

The Evolution of Faults System in Cretaceous Sequences, Offshore Cameroon

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Abstract: Located in Kribi-Campo sub-basin on the present day deep-water continental margin slope, the study area covers an area of 1500 km², and contains a sedimentary section up to 6.5 km thick, ranging in age from Upper Cretaceous to Recent. 3D seismic data used in this study covers the deep water section of the basin, and provides an opportunity to investigate the structural and morphological features of the basin in upper Cretaceous, bring a better understanding of the basins stratigraphic evolution. In the late Cretaceous the basin developed as a result of tectonism related to movement of the Kribi Fracture Zone (KFZ), which reactivated in the late Albian and early Senonian. This led to inversion of the early syn-rift section overlying the KFZ to the southeast. Two main fault-sets – N30 and N120 – developed in the center and south of the basin. These normal faults propagated from the syn-rift sequences: the N120 faults die out in the early post-rift sequence (Albian time) whilst N30 faults tend to be associated with the development of a number of fault-related folds in the late Cretaceous post-rift sequence, and have a significant control on later deposition.

Keywords: Cameroon, 3D seismic, Upper Cretaceous, West Africa

1. Introduction

The study area is located on the continental slope section of the Kribi-Campo sub-basin, covers an area of 1500 km², ups to 6.5 km thick from Upper Cretaceous to the present day (Fig. 1). Most of upper Cretaceous sequences are absent towards the onshore caused by the uplift of Kribi Fraction zone erosion (Pauken, 1992). This high topography controls the basin stratigraphic evolution. The entire sequence is subdivided into Upper Cretaceous and Cenozoic sequence.

Drilling results from the continental shelf, Sanaga Sud field approximately 10 km offshore, reveal the absence of most sequences in the Upper Cretaceous (Cenomanian to Campanian) and Cenozoic (Palaeocene to Oligocene). In the shelf, the most significant structure is an eroded, palaeo-topographic high composed of Lower Cretaceous sands and shales and overlain by Upper Cretaceous shales (Maastrichtian shale) (Pauken, 1992, Gonder, M. K et al., 2011). This eroded high topography controls the basin stratigraphic evolution; possibly most of the missing sequence in the shelfal area has been reworked and transported further offshore to deposit in the deep water area.

This study focus on the control on the Upper Cretaceous sequence evolution. The 3D seismic data which covers the deep water section of the basin gives a great opportunity to investigate the structural and morphological features of the basin in upper Cretaceous. These observations are linked to published data to better understand of the basin stratigraphic evolution of Upper Cretaceous formations in the deep water area of Kribi-Campo sub-basin.

2. Geological setting

The basin was formed during the break-up of North America, Africa, and South America, with continental separation gradually propagating south to north from the Late Jurassic to Late Cretaceous time. The Kribi-Campo sub-basin was one of the latest basins to open in the Late Cretaceous (Late Albian to Turonian), coeval with opening of the Gulf of Guinea, and forming a continuous restricted seaway from the Walvis Ridge to North Africa (Fig. 2) (Tissot et al., 1980). By the end of the Turonian, the Atlantic Ocean had developed, with fully oxic marine conditions.

The basin was initially a rift branch of the proto-Atlantic, which includes the Rio-Muni, North Gabon (West Africa), and Sergipe-Angolas (Brazil) (de Matos, 1992a, Davison, 1997). The basin had a number of significant regional tectonic events during the later passive margin phase, which led to gravity sliding in the Early/Mid/Late Tertiary period and inversion and folding in the Santonian. These events are marked by

major unconformities including the Albian-Aptian break up unconformity (115 Ma), middle Cretaceous (Santonian - ~ 85 Ma), late Cretaceous (K/T boundary - ~ 70 Ma) and mid-Oligocene (~ 30 Ma), mid-Miocene (~ 15 Ma) and late Tertiary event (~ 5.3 Ma) (Turner, 1995, Brownfield and Charpentier, 2006, Lawrence et al., 2017, Tchouatcha, M. S et al., 2023).

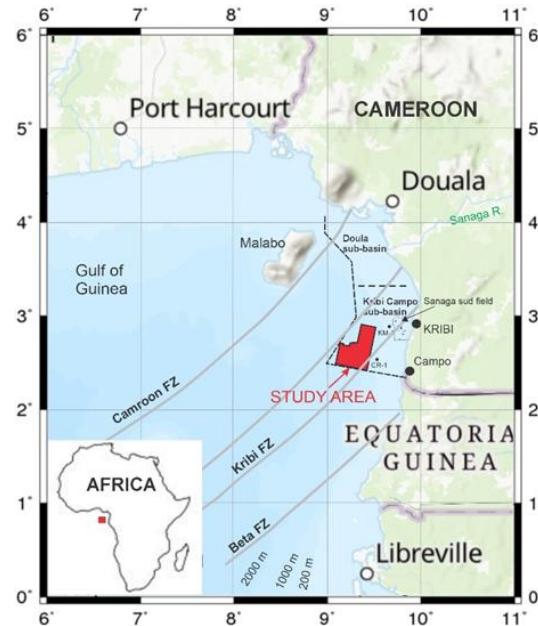


Fig. 1. Bathymetry map of the continental slope on the Cameroon margin showing the study area in red and the main fracture zones in the area (Le et al., 2015). The coast line map is extracted from National Centers for Environmental information (NCAA) (<https://www.ncei.noaa.gov/maps/grid-extract/>)

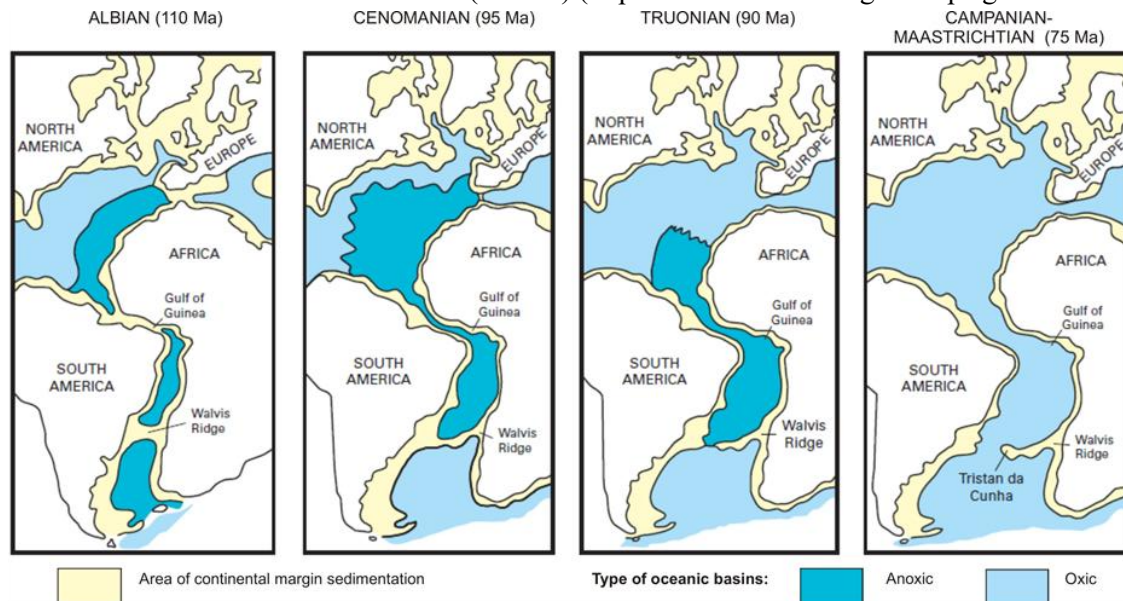


Fig. 2. Paleogeographic maps of the Cretaceous breakup of Africa and South America, showing the distribution of restricted seaways (anoxic) to fully open marine (oxic) environments through the Cretaceous in the Atlantic basins (after Brownfield and Charpentier (2006), adapted from Tissot and others (1980)

3. Dataset and methodology

This study using high-resolution 3D seismic data covering an area of 1500 km², upper Cretaceous sequence, in the deep water slope, offshore Cameroon. The dataset has inline and crossline spacing of 25m. The interpretation was carried out using two-way travel time 3D seismic data, however, when the depth is quoted, a velocity of 2600 m s⁻¹ is applied for the Cretaceous, based on analysis of nearby well data (Turner, 1995).

The seismic interpretation has carried out using the Schlumberger™ Petrel software to determine the key sequence stratigraphy boundaries, geometry, and internal structure of channels. The seismic interpretation started with line by line interpretation, auto-tracking, and seismic facies identification. Detail time structural maps were generated to visualize the main structure especially the faults patterns in upper Cretaceous. The study used the sequence stratigraphy method of Vail and Mitchum (1977) to define the key surfaces, creating a structure framework for the study area.

4. Results and discussion

4.1. Key surfaces

The Kribi-Campo sub-basin formed during the breakup of Africa and South America. Rifting began in the Late Jurassic and lasted until the onset of seafloor spreading in Albian-Cenomanian time (Pauken, 1992). This was followed by thermal sag, and the basin is classified as an Atlantic-type marginal sag basin (Lawrence et al., 2017). The Upper Cretaceous succession is divided into four seismic units, separated by five key surfaces labelled from KS_10 to KS_50, based on the combination of internal seismic reflection configuration and termination and the nature of the bounding surface.

KS_10 is top of the Albian sequence and is the deepest mapped reflection in this dataset, with a maximum depth of c. 7 s TWT. KS_10 is strong positive amplitude reflection, which is offset by numerous faults and characterized by truncation beneath and onlap above in the area of the Kribi High (Fig. 4). The surface is mapped with confidence in the basin, but is less clear over the Kribi High due to the erosional truncation.

KS_20 is a strong negative amplitude reflection. This reflection is characterized by onlap above in the southeast area (Fig. 4). The surface extends across almost all of the study area, but onlaps against the Kribi High in the southeast.

KS_30 is a weak to strong positive amplitude reflection. The surface is identified by downlap above and a change from dominantly high amplitudes below to an overlying lower amplitude seismic facies above. This surface extends across the whole area, but onlaps onto the Kribi High (Fig. 4).

KS_40 is the base of Unit 4 and has good continuity. It is a low to strongly positive amplitude reflection. The surface is characterized by onlap above in the Kribi High area (Fig. 4) and defines the base of a massive fan system which extends from the east to the southern half of the study area.

KS_50 is top of upper Cretaceous sequence, defined as a strong positive amplitude reflection. The surface is identified as a major unconformity surface characterized by downlaps onto an erosional surface. It marks the change from a low frequency sequence below to a higher frequency sequence above, from 17 Hz to 45 Hz, respectively (Fig. 4). The surface is cut by a large channel trending NE – SW and fully covers the Kribi High (Fig. 4).

The deep crustal structural controls on basin configuration are shown on Fig. 1. Two major fracture zones were formed by continental extension: The Kribi Fracture Zone (KFZ) to the southeast; and an unnamed fracture zone to the northwest (Meyers et al., 1996). Only the KFZ actually intersects the study area, associated with development of a structural high to the southeast. The KS_10 surface can be mapped over the structural high and is characterized as an erosional truncation surface with an elevation of ca. 2.6 km (Fig. 3 & 4). Further analysis of the prominent high reveals a thick succession of low amplitude discontinuous to parallel reflections that dip at an angle of 14°. Towards its core, seismic facies become increasingly chaotic and no clear boundary can be defined between the thick succession above and chaotic facies below.

The structure can be correlated with similar uplifted highs on the margin of the continental shelf (Fig. 1), first described by Pauken (1992). These eroded high consists of a thick syn-rift sequence (Lower Cretaceous) overlain by post-rift sediments (Upper Cretaceous). Inversion of the older syn-rift section has been documented on many of the margins of West Africa (Dailly, 2000, Brownfield and Charpentier, 2006). In this study, the Kribi High associated with the KFZ to the southeast (Fig. 1) is the main control on basin profile, forming the basin boundary to the southeast in the Upper Cretaceous.

4.2. N30 and N120 fault sets

Faults have been identified in the basin, striking N30 and N120, with average spacing of 2 km and maximum offset of 140 ms. The faults are planar in geometry and throw to the southwest, with steep dips of c. 40 – 50° (Fig. 3 & 4). The N120 faults are perpendicular to the transform trend and terminate abruptly at the KFZ. The N30 faults run parallel to the transform trend, developed close to the KFZ. They are interpreted to be mostly normal faults. In cross-section, the N120 faults die out below the top Lower

Cretaceous sequence (KS_10). The N30 faults often penetrate or show later movement that deforms the overlying interval, with aggradational convex-up reflections observed above these faults throughout the Upper Cretaceous section (Fig. 4). Further analysis reveals that the N30 faults decrease offset upwards from ~100 ms to ~20ms TWT (Fig. 4b). The convex-up reflections are symmetric or asymmetric, with gently dipping limbs ($5 - 10^\circ$ NW and SE) and structural relief of the central apex of about 140 -150 ms. They occur above the fault tip line and tend to drape the fault planes in the Upper Cretaceous. Based on the characteristic of convex-up reflections and their relationship with N30 faults, they are interpreted to be extensional fault-related folds, a result of either fault propagation producing monoclinical warps above the fault tips, frictional drag along the normal fault planes or differential compaction of sediments over a pre-existing extensional fault scarps (Schlische, 1995, Khalil and McClay, 2002).

Most of N120 faults die out within the syn-rift sequence, and terminate at, or close to, the fracture zone, the observations of both N30 and N120 fault sets in the syn-rift sequence (Lower Cretaceous), suggests that both fault sets may be related to a rifting stage during basin opening, and are related to evolution of the fracture zone. Similar normal fault characteristics have been documented in the Niger Delta (Briggs et al., 2009), Rio-Muni Basin (Dailly, 2000), and the Gabon Basin (Mbina Mounguengui and Guiraud, 2009). The development of fault-related folds in the Upper Cretaceous could be related to re-activation of the N30 faults associated with regional tectonic uplift during Senonian (post-rift) time.

In summary, three main structural features characterize the basin:

- The NE - SW Kribi High located in the southeast of the study area. It comprises a thick Lower Cretaceous syn-rift sequence, which is overlain by an Upper Cretaceous post-rift sequence.
- N120 faults run perpendicular to the KFZ and terminate in the syn-rift sequence (Lower Cretaceous).
- N30 faults parallel to the KFZ are developed in the Early Cretaceous. The faults are associated with the development of fault-related folds in the Upper Cretaceous with the axial planes that strike N30.
- Upper Cretaceous sediments filled the developing basin, which is bounded by the eroded paleotopographic high to the southeast (Kribi High).

The role of the faults in post-rift deposition varies significantly. While N120 faults show less control on post-rift deposition, as they all terminate in the Lower Cretaceous, N30 faults produced a number of fault-related folds in the Upper Cretaceous sequence which may have some effect on the geometry and distribution of channel and fan deposits in the Upper Cretaceous.

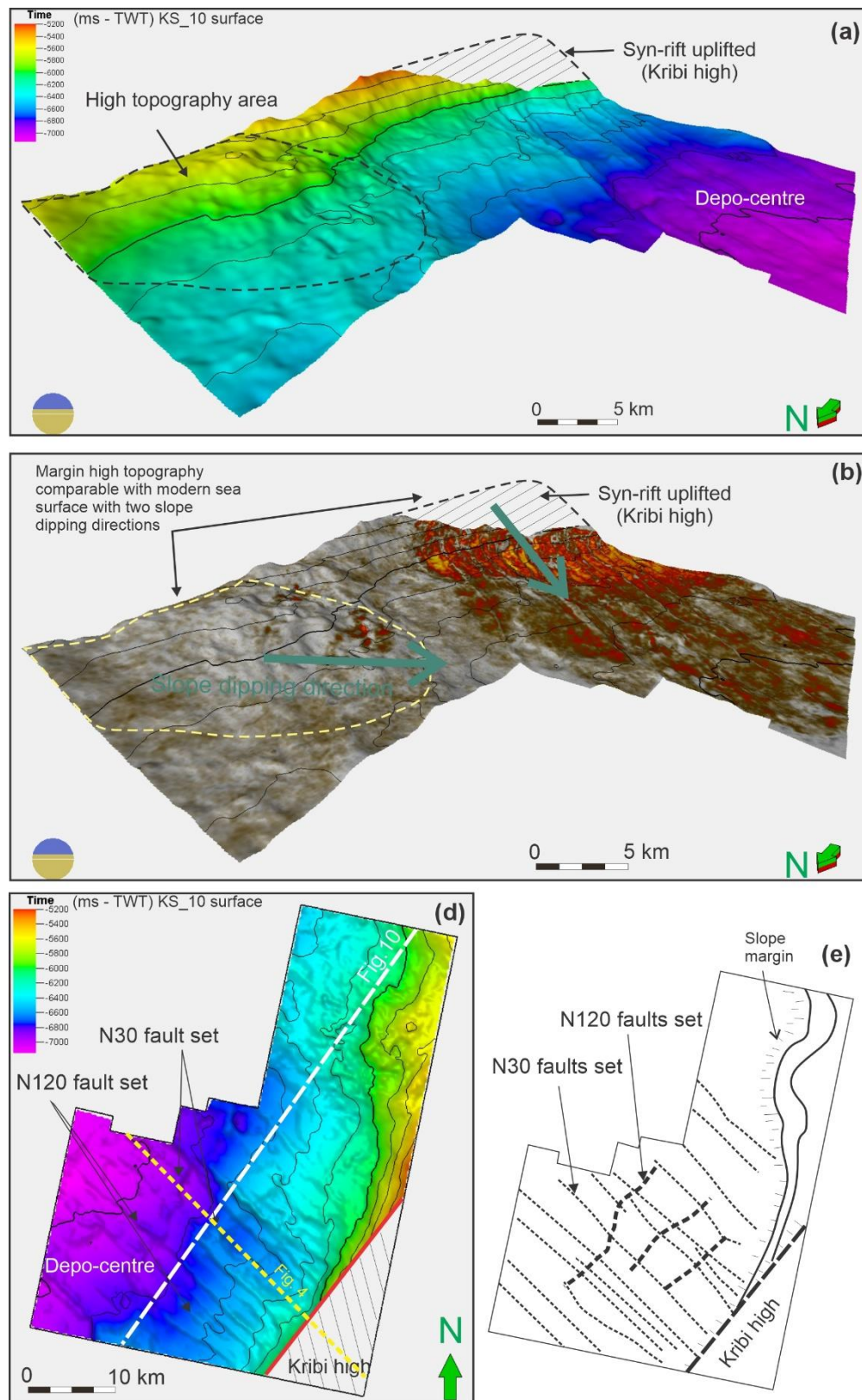


Fig. 3. (a) 3D view of the basal surface (KS_10) showing high palaeo-topography in the east and southeast, controlled by the uplifted syn-rift section. (b) The basal surface displayed as amplitude attribute revealing high amplitude in the southern area and lower amplitudes to the north. (c) Map of the basal surface illustrating the two main fault sets, N120 and N30. Line interpretation is shown in (d). N120 faults terminate below the KS_10 surface; N30 faults penetrate the Upper Cretaceous and develop a number of fault-related folds.

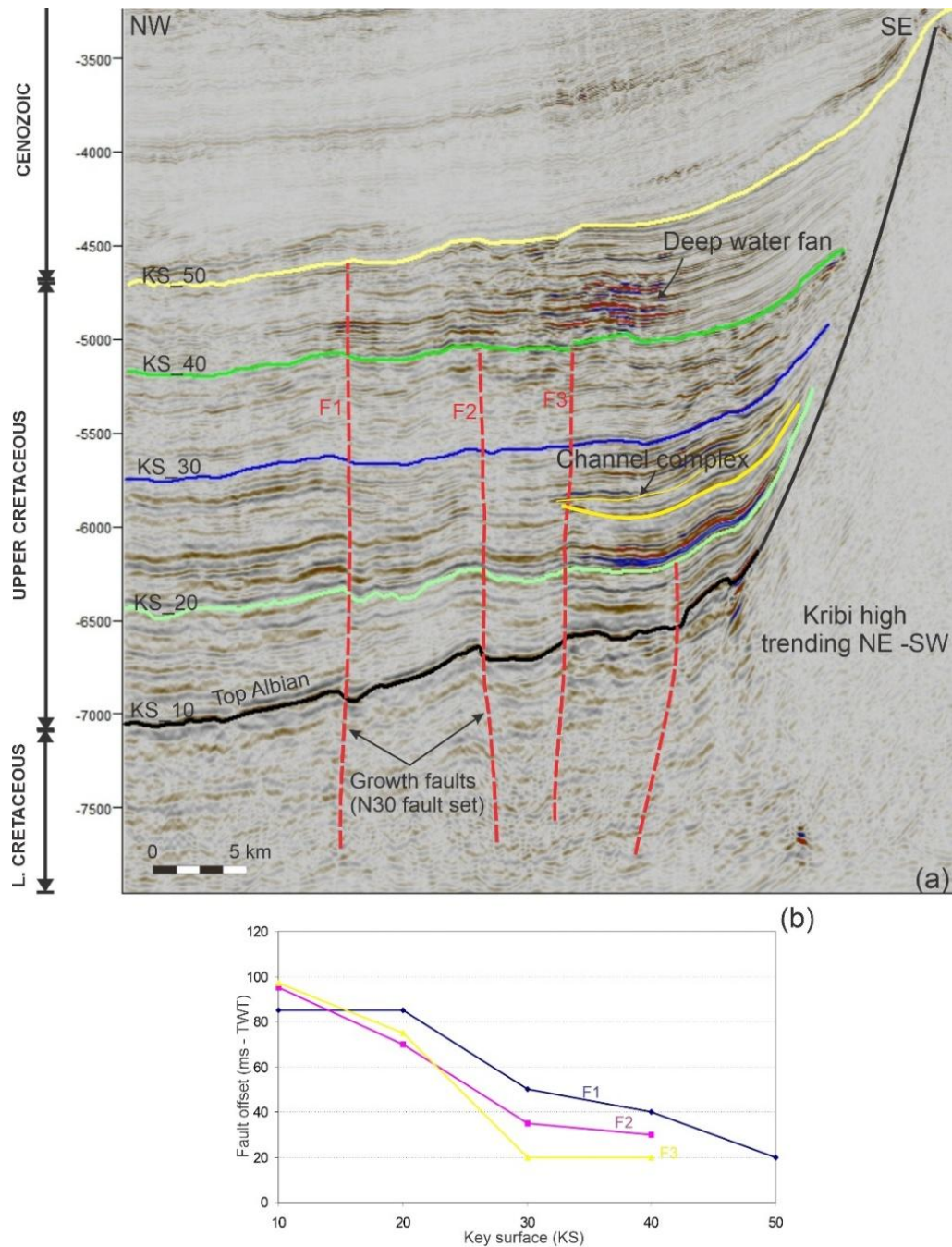


Fig. 4. (a) NW– SE seismic section perpendicular to the N30 faults illustrating for growing faults in the Upper Cretaceous which subtle controls the deposition of sands in these lower sequences. (b) The graph is a Cross-plot of growth fault vs. the key surfaces reveals the decrease of the fault throw upwards. (See fig. 3 for the seismic line location)

5. Conclusions

The Kribi-Campo sub-basin is located in the northernmost of a series of divergent basins along the West Africa continental margin. The tectonic history of the basin is controlled by the continental extension of NE – SW trending transform, Kribi Fracture Zone. The reactivations of the KFZ resulted in two uplift phases, creating the late Albian (KS-10) and early Senonian (KS_30) regional unconformities that have controlled the stratigraphic evolution of Upper Cretaceous post rift sequence.

In the Upper Cretaceous, the basin can be subdivided into a high and a low area by the Kribi High, as a result of extension associated with the Kribi transform margin in late Albian and early Senonian. The Upper Cretaceous sedimentation filled the low which is bounded by the eroded paleo-topography high to the southeast (Kribi high). There are two faults sets are detected in the Upper Cretaceous including N120 and N30 faults. The role of these faults in post-rift deposition varies significantly. While N120 faults show

less control on post-rift deposition as they all die out in the Lower Cretaceous, fault-related fold N30 may have some effect on the geometry and distribution of channel, fan deposits in the Upper Cretaceous.

References

- Briggs, S. E., Cartwright, J., & Davies, R. J. (2009). Crustal structure of the deepwater west Niger Delta passive margin from the interpretation of seismic reflection data. *Marine and Petroleum Geology*, 26(6), 936-950.
- Brownfield, M. E., & Charpentier, R. R. (2006). Geology and total petroleum systems of the West-Central Coastal Province (7203). West Africa: US geological survey bulletin, 2207, 52.
- Dailly, P. (2000). Tectonic and Stratigraphic Development of the Rio Muni Basin, Equatorial. Atlantic rifts and continental margins, 105.
- DAVISON, I. A. N. (1997) Wide and narrow margins of the Brazilian South Atlantic. *Journal of Geological Society*, 154 (3), 471-476.
- De Matos, R. M. D. (1992) The northeast Brazilian rift system. *Tectonics*, 11, No. 4, 766-791.
- Gonder, M. K., Locatelli, S., Ghobrial, L., Mitchell, M. W., Kujawski, J. T., Lankester, F. J., ... & Tishkoff, S. A. (2011). Evidence from Cameroon reveals differences in the genetic structure and histories of chimpanzee populations. *Proceedings of the National Academy of Sciences*, 108(12), 4766-4771.
- Lawrence, S. R., Beach, A., Jackson, O., & Jackson, A. (2017). Deformation of oceanic crust in the eastern Gulf of Guinea: role in the evolution of the Cameroon Volcanic Line and influence on the petroleum endowment of the Douala-Rio Muni Basin.
- Mitchum Jr, R. M., Vail, P. R., & Thompson III, S. (1977). Seismic stratigraphy and global changes of sea level: Part 2. The depositional sequence as a basic unit for stratigraphic analysis: Section 2. Application of seismic reflection configuration to stratigraphic interpretation.
- Mounguengui, M. M., & Guiraud, M. (2009). Neocomian to early Aptian syn-rift evolution of the normal to oblique-rifted North Gabon Margin (Interior and N'Komi Basins). *Marine and Petroleum Geology*, 26(6), 1000-1017.
- Pauken, R. J. 1992. Sanaga sub field, offshore Cameroon, West Africa. In: HALBOUTY, M. J. (ed.) *Giant oil and gas field of the decade 1978-1988*, Mobil exploration ventures Co Texas: AAPG Memories 54.
- Tchouatcha, M. S., Kouske, A. P., Galal, W. F., Mahmoud, M. S., Sobdjou, C. K., Ngantchu, L. D., ... & Njike Ngaha, P. R. (2023). The Cretaceous of the Cameroon Atlantic Basin (Central Africa): sediment provenance, correlation, paleoenvironment and paleogeographic evolution of the Eastern Proto-Atlantic margin (Central Gondwana). *Environmental Earth Sciences*, 82(4), 103.
- Tissot, B., Demaison, G., Masson, P., Delteil, J. R. & Combaz, A. (1980) Paleoenvironment and petroleum potential of middle Cretaceous black shales in Atlantic basins. *AAPG Bulletin*, 64 (11), 2051-2063.
- Turner, J. P. (1995) Gravity-driven structures and rift basin evolution - Rio-Muni basin, offshore Equatorial West Africa. *AAPG Bull*, 79 (8), 1138-1158.

