Tectonic Inversion and Petroleum System Implications in the Rifts of Central Africa

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Summary

The rift system of western and central Africa (Fig. 1) provides an opportunity to explore a spectrum of relationships between initial tectonic extension and later compressional inversion. Several seismic interpretation examples provide excellent illustrations of the use of basic geometric principles to distinguish even slight inversion from original extensional “rollover” anticlines. Other examples illustrate how geometries traditionally interpreted as positive “flower” structures in areas of known transpression/ strike slip are revealed as inversion structures when examined critically. The examples also highlight the degree of compressional inversion as a function in part of the orientation of compressional stress with respect to original rift structures. Finally, much of the rift system contains recent or current hydrocarbon exploration and production, providing insights into the implications of inversion for hydrocarbon risk and prospectivity.

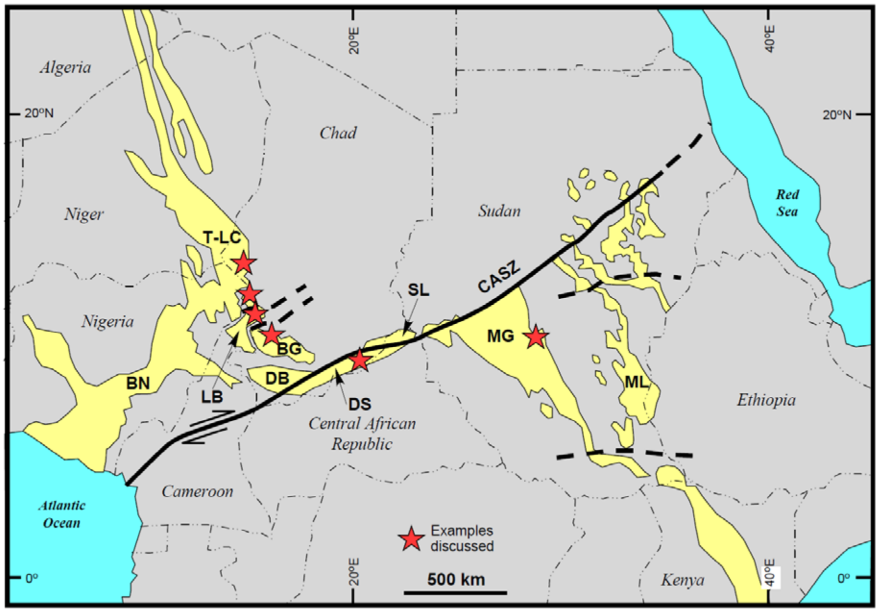

Figure 1: Mesozoic-Tertiary rift systems of central and western Africa. Individual basins referred to in text: T-LC = Termit/ Lake Chad; LB = Logone Birni; BN = Benue Trough; BG = Bongor; DB = Doba; DS = Doseo; SL = Salamat; MG = Muglad; ML = Melut. CASZ = Central African Shear Zone (bold solid line). Bold dashed lines = inferred subsidiary shear zones. Red stars = Approximate locations of example sections shown in Figs. 2-5. Modified after Genik 1993 and Manga et al. 2001.

Inversion setting and examples

The Mesozoic-Tertiary rift system in Africa was developed primarily in the Early Cretaceous, during south Atlantic opening and regional NE-SW extension. NNW-SSE oriented extensional basins developed extensively in two systems in western Africa (e.g Niger) and in east-central Africa (e.g. Sudan), linked by the Central Africa Shear Zone dextral fault system and related transtensional basins in central Africa (e.g. Genik 1993; Fig. 1). Several kilometres of Lower Cretaceous clastic sediments, primarily lacustrine shales and sandstones, were deposited during rifting. By late Albian time, active rifting had given way to thermal subsidence, allowing progradation of widespread fluvial, deltaic and, locally in the west, shallow marine facies (Schull 1988, Giedt 1990, Genik 1993 and references therein).

Compressional inversion occurred locally in Santonian time (Petters & Ekweozor 1982, Genik 1993, Reynolds & Jones 2004), related to change in relative plate motions, specifically convergence between Africa and Europe (Guiraud & Maurin 1992). Following a widespread Santonian unconformity, there were two cycles of renewed extension and subsidence in latest Cretaceous and early Tertiary time, and finally regional uplift in Miocene time, particularly in western Africa.

Most basin profiles in the rift system remain dominated by extensional geometry. For example, the Niger Termit basin profile (Fig. 2) shows a "classic" rift geometry with simple extensional rollover anticlinal structure. Even where obvious, the compressional overprint is generally subtle compared to the extensional fault geometry, for example in the Chad Bongor basin (Fig. 3a; Genik 1993).

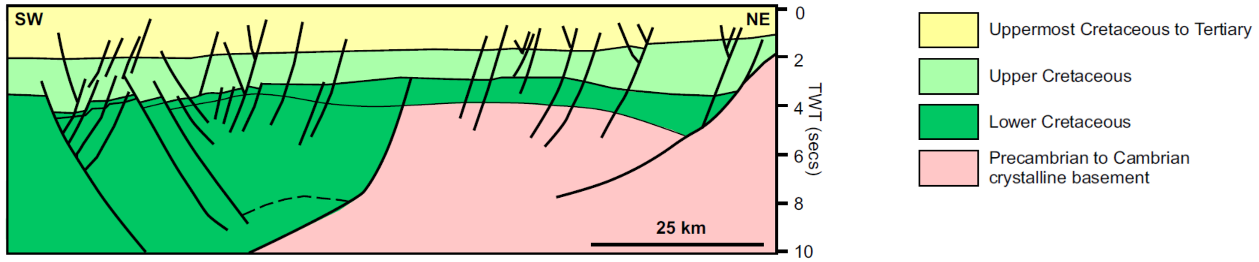

Figure 2: Cross section showing preserved extensional geometry, Termit-Lake Chad Basin, Niger. After Genik (1993). Legend applies also to subsequent figures.

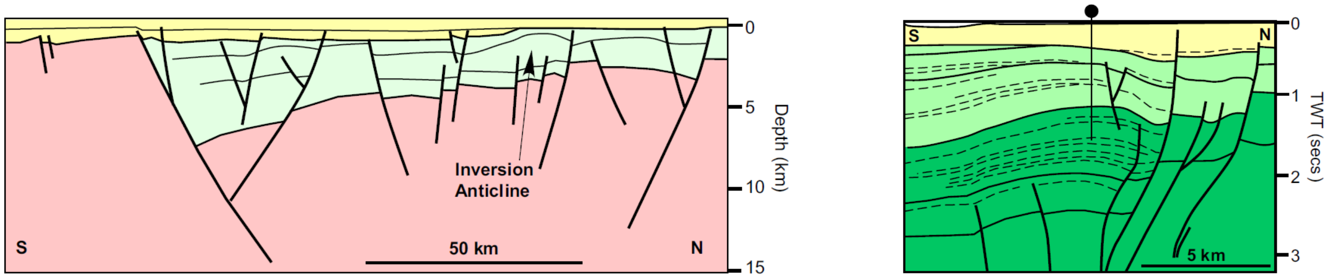

Figure 3: Inversion examples. A (left): Cross section showing inversion in Bongor Basin, more notable in northern part of basin. After Genik (1993). B (right): Inversion structure and petroleum trap in Doseo basin. Redrawn from interpreted seismic section in Genik (1993).

Critical examination of the geometry is what reveals the inversion component. For example, inversion is easily shown in Fig. 3b from Doseo basin (Genik, 1993) by these criteria: 1) thickening of Lower Cretaceous isochrons from footwall (FW) to hangingwall (HW) indicating early extension, yet 2) elevation of top Lower Cretaceous in HW anticline relative to FW; 3) thinning of uppermost Cretaceous interval from FW to HW anticline; 4) thinning and onlap of the Tertiary sedimentary sequence onto the fold forelimb.

However, some structures are far less clearly the result of inversion. The structural setting for the Heglig oil field, Muglad basin, Sudan (Fig. 4a) has been interpreted as purely extensional (Mohamed et al. 2000), but close examination reveals subtle yet convincing evidence for inversion. The field lies in a Lower Cretaceous sub-basin controlled primarily by SW-dipping extensional faults. From NE to SW Lower Cretaceous and lower Upper Cretaceous intervals thicken across the faults, and the top Lower Cretaceous shows extensional offset across the faults. Yet where thickening across faults is apparent in basal Upper Cretaceous, the intermediate Upper Cretaceous horizon is also structurally elevated in HW relative to FW, indicating slight inversion. Similar relationships might be argued for the Unity field structure (Fig. 4b) in the same basin. There is also arguably a FW shortcut splay at the NE edge of the Heglig field graben (Fig. 4a), where compressional faulting has cut through the basement into the adjacent half-graben to the NE. The FW shortcut can be recognized because the Lower Cretaceous interval is notably thinned above a tilted basement high in the HW, but the top Lower Cretaceous is subtly elevated in the shortcut fault HW.

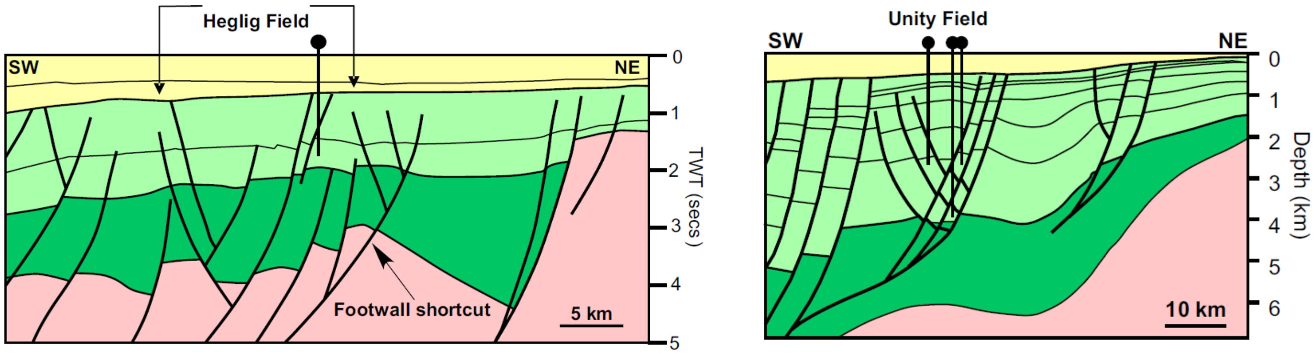

Figure 4: Recognizing inversion versus pure extension in Muglad basin, Sudan. A (left): Preserved extensional geometry, interpreted inversion fairway (arrow brackets) and setting for the Heglig oil field. Redrawn from interpreted seismic section in Mohamed et al. 2000. B (right): Cross section showing preserved extensional geometry, possible subtle inversion and setting of the Unity oil field. After Giedt (1990).

Inversion can also be recognized in structures originally interpreted as transpressional "flower" structures. Fig. 5a from Logone-Birni basin shows steeper horizon dips at depth, revealing a syn-rift growth sequence, although it was not recognized by the original authors (Manga et al. 2001). The top syn-rift has been gently folded and some faults show compressional offset. Therefore even without confident seismic correlations, geometric relationships alone indicate a subtly inverted syn-rift basin. Figure 5b from the same basin shows an asymmetric graben, originally described as a "half-flower" structure (Manga et al. 2001). Two syn-rift growth sections are suggested by dip changes with depth in the Lower Cretaceous section: an older interval that thickens to the southern basin-bounding fault, and a younger interval that thickens to the northern basin-bounding fault. The southern fault has been compressionally reactivated, causing uplift and erosional truncation of Lower Cretaceous sediments. In both examples, the structures may have a transpressional component, but the important point is that there is an early extensional history.

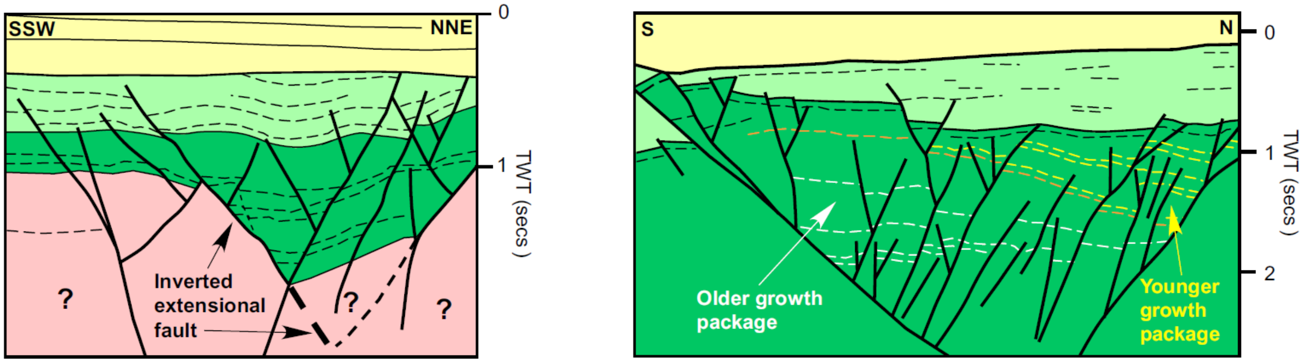

Figure 5: Recognizing inversion versus simple transpression in Logone Birni basin, Cameroon. Redrawn from interpreted seismic sections in Manga et al. (2001). **A (left):** Previously interpreted "flower structure" Bold dashed line indicates proposed basin-bounding fault at depth; more compatible with section than the south-dipping fault (finer dashed line) shown in the original paper. **B (right):** Previously interpreted "half-flower" structure showing syn-rift growth sections associated with both basin-bounding faults, and inversion on the southern fault.

It is important to note that the Santonian compressional stress was nearly orthogonal to the Early Cretaceous extension direction (Genik 1993, and references therein). The resulting inversion is best documented in the ENE-WSW oriented Benue, Logone Birni, Bongor, Doba and Doseo basins (Fig. 1); Petters & Ekweozor 1982, Genik 1993, Manga et al. 2001), perhaps because their major faults were more favourably oriented with respect to later compressional stress. Inversion is least pronounced in the NW-SE Termit-Lake Chad, Muglad, Melut and other Sudan basins, where extensional geometries are commonly fully preserved with little or no direct evidence of compressional reactivation (e.g. Fig. 2).

Petroleum System Implications

Recognizing inversion is important when considering petroleum system risks and opportunities. Lack of significant inversion preserved original extensional fault trap geometry. Most of the extensional geometry was already in place relative to initial maturation of source rocks and peak migration. Structures remained fully buried rather than uplifted and partly eroded, thus preserving seals and also keeping source rocks within generating windows. These favourable conditions may be partly responsible for several large established hydrocarbon fields in Sudan, e.g. Muglad and Melut basins (Schull 1988, Mohamed et al. 2000, Idris & Yongdi 2004), where basins and largest extensional structures are oriented NNW-SSE and therefore least favourable for reactivation during the Santonian compressional event. However, tilted extensional fault blocks require lateral fault seal and therefore this is a key exploration risk (Idris & Yongdi 2004).

In contrast, subtle inversion potentially created four-way dip closed structures (HW anticlines) that do not depend on fault seal and are favourably positioned relative to thick syn-rift lacustrine shale source kitchens. Inversion anticlines form the main hydrocarbon traps in the favourably oriented E-W trending basins (Genik 1993, Reynolds & Jones 2004). However, inversion anticlines may post-date initial migration from source rocks, introducing some charge risk. Because the compression modified the original extensional geometries there is also risk of loss of hydrocarbons during re-migration (Petters & Ekweozor 1982, Giedt 1990).

With very large amounts of inversion, risk outweighs opportunity at both prospect and play scales. Doba, Bongor and Logone-Birni basins have been uplifted as much as 2 km (Genik 1993, Manga et al. 2001), potentially eroding seals and the best late-rift fluvial and deltaic reservoirs beneath the Santonian unconformity (Figs. 3a-b, 5a-b). Uplift also potentially exposed light oils to meteoric waters and cooler temperatures, resulting in a biodegradation risk (Petters & Ekweozor 1982, Genik 1993, Manga et al. 2001).

Conclusions

- Subtle compressional inversion can be distinguished from purely extensional or strike slip geometries with critical examination of data.
- The degree of inversion is dependent on orientation of extensional faults to compressional stress.
- Subtle inversion introduces different advantages and risks for hydrocarbon prospectivity compared to original extensional fault traps.
- Significant inversion introduces very large risks to overall petroleum prospectivity.

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