# Geodynamic Characteristics and Their Effect on the Petroleum Geology Conditions for Passive Rift Basin in Central-Western African Region*

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## Abstract

Recently, a significant breakthrough has been achieved for petroleum exploration in the Central-Western African Rift basins, which is a hotspot for the petroleum geologist. The exploration practice showed there are similarities and differences for the hydrocarbon accumulation conditions and rules in the rift basins of the Central-Western African region. Combined with the regional background information and data from wells, geology, and geophysics in the Central-Western African rift basins, this paper concluded that three rifting-sagging stages and two structural inversion events developed in the basins since early Cretaceous. The first rift developed in the early Cretaceous is a typical passive rift formed as a result of strike-slip activity on the Central African Shear Zone. By systematic analysis and comparison the differences between the Central-Western African Rift basins and the active rifts in Eastern China, the author summarized that the passive rift basin is formed by crustal extension induced by non-mantle upwelling. The scale of mantle upwelling is smaller than the active rift, which resulted in the significant differences between the passive and active rifts in terms of geothermal history. Subsidence history in the rifting period, structural style of major faults, and sediments in the sagging stage represent differences that directly affected the petroleum geology conditions in the passive rift basin. Based on the geodynamic and geological characteristics of the passive rift basin, five unique geological features are concluded: source rock, reservoir in sagging period, controlling factors for regional cap rock, major trap types, and favorable accumulation zones.

## Introduction

Rift basin is one of the most hydrocarbon rich basins in the world (Klemme, 1980; Mann et al., 2001). Genetically, two types of rifts are classified, active and passive rifts by Sengor and Burke, 1978; Morgan and Baker, 1983; and Khain, 1994. Since the1980s, most researchers focused on the active rifts. The formation mechanism, geodynamic characteristics, structural styles, and hydrocarbon accumulation rules in the active rifts are widely discussed and studied (Zhai and Zha, 1982; Ma et al., 1982; Tian et al., 1983; Lu and Dai, 1997; Hu and Huang, 1991; Dou and Li, 1997; and Landon, 2003). However, regarding the passive rift, only three types of genetic models, such as pure shear, simple shear, and mixing shear are concluded by McKenzie 1978, Wernicke 1981, and Wernicke1985. No papers intensively discussed the geodynamic characteristics and petroleum geological features for the passive rift before 2000. Muglad and Melut basins, which are located in Sudan and Southern Sudan, are considered the typical passive rift basin. The geological and reservoir forming models are discussed for the Muglad Basin by Tong et al., 2004; Tong et al., 2006; and Dou et al., 2006. The hydrocarbon accumulation rules for the Melut passive rift in Southern Sudan are concluded by Tong et al., 2006.

Combined with the regional background information and data from wells, geology, and geophysics in the Central-Western African Rift basins, this paper systematic analyzed and compared the geological differences of the Central-Western African Rift basins and the active rifts in Eastern China. Also discussed is the geodynamic characteristics and their effect on the petroleum geology conditions for the passive rift basins in the Central-Western African region.

## Geological Setting

### The Central-Western African Rift System (CWARS)

The Central-Western African Rift System (CWARS) is located in central Africa. Many Mesozoic-Cenozoic rift basins are developed along the Central African Shear Zone (CASZ) in Sudan, Southern Sudan, Chad, and Niger (Browne and Fairhead, 1983; Browne et al., 1985; and Jorgensen and Bosworth, 1989). These rift basins can be further divided into the Western African Rift System (WARS) and the Central African Rift System (CARS), which are separated by the Adamaoua uplift in Cameroon (Peterson, 1985 and Genik, 1993). Rift basins in the CWARS are arranged in two distinct orientations, NE-SW and NW-SE, respectively. The most prominent basin among the NE-SW striking group is the Benue Trough. The others are distributed along the CASZ, from west to east: Doba, Doseo, Salamat, and Bagarra basins. All these basins are interpreted as pull-apart structure as a result of strike-slip faulting along the CASZ as evidenced by their basin geometry, intra-basin flower structures, and tectonic situation. The group of NW-SE striking basins that are widely distributed in the West African Rifts are the Tenere Rift in East Niger, the Central Africa Rifts, such as the Muglad, White Nile, Blue Nile, and Atbara basins which comprise the south Sudanese rift-related system, and the Anza Rift in North Kenya (Fairhead, 1988; Schull, 1988; Bosworth, 1992; McHargue et al., 1992; and Genik, 1993).

### The Central African Shear Zone

The Central African Shear Zone (CASZ) is a reactivated fault zone inherited from the Pan-African orogen (Genik, 1993). It separates the NW-SE-trending rifts of West Africa from the Central Africa, and played an important role in initiation and development of the NE-SW trending rifts. The Shear Zone is identified by geophysical means and has been demonstrated to have experienced right lateral movement in the Cretaceous. All the basins of the Sudanese rift-related system, such as the Muglad, White Nile, Blue Nile, and Atbara basins, terminate northwards at the Shear Zone (Figure 1). In particular, basins near and within the Shear Zone show their basin axes parallel or sub-parallel to the shear and possess typical flower structures. All these explicitly indicate apparent strong control of the CASZ on the evolution of the Central African rifts (Fairhead, 1988; Schull, 1988; McHargue et al., 1992; Binks and Fairhead, 1992; Guiraud and Maurin, 1992; and Genik, 1993).

## Structural Evolution History for CWARS

The West and Central African Rift basins experienced multiphase subsidence from the early Cretaceous to the Recent in response to the change of regional crustal stress field (Bosworth, 1992; Guiraud and Maurin, 1992; McHargue et al., 1992; Wilson and Guiraud, 1992; and Wei and Liu, 2003). Three rifting-sagging stages and two structural inversion events developed in the basins since the early Cretaceous (Figure 2).

The onset of the first rifting is related to the opening of the Atlantic Ocean on the western side and the Indian Ocean in the eastern side of Africa during the middle/late Jurassic to the early Cretaceous. The subsidence is fault-controlled in the early stage and characterized by sagging in the late stage. Transcurrent faulting along the CASZ may have exerted a strong influence upon basin development, especially upon early-stage rifting. Extension in NE-SW orientation, or normal to basin axis, can easily be perceived because the early Cretaceous extensional basins are not restricted to the region near the CASZ, but distributed over a large area (Fairhead, 1988; Schull, 1988; McHargue et al., 1992; Guiraud and Maurin, 1992; and Genik, 1993). Therefore, the early Cretaceous subsidence resulted from a combined effect of strike-slip faulting and normal extension related to CASZ, which makes a passive rift different from the typical active rift resulting from mantle upwelling.

The second rifting accrued in the late Cretaceous (96-70 Ma). The basin inversion is attributed to the far-field effect of initial collision of the African and Eurasian plates along the Alpine orogenic belt (Mascle et al., 1988). The NW-SE-trending basins, such as the Tenere Rift in the Niger and Sudanese rifts escaped the inversion, because these basin axes are sub-parallel to compressional stress direction caused by the collision (Guiraud et al., 1992). As a result, the derivative tensile force in the NE-SW direction promotes the second phase of subsidence of the basins. This phase of subsidence is also possibly strengthened by the change of movement direction of the African plate relative to the Eurasian plate according to geomagnetic data, leading to crustal-scale horizontal extension in the NE-SW direction in association with wrench-related basin inversion along the CASZ.

The third phase of rifting began from the late Cretaceous to Eocene (74-30 Ma) and only occurred in the Tenere Rift in Niger and some parts of the Sudanese rifts system (Guiraud and Maurin, 1992; and Genik, 1993). The rifting of the Sudanese rifts is in a transtensional tectonic regime during this period, and genetically related to the generation of the East Africa rift-related system. It has been widely accepted that the East Africa Rift (EAR) serves as the southern arm of a triple junction, created by upwelling of mantle materials, with the Red Sea and the Gulf of Aden being the other two (Guiraud, 1992; Genik, 1993). The EAR underwent differential extension, thus producing transfer faults or accommodation zones between different segments.

The first structural inversion events happened during the Santonian Epoch. The regional stress field changed dramatically during the epoch when the African plate began to collide with the Eurasian plate, leading to form N-S-orientated compressional tectonic setting in the African interior. As a result, most of the E-W trending basins in west and central Africa are inverted, such as the Bongor Basin in Chad and other pull-apart basins along the CASZ (Benkhelil et al., 1988; and Guiraud et al., 1992).

The second structural inversion event occurred during the late Eocene to Miocene when the Adamawa uplift was active with volcanic rock in the Neogene (Guiraud and Maurin, 1992; and Genik, 1993). In the rift basins of the WCARS, the faults were activated and uplifting and erosion are obvious.

## Geodynamic Characteristics of Passive Rift Basin

### Basin Formation Mechanism of Passive Rift

Basin formation mechanism is related to the geodynamic setting. The basin formation mechanism of the passive rift is the activity of the mantle plume. While the rifting resulted from regional extension stress for the passive rift, there was only passive underplating beneath the crust without the mantle plume between the crust and the mantle (Ziegler and Cloetingh, 2004).

For the formation of the active rift, the mantle plume, hot spot, or mantle upwelling are obvious. The extension stress produced by the thinning of the lithosphere is due to the heat convection and the regional uplift is clear in the initial stage of rifting. While the extension field of the passive rift originated from inner-plate stress, the resulting thinning of the lithosphere and the asthenosphere is upwelled passively. There is no obvious regional uplift and the geological thermal events and volcanics did not happened in the initial stage of passive rifting.

The thickness of the crust of the active rift is thinner than that of the passive rift. According to the gravity study, the thickness of crust for the rift in CWARS is about 35 Km (Browne and Fairhead, 1983; and Browne et al., 1985), which is thicker than the Bohai Bay Basin which is a typical active rift basin in Eastern China (Yang, 1989).

The active rift basin is initialed by mantle upwelling. The events happened in this chronological order for basin formation: origin status, mantle upwelling, initial rift phase, crustal equilibrium, and thermal subsidence. The magnitude of the mantle upwelling is composed by the active upwelling and crustal equilibrium. While the passive rift is created from crustal extension which is not a result of mantle upwelling. The events happened in this chronological order for basin formation: origin status, crustal extension, initial rift phase, crustal equilibrium, and thermal subsidence. The magnitude of mantle upwelling is less than that of the active rift (Figure 3).

### Geodynamic Characteristics and Effect on Petroleum Geology Conditions

The different basin formation mechanisms for active and passive rifts arouse from different geodynamic characteristics in terms of geo-thermal history, subsidence history in the rifting stage, structural style of major faults, and sediments in the sagging stage. These differences directly affected the petroleum geology conditions in the two types of rift (Table 1).

### Geothermal History

The difference of geothermal history for the rift basins is caused by the onset time and extent of mantle upwelling. For the active rift, the mantle upwelling happened before the initial rift phase with high geothermal gradient and volcanic eruptions in the pre-rift stage. The geothermal gradient is gradually increased due to mantle upwelling caused by crustal equilibrium followed by suddenly decreasing in the thermal subsidence stage (Lu and Dai, 1997; Chen et al., 1992; Chen, 1993; Chen and Wang, 1997). For the passive rift, there is no mantle upwells before the initial rift stage, so the geothermal gradient is low in the pre-rift stage without volcanic development and gradually increases in the crustal equilibrium stage by small scale mantle upwellings followed by slowly decreasing in the post-rift stage. In general, the initial geothermal gradient for the active rift is high in the pre-rift phase and increases higher in the syn-rift phase following by suddenly cooling in the post-rift phase. For the passive rift, the initial geothermal gradient is low in the pre-rift phase and gradually increases in the syn-rift phase following by gradually cooling in the post-rift phase.

The different geothermal histories for active and passive rifts heavily affected the onset and duration of the oil window. For the active rift basin, the oil window was early initiation and short duration. Hydrocarbons migrated vertically with short distance and only the reservoirs and traps formed shortly after the hydrocarbon generation had a chance to be charged. For the passive rift basin, the oil window was relatively late initiation and long duration. The post-rift or even younger reservoirs and traps had a chance to be charged due to the hydrocarbons generated later and longer duration of the oil window.

## Subsidence History in the Rifting Stage

For the active rift basin, because the mantle upwelling and large scale crustal equilibrium, the subsidence rate in the rifting period is successive with high rate (Lu and Dai, 1997; Chen et al., 1992; Chen, 1993; Chen and Wang, 1997). The passive rift basin, due to no mantle upwelling and very small scale crustal equilibrium, originated by extensional/transtensional stress field. The subsidence in the rifting stage is intermittent and interrupted by short period of lower rate subsidence.

The subsidence history affected the sedimentation, litho-facies, and source rocks in the rifting phase. For the active rift basin, a long-standing lake system developed in the rifting phase, and the sediments are mainly thick claystone/shale with very thin layers of sands. The source rock developed in the rifting stage is normally massive shale with thick single layers with a poor hydrocarbon expulsion efficiency. For example, the hydrocarbon expulsion efficiency for the Bohai Bay active basin is about 20-25% (Lu and Dai, 1997; Chen et al., 1992; Chen, 1993; Chen and Wang, 1997). For the passive rift basin, a short-lived lacustrine alternated with fluvial developed in the rifting stage, and the sediments are interbeds of sands and shale with comparatively high sand content. The source rock developed in the rifting stage is thin layers of shale but comparatively thick for the total thickness. The hydrocarbon expulsion efficiency is double for the passive rift versus the active rift (Tong et al., 2004; Tong et al., 2006; Dou et al., 2006; and Dou et al., 2013).

## Structural Style of Major Faults

For the active rift basin, the major boundary faults always detached along the easy-slip-zones, showing listric style due to the easy-slip-zones along sediments beddings developed by the crust bending in the rifting stage (Lu and Dai, 1997; Chen et al., 1992; Chen, 1993; Chen and Wang, 1997). So the main trap types were rollover, anticlines, faulted anticlines, and faulted blocks in the active rift basin. For the passive rift basin, there are no obvious easy-slip-zones due to no bending of the crust and the major boundary faults are high angle without significant deep detachment. The main trap types are antithetic/synthetic faulted blocks, faulted horsts, and rollover anticlines are rarely observed (Figure 4). For example, more than 90% of hydrocarbons are entrapped in antithetic faulted blocks in Sudanese Melut and Muglad passive rift basins (Tong et al., 2004; Tong et al., 2006; Dou et al., 2006; and Dou et al., 2013).

## Sediments in Sagging Stage

In post-rift stage (or sagging stage), the thermal subsidence and sagging is caused by the cooling and contraction of the mantle. The scale of the thermal subsidence is positively correlated to mantle contraction.

For the active rift basin, the sagging stage is long, large scale, and sandstone and claystones are deposited. Normally, the thickness of sediments in the sagging stage is about the same as in the rifting stage (Lu and Dai, 1997; Chen et al., 1992; and Chen, 1993). For the passive rift basin, the sagging stage is short, massive sandstone deposited, and the thickness of sediments in the sagging stage is less than in the rifting stage.

## Characteristics of Petroleum Geology for the Passive Rift Basin

Based on the geodynamic characteristics of the passive rift basin and geological conditions analysis for the Muglad and Melut rift basins in CARS, the features of petroleum geology for the passive rift basin are concluded (Table 1):

### Source Rock

For the passive rift basin, only one set of source rocks developed in the syn-rift stage. The single layers of source rock shale is thin but the total thickness of source rock shale is enough for hydrocarbon generation. For example, the thickness of single shale is 3-10 meters in the early Cretaceous syn-rift sediments with a total thickness of 300-800 meters in the Sudanese Muglad rift basin (Tong et al., 2004; Tong et al., 2006; Dou et al., 2006; and Dou et al., 2013). The hydrocarbon expulsion efficiency is high because the source rock developed in the sediments of interbeds of sands and shale. Because of the comparatively lower geothermal gradient in the rifting stage, the hydrocarbons generated later and the duration of the oil window is longer than the active rift.

### Reservoir

The major reservoir developed in the passive rift basin is thick massive sands formed in the sagging stage. The thin sand formed in the syn-rift stage is the secondary reservoir. The reservoir developed in the sagging stage has good property with porosity more than 25% and distributed widely (Tong et al., 2004 and Tong, et al., 2006). The reservoir property of the thin sands formed in the syn-rift stage is poor with porosity less than 20% due to deep burial depths (Tong et al., 2004; Tong et al., 2006; Dou et al., 2006; and Dou et al., 2013) and controlled by the sedimentary facies.

### Cap Rock

The development of the regional cap rock of the passive rift basin depended on the second or the third rifting-sagging cycle developed in the post rift stage. Because the massive sand developed in the sagging stage for the passive rift, there is no regional cap developed in the sediments of the passive sagging cycle. For the passive rifts in CWARS developed the second or the third rifting-sagging cycles in the post rift stage and the regional cap can be the shale deposited in the second rifting stage or the third rifting stage.

For example, the regional cap rock of the Muglad Basin in Sudan is the Aradeiba Shale developed in the late Cretaceous second rifting stage. 70% of the reserves found are capped by this regional distributed shale (Tong et al., 2004; Tong et al., 2006; Dou et al., 2006; and Dou et al., 2013). The massive high porosity sandstone developed in the sagging stage of the passive rift is the major reservoir, capped by the above mentioned regional shale. For the Melut Basin in Southern Sudan, due to the second rifting in the Lower Cretaceous, cap rock is very weak and no regional shale overlays the massive sandstone formed in the sagging stage of the early passive rift. However, the third rifting sagging cycle in the Tertiary was strong in the Melut Basin, and the regional Adar Shale formed in the Paleocene during the third rifting stage is an effective cap in the basin. Currently, more than 90% of the reserves are found in the sand reservoir directly overlaid by the Adar Shale (Tong et al., 2006).

### Major Play Types

Because the boundary and major faults in the passive rift is high angle without significant deep detachment, the major trap type developed in the passive rift basin is the faulted block. Most of the faults are activated during the second or the third rifting-sagging cycles. The traps in the passive rift basins are related to faults. The major play type is the antithetic faulted block with reservoirs formed during the sagging stage of the passive rift laterally sealed by shale formed during the rifting stage of the second or the third rifting-sagging cycles. Anticlines and rollovers are the major trap types in the active rift basin are not common to see in the passive rift basin (Tong et al., 2004 and Tong et al., 2006).

### Favorable Hydrocarbon Accumulation Zones

Half grabens and hosts are very common in the passive rift basin. Grabens distributed as en echelon patterns are related to strike-slip stress field during the early Cretaceous passive rifting stage in the Muglad and Melut rift basins of CWARS. The flank of half graben is favorable for hydrocarbon accumulation which is near the active source kitchen. The structural transitional zones developed between the half graben with faulted blocks and good reservoir cap rock assemblages developed. For example, most of the oil fields found in the Melut Basin are in the eastern flank of the north sub-basin (Tong et al., 2006 and Dou et al., 2006).

## Conclusions

Basins in the Central-Western Africa Rift System are passive rift basins formed as a result of strike-slip activity on the Central African Shear Zone during the early Cretaceous. Three rifting-sagging stages and two structural inversion events developed in the Central-Western Africa Rift System since early Cretaceous, which contributed very complicate geological condition for the petroleum system. The passive rift basin is formed by crustal extension induced by non-mantle upwelling. The scale of mantle upwelling is smaller than the active rift, which resulted in the significant difference between passive and active rifts in terms of thermal history, subsidence history in rifting period, structural style of major faults, and sediments in the sagging stage. These difference directly affected the petroleum geology conditions in the passive rift. Five unique geological features are concluded: source rock, reservoir, controlling factors for regional cap rock, major play types, and favorable accumulation zones in the passive rift basin.

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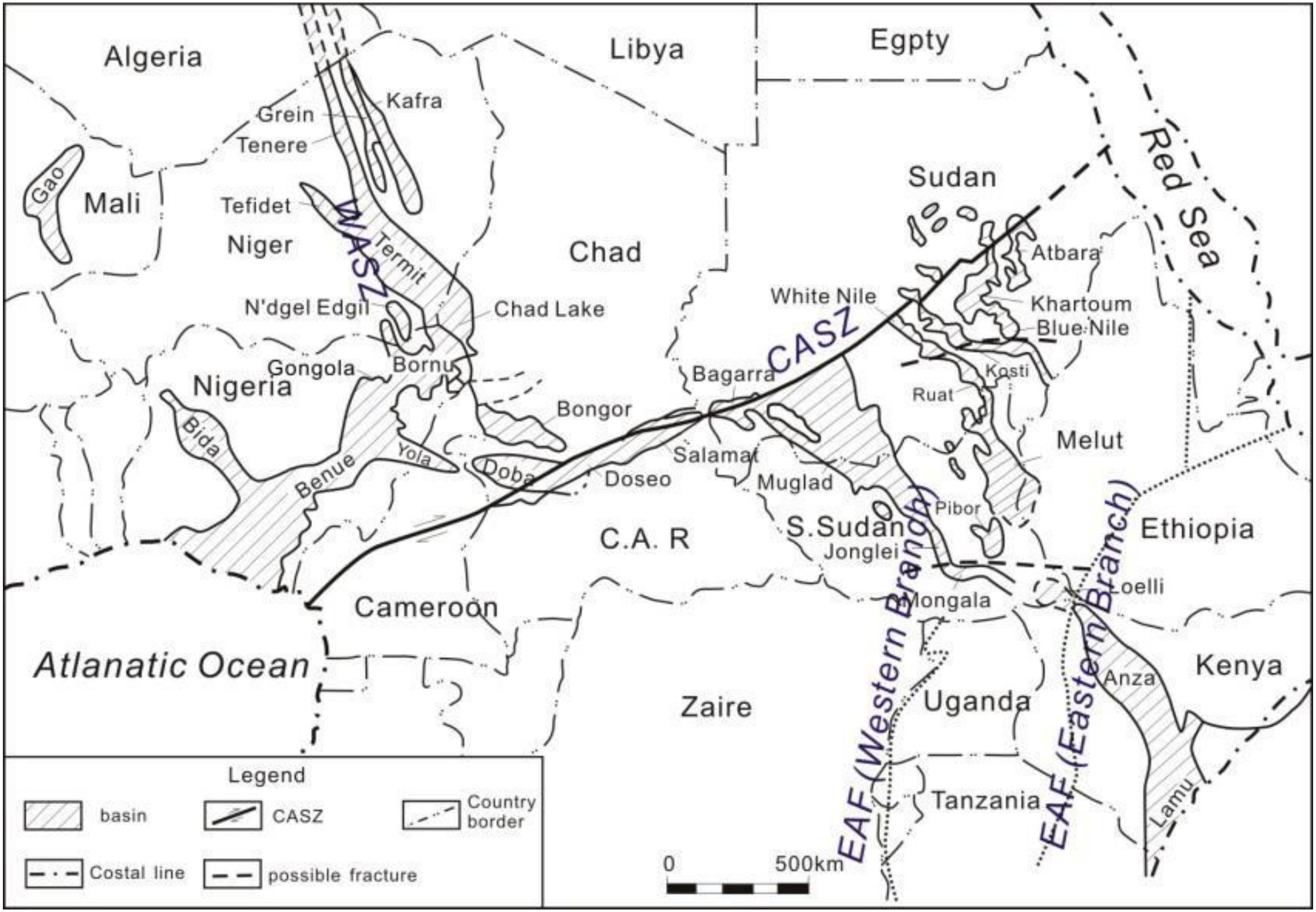


Figure 1. Tectonic settings in the Central-Western African Rift System (Modified from Genik, 1993).

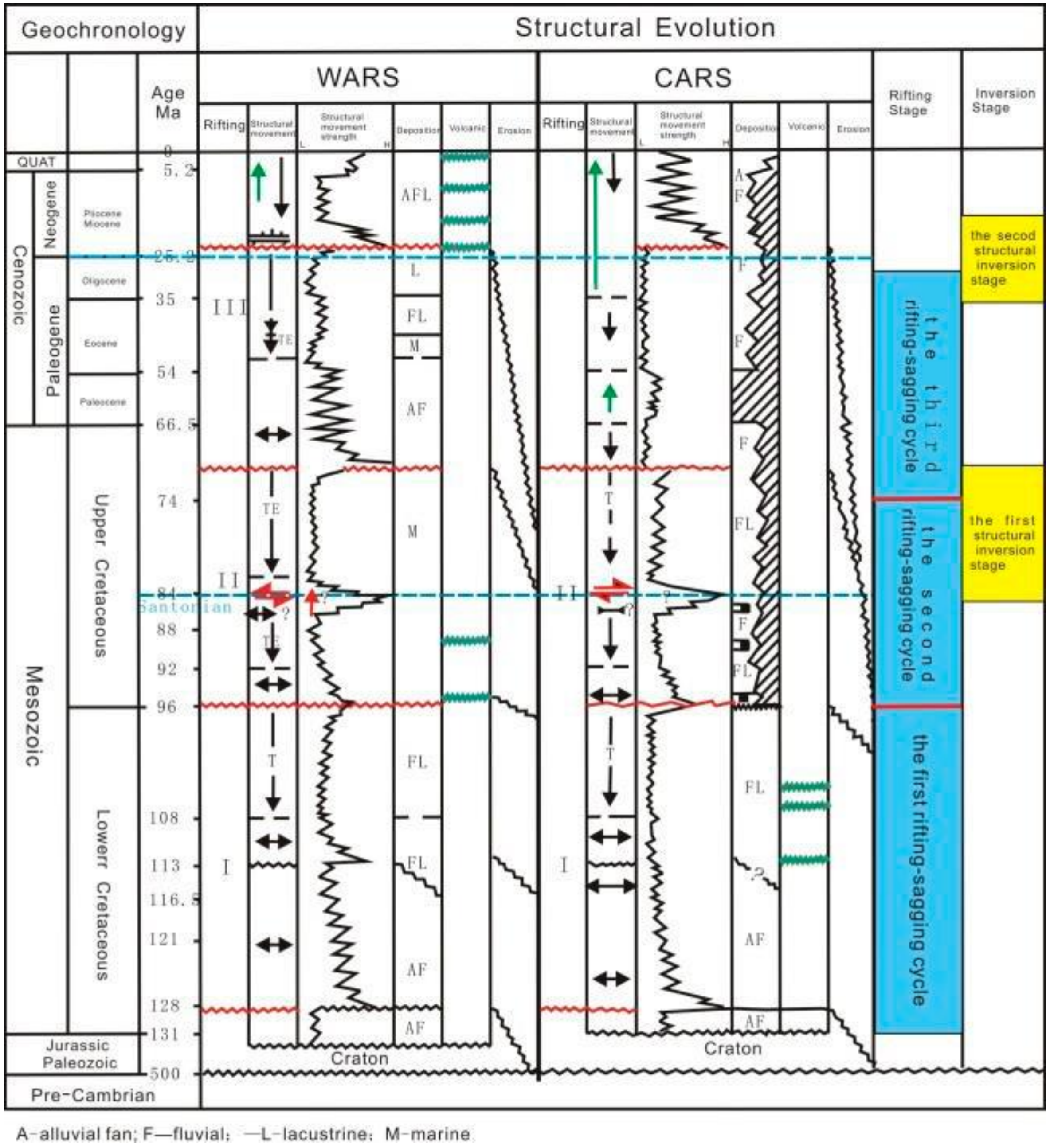


Figure 2. Structural Evolution History for CWARS.

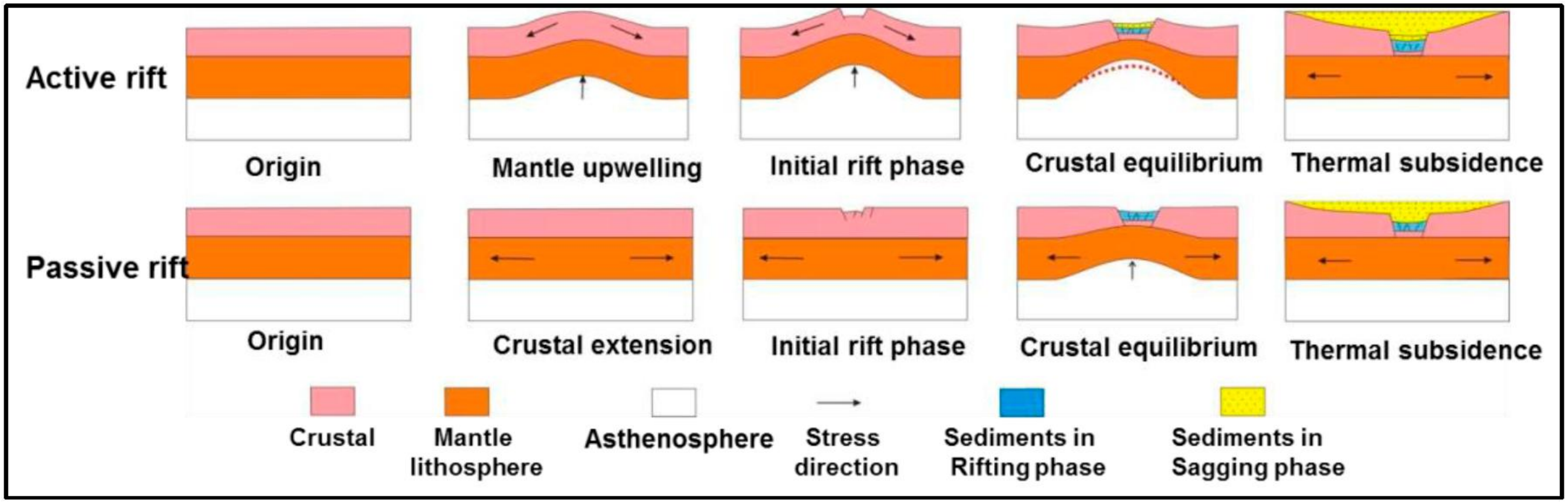


Figure 3. Sketch maps showing the different basin forming mechanics for active and passive rifts.

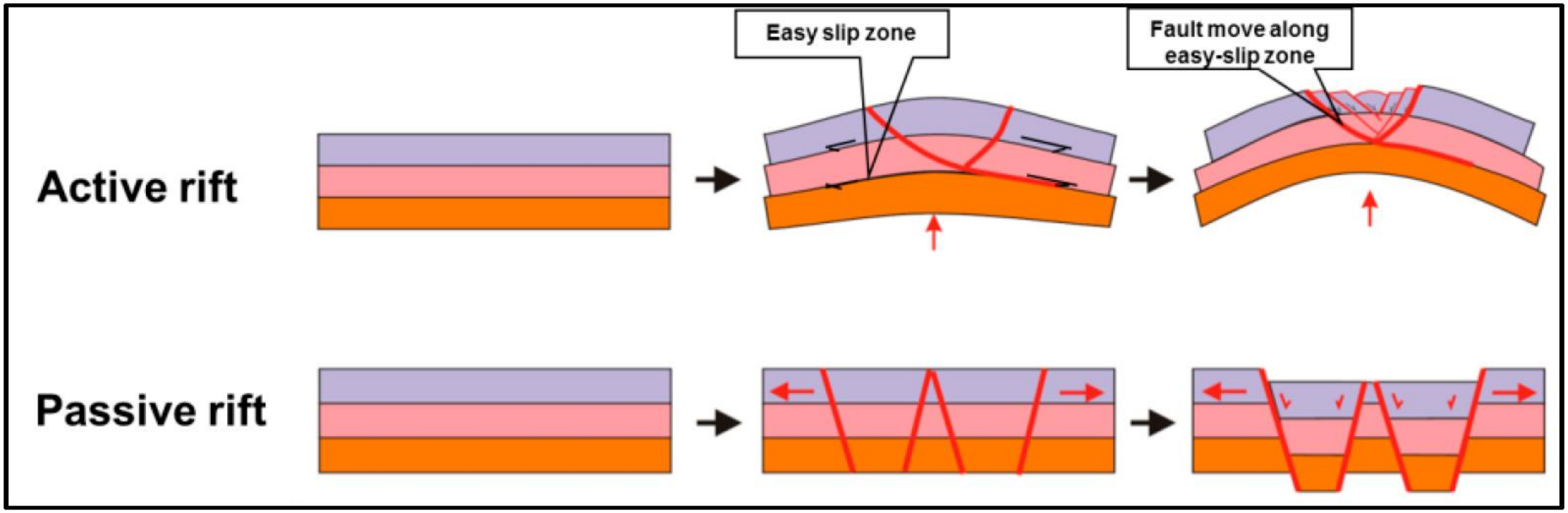
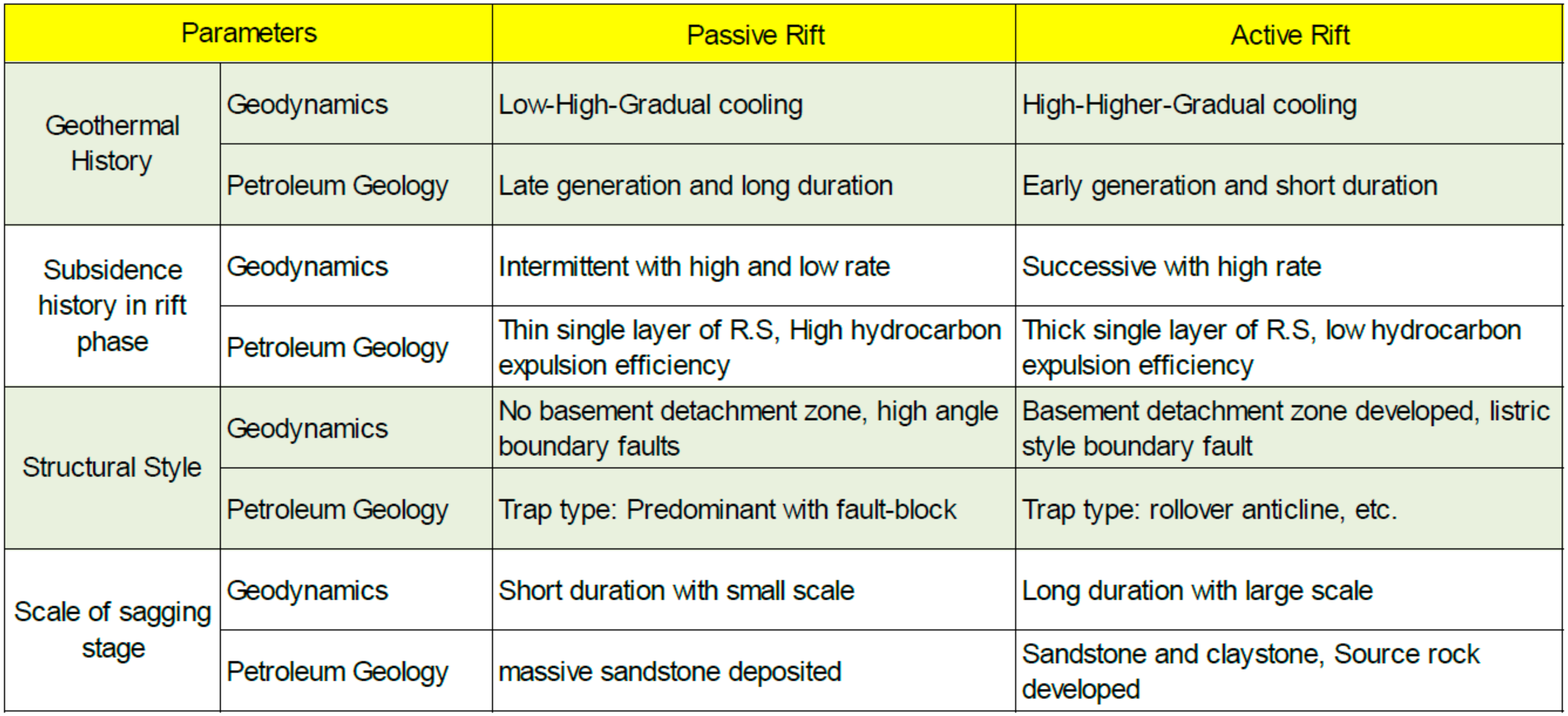


Figure 4. Structural style of boundary/major faults in active and passive rifts.



| Parameters | | Passive Rift | Active Rift |
|---|---|---|---|
| Geothermal History | Geodynamics | Low-High-Gradual cooling | High-Higher-Gradual cooling |
| | Petroleum Geology | Late generation and long duration | Early generation and short duration |
| Subsidence history in rift phase | Geodynamics | Intermittent with high and low rate | Successive with high rate |
| | Petroleum Geology | Thin single layer of R.S, High hydrocarbon expulsion efficiency | Thick single layer of R.S, low hydrocarbon expulsion efficiency |
| Structural Style | Geodynamics | No basement detachment zone, high angle boundary faults | Basement detachment zone developed, listric style boundary fault |
| | Petroleum Geology | Trap type: Predominant with fault-block | Trap type: rollover anticline, etc. |
| Scale of sagging stage | Geodynamics | Short duration with small scale | Long duration with large scale |
| | Petroleum Geology | massive sandstone deposited | Sandstone and claystone, Source rock developed |

Table 1. Summary of geodynamics and petroleum geology for active and passive rifts.