

## **Lateral Seal – A Major Exploration Risk in the Faulted Traps of the Cretaceous Petroleum System - Central Muglad Basin, Sudan**

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### Introduction

Sudan is the largest country in Africa with an area of 2.5 million Km<sup>2</sup> and common borders to eight countries (Fig. 1). Oil exploration began in the late fifties but has been focused in the offshore areas of the Red Sea. In 1974 Chevron commenced exploration in the interior rift basins including the Muglad Basin. To date significant hydrocarbon reserves have been discovered and the country currently produces about 280,000 BOPD.

Muglad Basin is a northwest-southeast trending rift Basin in Sudan. Blocks 1, 2 and 4 lie in the Central part of this Basin (Fig. 2). Greater Nile Petroleum Operating Company operates these Blocks for a consortium of China National Petroleum Company (CNPC) 40%, Petronas Carigali Overseas Bhd (PCOSB) 30%, ONGC Videsh Limited (OVL) 25%, and Sudanese Petroleum Corporation (SUDAPET) 5%.

### Petroleum Geology:

Muglad Basin is covered by thick sequence of non-marine sediments, which vary in age from Cretaceous to Tertiary. A generalized stratigraphic column is shown in Fig. 3 reflecting the rifting and sagging episodes in relation with the basin filling and sedimentation.

Exploration results have indicated proven hydrocarbon system in both Tertiary and Cretaceous sections

The main hydrocarbon play is the Cretaceous petroleum system. This petroleum system has a perfect assemblage of source, reservoir and top seal. The source is the Lower Cretaceous lacustrine shale of “Abu Gabra” Formation. The reservoir is the braided stream sandstones of “Bentiu” Formation, and the top seal is the fluvial shale of Aradeiba Formation. More than 70% of traps are tilted fault blocks with high dependency on the lateral seal across the bounding fault. Therefore, the above perfect marriage of source, reservoir, and top seal is counter-acted by a higher risk in the lateral seal.

Bentiu Formation comprises a massive thick sand (over 1500 m in some parts) of good quality reservoir with localized interbeds of 20-60 m thick shale.

### Lateral Seal:

Lateral seal depends on the thickness and the lithology of the Aradeiba shale and the amount of fault throw (Fig. 4 is schematic illustration of this relationship).

The Aradeiba Formation is highly variable in thickness and in sand/shale ratio. Thickest Aradeiba Formation penetration to date is in excess of 1000 m in the central part of the basin decreasing to less than 20 m along the basin edges. Most of the perfect lateral seals are due to direct juxtaposition of Bentiu sandstone reservoirs against Aradeiba shale. Examples of this situation are illustrated in Figs. 5, 6, 7 and 8.

In some cases clay smear and shale gouge ratio play an important role in lateral seal integrity. The shale gouge ratio seems to depend on shale thickness and amount of displacement along the fault plane. Shale gouge will of course also depend on clay mineralogy, but this aspect has not been fully investigated.



Figure 1. Sudan - Heart of Africa

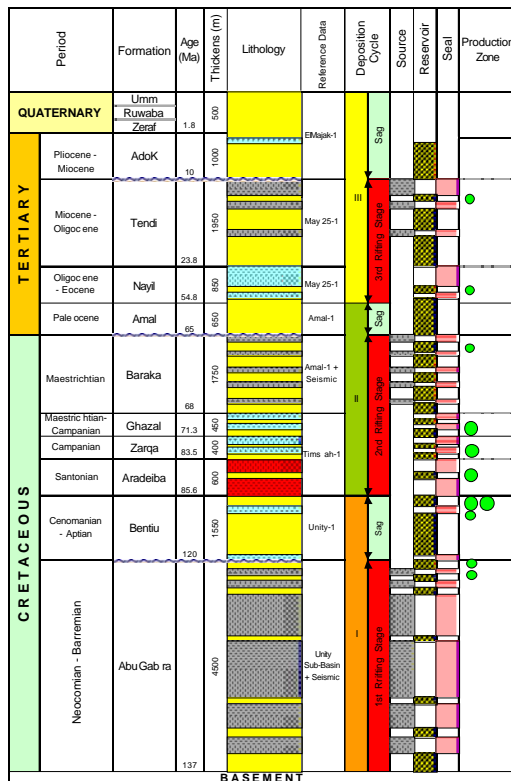
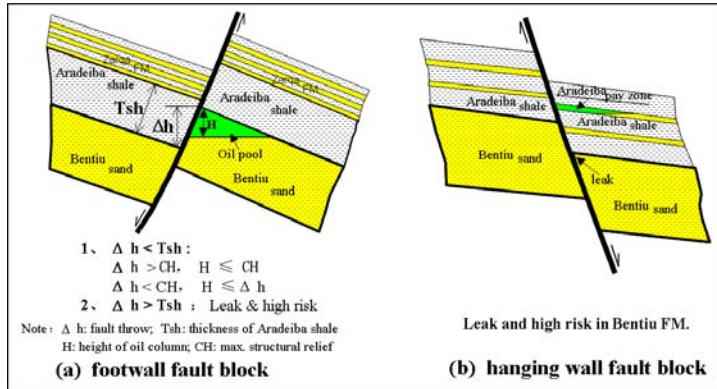
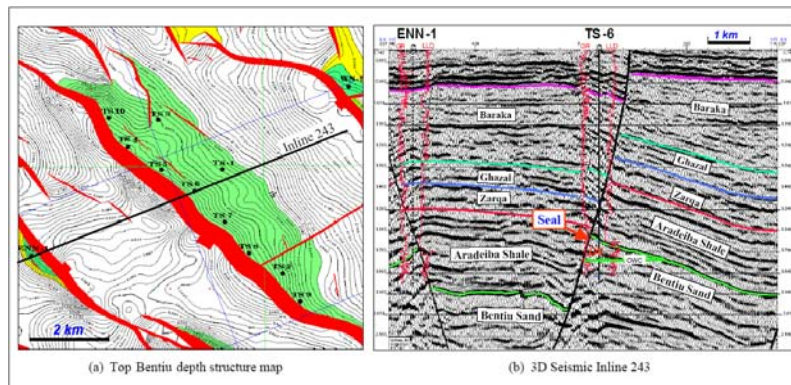


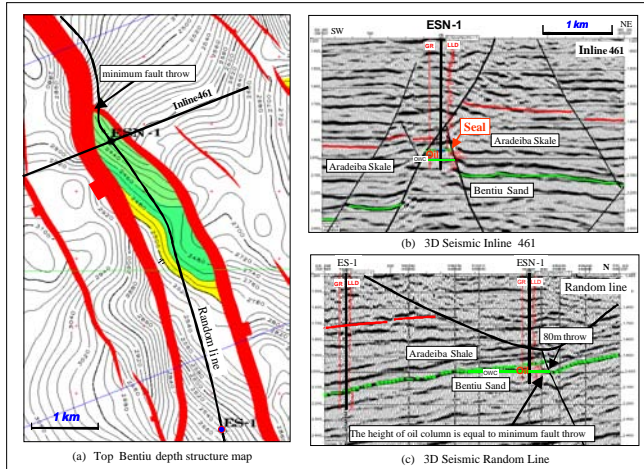
Figure 3. General Stratigraphic Column - Muglad Basin Sudan, showing three geological cycles



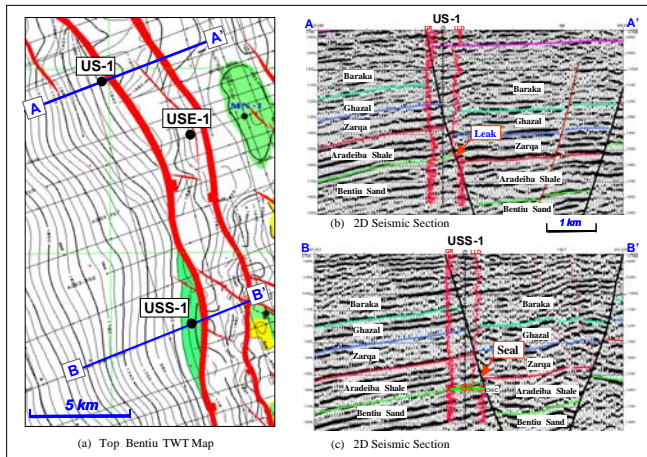
**Figure 4.** Schematic illustration of lateral seal dependence on the Aradeiba thickness, lithology, and the amount of fault throw (a) Footwall block; fault throw is less than the thickness of Aradeiba shale, massive Aradeiba shale provides the top and lateral seal for Bentiu reservoir. Oil column increases with increasing fault throw. When fault throw is larger than the thickness of Aradeiba shale, Bentiu objective is juxtaposed against Zarqa sand resulting in lateral seal failure. (b) Hanging wall fault block; Aradeiba intra-fomational shale and fault smear provide the top and lateral seal for Aradeiba reservoirs; for Bentiu sand, the objective is juxtaposed against the Bentiu massive sand across fault causing lateral seal failure. However, fault smear can provide weak lateral seal to form a limited oil column.



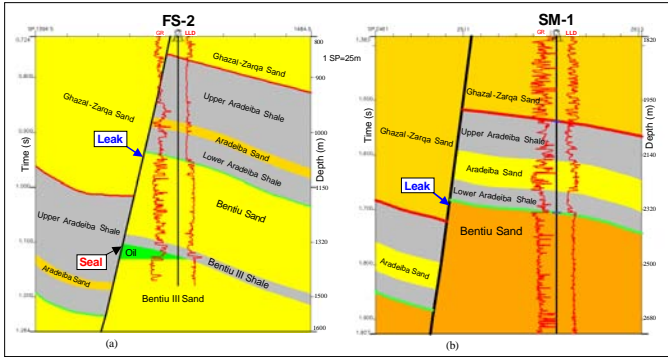
**Figure 5.** An excellent fault-sealing example. (a) The top Bentiu depth map shows a field charged to structural spill point with 140m oil column. (b) 3D seismic section illustrates that the thick massive Aradeiba shale (480 M) provided good top and lateral seal for Bentiu reservoir. The fault throw (430 M) is less than the thickness of Aradeiba shale.



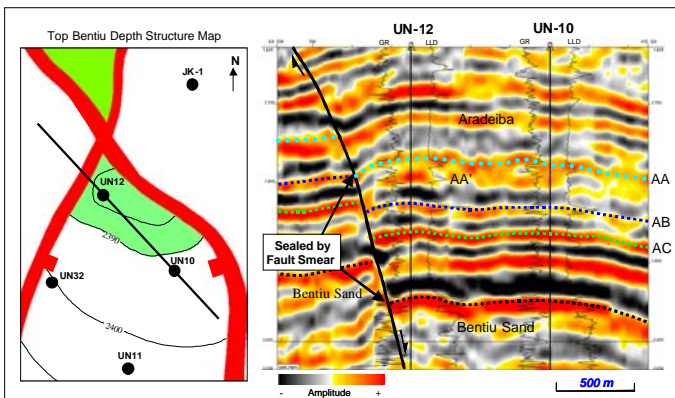
**Figure 6.** Another excellent fault-seal example. (a) Shows that the oil column is controlled by the fault throw at the northern part. (b) Illustrates that the thick (approx. 400 m) massive Aradeiba shale provided good top and lateral seal for Bentiu reservoir. (c) 3D random section illustrates that the oil column is nearly equal to minimum fault throw (80 m) at which point we have sand against sand juxtaposition



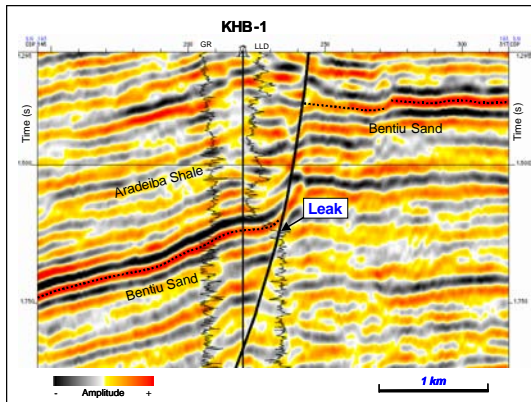
**Figure 7.** (a) Top Bentiu TWT map shows a tilted footwall fault block with US-1 water bearing well at Bentiu and USS-1 an oil discovery well. The throw of the bounding fault varies from 400 m in the north (across US-1) to 300 m in the south (across USS-1). (b) The section illustrates the fault throw across US-1 well is larger than the thickness of Aradeiba shale (360m) juxtaposing Bentiu reservoir against Zarqa sands resulting in lateral leakage, hence Bentiu sand is water-bearing. (c) The section illustrates that the fault throw is smaller than thickness of Aradeiba shale to provide good lateral seal, resulting in USS-1 discovery (drilled after US-1).



**Figure 8.** (a) Cross-section showing water bearing zones in Upper part of Bentiu reservoir due to lateral seal failure and pay zone in lower part (Bentiu III sand). Bentiu III sand is juxtaposed against Aradeiba shale resulting in good lateral seal. Top seal is provided by intra Bentiu shale. (b) Cross-section with dry hole, where there is lack of lateral seal for Bentiu reservoir. These two cross-sections illustrate lateral seal risk associated with footwall closures. Optimum fault throw in comparison with Aradeiba shale section is critical for trap integrity.



**Figure 9.** This is an example of oil discovery in a hanging wall fault block. AA, AB & AC sands are production zones with more than 50m oil columns. AB & AC sands juxtaposed against Aradeiba intra-fomational shale across the fault to provide good lateral seal; AA & Bentiu sand juxtaposed against AB sand and Bentiu massive sand respectively, but fault smear provided good lateral seal, resulting in a small oil column in Bentiu reservoir.



**Figure 10.** 3D Seismic Section, showing a dry hole in the hanging wall fault block. This illustrates why the hanging wall closure bounded by fault has high lateral seal risk. Bentiu reservoir objective is juxtaposed against Bentiu massive sand in the upthrown block across the fault.