotiates a right step north the the Muglad Basin, a restraining situation where basement is brought to the surface, and then persists through the Doseo pull apart basin seemingly all the way to the Atlantic coast. The offset furthermore seems to be at least partially offset west of Doseo by the Bongor and Doba Basins in Chad, on the north side (and possibly others), so that the offset falls considerably by the time it reaches the triple junction. Although the amount of offset appears to change along the system, the amount of northern extension does not appear to be large enough to reverse the sense of motion as in Figure 2. In Cameroon, however, there may be reactivation and uplift on the NE edge of the craton, cross-cutting the Pan-African outcrop, at the black arrow in Figure 3, that signifies a restraining relationship and perhaps a reversal in the sense of motion along the CASZ. Other faults that may participate in the system lie to the south, the Sanaga Fault zone for example, that would make this a more complicated situation than appears at first sight. This tectonic synthesis could be quantified and tested by creating restored cross sections across its component elements, and summing up the results. The missing elements in the system, would be further clarified, thus identifying fertile ground for additions that may have hydrocarbon prospectivity.

The Benue Trough forms the other part of the CARS-WARS intra-continental system. Although little subsurface information is available, it seems to be a cascading set of left-stepping bends and overlaps on a broad left lateral shear. It transfers the opening at the Termit-Tenerife Basins in Niger into the triple junction region, and its southwestward broadening may belie a clockwise rotation of northwest Africa.

The background in Figure 3 is an inversion of Free Air gravity to a Depth-to-basement (D2B) display, giving a first order sedimentary thickness map from the MARIMBA Project, a total sediment isopach or TSI (Dickson & Odegard, 2013). It shows a deep northwest of the Bongor Basin that supports the inferences above from the kinematic system, as well as some other potentially overlooked basins.

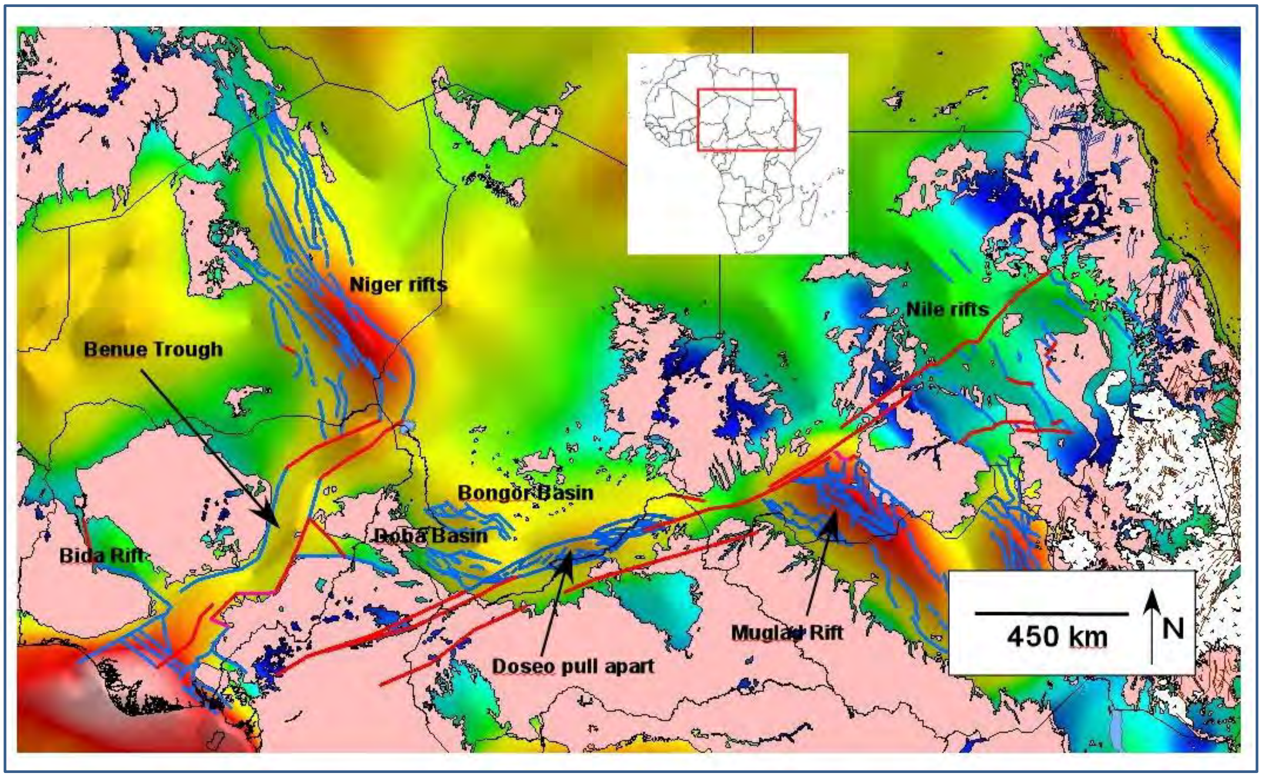

Figure 3. Excerpt from a GIS compilation of the tectonic elements, basement outcrop (in pink), and gross sediment thickness distribution as a backdrop; highs in the basement in cool colors, thicks in warm colors: red is the deepest basement. The MARIMBA Project total sediment isopach or TSI (Dickson and Odegard, 2013). The TSI is generated via Spectral Inversion of both gravity and magnetics data across large, overlapping windows. While providing stable, fairly good signal-to-noise values with depth accuracies of 5 - 10%, the output has low spatial (x-y) resolution because of averaging across, in this case, 40km x 40km windows. Black arrows point to locations along CASZ where possible restraining overlaps might lead to basement uplifts. Faults in extensional basins are plotted in blue while the components of the mega-shear are in red. There is no color coordination to the red and green significance of Figs. 1 and 2.

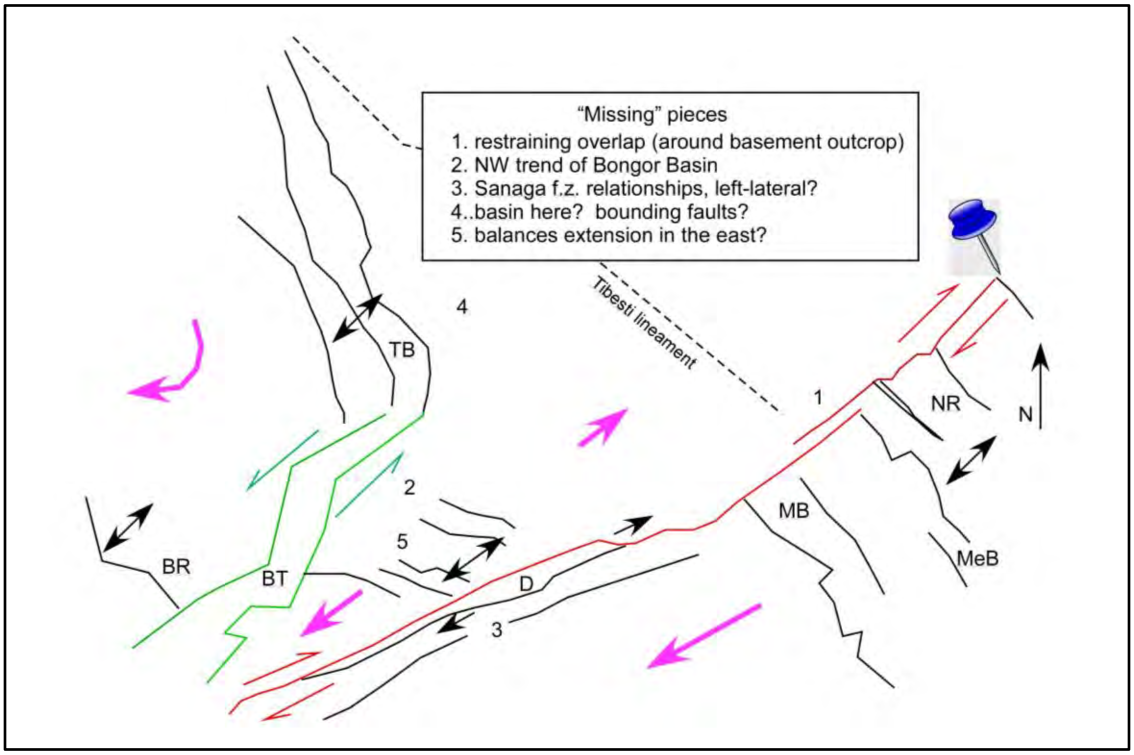

Figure 4. Kinematic summary of the CARS and CASZ systems in terms of the color scheme in Figs. 1 and 2. Predictive issues include the five "missing"pieces located on the map by numbers 1-5. BT Benue Trough, BR Bida Rift, MB Muglad Basin, NR Nile Rifts, MeB Merlot Basin, TB Termit Basin, D Doseo Basin (pull apart). See text for further discussion.

STARZ

A similar, apparently older system of Karoo age with perhaps late Mesozoic reactivation, seems to connect across southern Africa from Namibia to Tanzania (Fig. 5). Elements of this Southern Trans-African Rift Zone (STARZ) have been recognized previously, particularly as a Precambrian suture (Burke et al., 1977). Newly recognized is the possibility that the trans-African suture may have been reactivated in Namibia, NW Botswana, and southern Zambia to fully span the continent.

Two basins occur in that gap. Cathey (2015) performed a Werner inversion of legacy high-resolution aeromagnetic data in northeast Namibia that revealed a deep, apparently narrow basin within the greater Owambo Basin that we have dubbed the Kavango Basin or Sub-Basin (Fig. 5). This depth-to-basement inversion imaged a number of apparently extensional basement fault blocks beneath sedimentary fill ranging from 2 to 7 km (with an uncertainty of ± 10%). Seven profiles were then interpreted in terms of a theoretical sedimentary fill consisting of the Neoproterozoic, lower Paleozoic, Karoo, Cretaceous, and Kalahari sections known from the region.

Selected sections were reconstructed in Lithotect™ structural modeling software. These models are necessarily generalized because geological control is remote from the region, but do suggest something like 60 km of extension in a NE-SW direction has been localized in the NE corner of Namibia, probably during recurrent extension during the Neoproterozoic, the Karoo, and the Cretaceous time periods of known southern African extension. The narrow, deep basin most simulates typical pull apart basins, and is interpreted as such in Figure 5.

In addition to the Kavango basin, exploration in the Namibian panhandle has mapped a feature called the Caprivi Basin (Fig. 5). The exact relationship between these and other possible features in the area is not clear, but several lineaments emanating from the Damara inlier in western Namibia may represent their southwestward extension. Northeastward projection of the Omaruru lineament in particular (Fig. 5) along gravity and magnetic trends appears to be relevant, and may represent one of the principal reactivated basement trends that link to the structure of the basin. Others may occur to the north of the Damara inlier where seismic data has detected fault systems that penetrate into the supracrustal section (Hoak et al., 2014). To the east, the suture trend is well represented in southern Zambia, where it crosses basement outcrop and connects to several Karoo rift basins (the Kafue, Luano, Lukusashi,

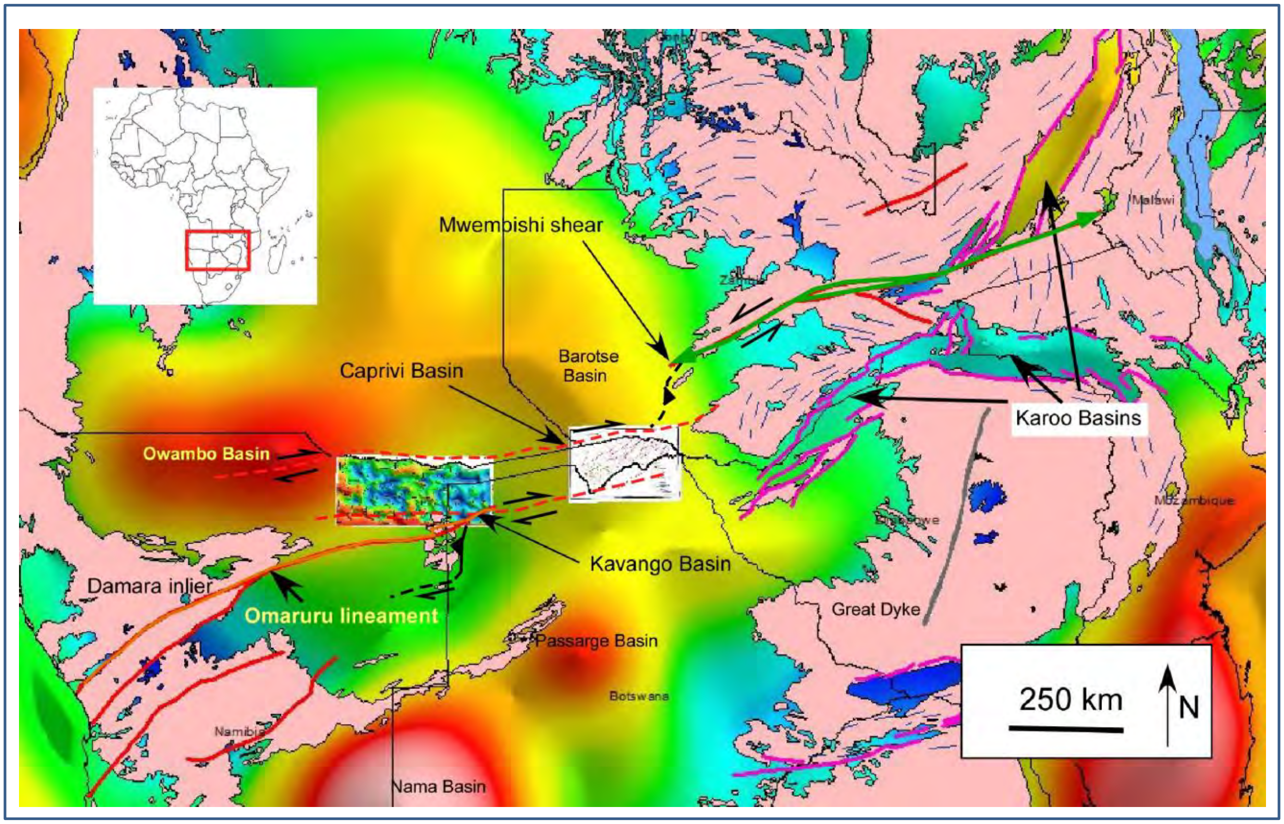

Figure 5. Features of intra-cratonic deformation along the STARZ system in southern Africa, illustrating faults and basins associated with reactivation along the suture zones between various crustal cratons. Kavango and Caprivi Basins are interpreted to be pull apart basins along an extension and connection of the Omaruru and Mwembishi shear systems. Tectonic interpretation in dashed lines is conjectural, and remains to be tested with new data. Firm conclusions are difficult to draw but the thick spans the area of the Kavango and Caprivi sub-basins suggests missing tectonic elements. The background is from the MARIMBA Project total sediment isopach or TSI (Dickson & Odegard, 2013).

Zambesi, and Luangwa Basins) and on into Malawi where it is transected by the Neogene East African Rift System. The level of exposure there is such that the reactivation history is easily read (e.g. Daly et al., 1989)

Several interpretations of the local relationships between the East African Karoo basins and the Namibian basins are possible. One is shown in Figure 5, wherein the two basins open as pull apart basins along subparallel shears. Isolated basement outcrops in eastern Namibia and on the edge of the Barotse Basin in Zambia may fit into the picture as restraining bend uplifts, as shown in Figure 5. The intervening territory, in Botswana, Zambia, and Zimbabwe is largely covered so that outcrop geology cannot fill in the structural connections, but potential methods data suggest a similar situation to the CARS. The background to Figure 5 is the same inversion of Free Air gravity to sedimentary thickness/D2B as in Figure 3: it suggests a connection between the Owambo Basin thick in southern Angola-Namibia into western Zambia and southward into Botswana across the Namibian panhandle.

The African continent itself is not appreciably offset along either the CASZ or the STARZ, indicating that these trans-African shear zones are not major plate margin transforms. But it is notable that in most cases they have been reactivated during subsequent tectonics, i.e. the Gondwana breakup in Cretaceous time or the East African Rift activity in Neogene. In some cases they themselves appear to be reactivations of earlier, usually Precambrian, tectonic features.

Exploration applications

Recognition of the kinematics of CARS, CASZ, and STARZ, and particularly of their architectural details allows for informed focusing of exploration programs, e.g. in the form of either leasing strategies or the layout of seismic programs. The strategy is to use known rift-related trapping geometries to build kinematically sensible regional models. In the case of CARS (Fig. 3 & 4), there are several missing elements in the system, as detailed in Figure 4. The entire region in western Zambia and neighboring Botswana and Namibia might contain significant structures worthy of exploration. These are blue sky exploration opportunities.

References

Binks, R. M., & Fairhead, J.D., 1992: A plate tectonic setting for Mesozoic rifts of West and Central Africa. Tectonophysics v. 213, p. 141-151.

Bosworth, W., 1994: A model for the three-dimensional evolution of continental rift basins, north-east Africa. Geol. Rundsch. v. 83, p. 671-688

Burke, K., Dewey, J.F., & Kidd, W.S.F., 1977: World distribution of sutures-the sites of former oceans. Tectonophysics v. 40, p. 69-99.

Cathey, W., 2015: Namibia Werner profiles. Proprietary report submitted to Reconnaissance Energy International from Earthfield Technology.

Daly, M.C., Chorowicz, J., & Fairhead, J.D., 1989: Rift Basin evolution in Africa: the influence of reactivated steep basement shear zones. Geol. Soc. London Special Pubs. No 44, pp. 309-334.

Darin, M.H., & Dorsey, R.J., 2012: A new estimate for total offset on the Southern San Andreas Fault: implications for cumulative plate boundary shear in the northern Gulf of California (abs). Am. Geophys. Union Fall Meeting Abstract #T44A-05.

Dickson, William and Odegard, ME, 2013: Mapping Narrow Rift Basins from Inverted Gravity and Magnetic Compilations: Potiguar Basin, Brazil and the East African Rift System. SEG Annual Conference Workshop

Dickson, WG and Schiefelbein, CF., 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, GCSSEPM Perkins-Rosen Conference, Houston, 9 pp.

Dou, L., Xiao, K., Cheng, D., Shi., Buqing, & Li, Z., 2007: Petroleum geology of the Melut Basin and the Great Palogue Field, Sudan. Marine & Petrol. Geol. V 24, p. 129-144.

Ebinger, C. J., Rosendahl, B. R. & Reynolds, D. J.,1987. Tectonic model of the Malawi rift, Africa. In: Ben-Avraham, Z. (ed.) Sedimentary basins within the Dead Sea and other rift zones. Tectonophysics v. 141, 215-235.

Fairhead, J.D., & Green, C.M., 1989: Controls on rifting in Africa and the regional tectonic model for the Nigeria and East Niger rift basins. Jour. African Earth Sci. v. 8, p. 231-249.

Genik, G.J. 1993: Petroleum geology of Cretaceous-Tertiary rift basins in Niger, Chad, and Central African Republic. Amer. Assoc. Pet Geol. Bulletin v. 77, p. 1405-1434.

Granath, J.W., 2001: The Nogal Rift of northern Somalia: Gulf of Aden reactivation of a Mesozoic rift; *In:* Ziegler, P.A., Cavazza, W., Robertson, A.H.F., & Crasquin-Soleau, S. (eds), Peri-Tethys Memoir 6; Peri-Tethyan Rift/Wrench Basins and Passive Margins. *Mem. Mus. nam. Hist, nat.,* **186** : 511-527.

Guiraud, R., & Maurin, J-C., 1992: Early Cretaceous rifts of Western and Central Africa: an overview. Tectonophysics v. 213, p. 153-168.

Hoak, T.E., Klawitter, A.L., Dommer, C.F., & Scaturro, P.V., 2014: Integrated exploration of the Owambo Basin, onshore Namibia: hydrocarbon exploration and implications for a modern frontier basin. Search and Discovery Article #10609.