

# Geological Conditions and Petroleum Exploration Potential of the Albertine Graben of Uganda

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**Abstract** The Albertine Graben in western Uganda is a Mesozoic-Cenozoic rift basin with petroleum exploration potential. A fundamental evaluation of petroleum potential of the graben is given based on field research, data processing of gravity and magnetism, analysis of graben structure, geochemistry, reservoir and composition research. The basin has a double-layered framework and a large thickness of sediments. Gravity highs shown in a residual anomaly map might indicate central uplift zones. There exist at least two sets of mature or low-maturity source rocks corresponding to a certain source rock in the Cretaceous or Paleogene and Neogene strata. The graben has basement rock with potential reservoirs and Tertiary sandstone reservoirs and thus has petroleum exploration potential.

**Key words:** Albertine Graben, geophysics, geology, oil, gas, exploration potential, Uganda

## 1 Introduction

The Albertine Graben is a Mesozoic-Cenozoic rift basin developed on the inner Africa Craton. The thick sedimentary pile shows some potential for oil and gas exploration (Morley et al., 1990; Nelson et al., 1992; Patton et al., 1995). E. J. Wayland first reported that oil and gas shows existed in 52 places within and around Lake Albert (Wayland, 1934). At present, five oil and gas shows are still active in the Albertine Graben, in Paraa, Kibiro and Kibuku, respectively (Fig. 1). The existence of these oil seepages indicates that not only good source rocks exist, but also some source rocks have experienced the process of oil generation, expulsion and migration.

In order to accurately evaluate the petroleum exploration potential of three blocks in the Albertine Graben (exploration areas EA 1/2/3) (Fig. 1), the China National Oil and Gas Exploration and Development Corporation (CNODC) assigned a research group to visit Uganda in 2001. The group made a field trip in order to assess the outcrop geology and oil seepages in EA 1/2/3 and 16 samples were collected, including argillite, oil seepages, oil sands, mudstones, sandstones and quartz vein samples. These samples were analyzed by the Key Laboratory of

Petroleum Geochemistry and Key Laboratory of Oil & Gas Reservoir of China National Petroleum Corporation (CNPC). Meanwhile, geophysical data were reprocessed and reinterpreted, including gravity, magnetic and aeromagnetic data provided by the Petroleum Exploration and Production Department of Uganda in Uganda. In order to assess the petroleum potential of EA 1 and EA 2, the Albertine Graben was compared with the geologically similar Yi-Shu Graben of the Songliao Basin in northeastern China based on the continental facies petroleum geology theory (Yang, 1986).

## 2 Geological Background

The Albertine Graben, covering an exploration area of 25,000 km<sup>2</sup>, is the principal potential petroleum prospective region in Uganda, with a length of 570 km and an average width of 45 km (Fig. 1). As a NE-SW trending narrow rifting trough, it is made up of a series of discontinuous faulted segments which form the northernmost part of the Western Branch of the roughly N-S striking East African Rift System (EARS). Lake Albert covers the central part of the graben that is limited by the high and steep Congo Mountain on its western boundary.

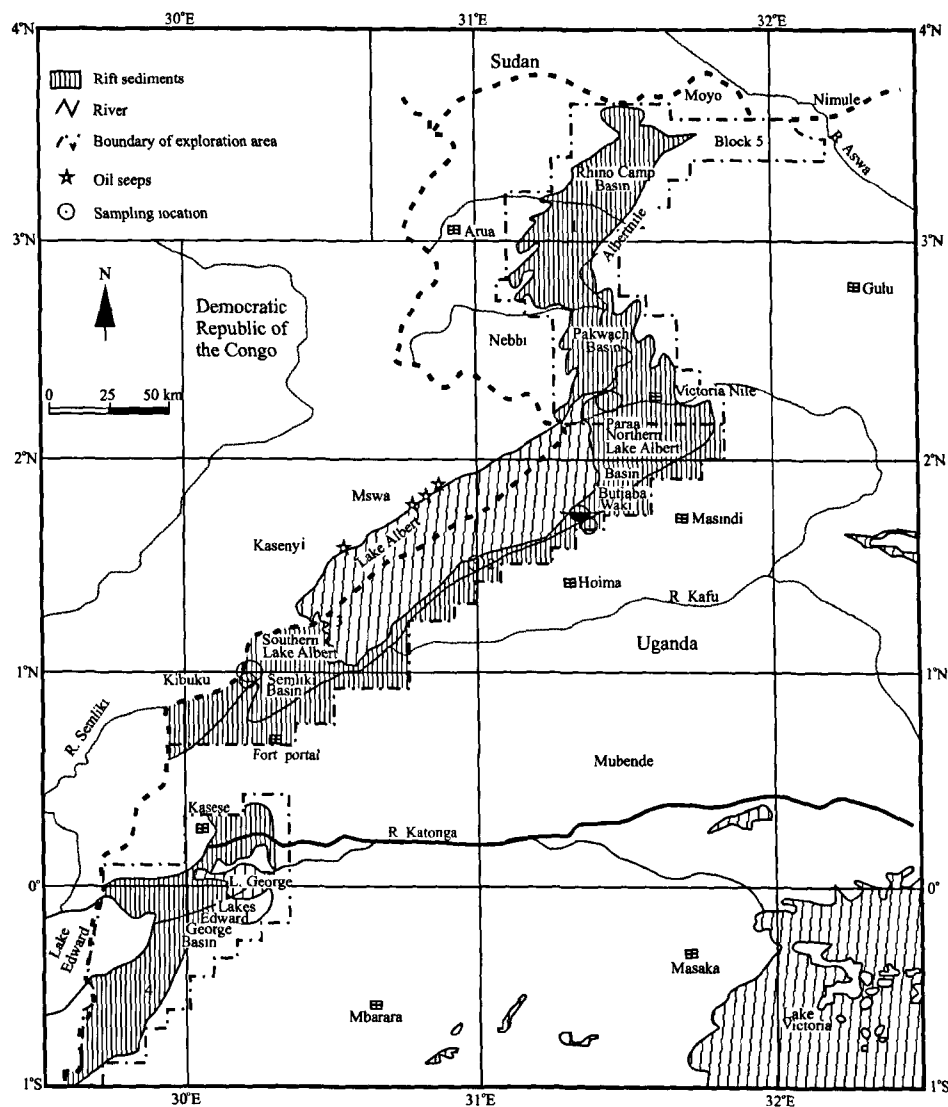


Fig. 1. Oil seepage distribution and sample location in the Albertine Graben, Uganda.

The basement is composed predominantly of metamorphic rocks and mafic intrusive rocks. During the Carboniferous-Permian period, this region underwent an intra-cratonic evolution (Gan et al., 1978). Metamorphism in the Triassic affected the underlying formations because of strong magmatic activity, and so rendered the pre-Mesozoic formations in the Albertine Graben inopportune for hydrocarbon exploration.

The rifting processes within the EARS controlled the formation and evolution of the graben. Since the Middle Jurassic to Middle Cretaceous, faulting of unknown age occurred. During the Early Cretaceous, the sediment thickness of the rift trough was over 5000 m, with formations formed from a red lacustrine facies (Ebinger, 1989). Fish and hexapod fossils can be found in the Jurassic-Cretaceous. There are 350-m thick Jurassic and Cretaceous strata composed of variegated siltstone and fine sandstone interlaid with a 70-m thick bituminous shale

outcropping about 600 km to the southwest of the Graben (Gan et al., 1978). Upper Jurassic to Middle Cretaceous fluviolacustrine sediments also exist in Turkana, northwest Kenya. In the Muglad and White Nile basins of Sudan, the Cretaceous strata are the principal sedimentary systems and hydrocarbon-bearing formations.

In 1938, Jurassic bituminous shale and fluviolacustrine clastics of about 200m thick were also encountered in well Butiaba Waki-1 east of the Albert Lake (Upcott et al., 1996). Thus, it can be concluded that the residual Jurassic and Cretaceous fluviolacustrine sediments are preserved in the deep part of the Albertine Graben.

The second rifting stage began in the Late Eocene. The rifting during this stage developed mainly in some rift basins of Sudan and the Anza Basin of Kenya and surrounding areas where the Western Branch of the

EARS is located, including the Albertine Graben.

The third stage of rifting mainly occurred from the Neogene to Quaternary. A NW-SE-strike trans-extensional basin was formed by the accelerated subduction of the Africa-Arabian Plate toward the Eurasian Plate. The Neogene was the main developmental period of the Albertine Graben.

In short, the Tertiary formations in this area are flesh-colored river, lake and floodplain sediments, with many sandstone lenses. In EA 3 the total thickness is over 500 m.

### 3 Geological Framework and Structural Style

The analysis of basin structural styles in the Albertine Graben is based on the processing and interpretation of the gravity and magnetic data. The Albertine Graben trends NE through most of its length. There are five asymmetric along-axis fault segments. The fault segments are 50–80

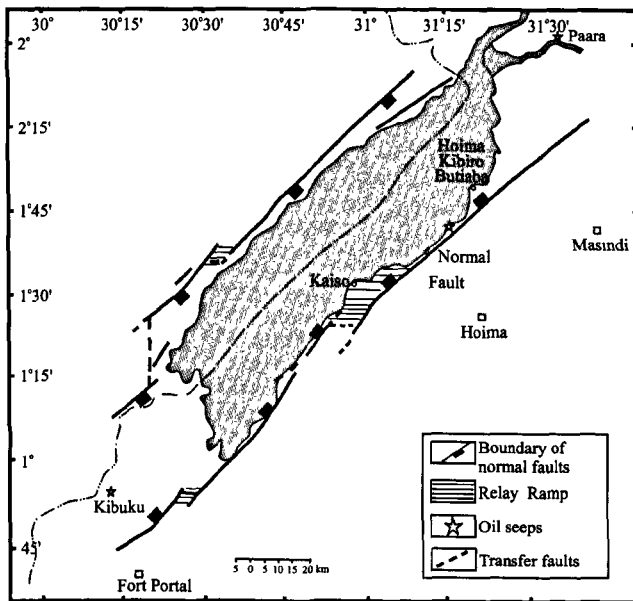


Fig. 3. Sketch structural map of the Albertine Graben.

km long and about 40 km wide, which are consistent with the tight Bouguer lows. The structural uplifts and accommodation zones link the segments (Upcott et al., 1996). The amplitude of the gravity anomaly is from  $-60$  to  $-80$  mGal, which reflects the sedimentary thickness of 5,000–6,000 m.

### 3.1 Basin framework

In EA 1/2/3, there are three basins shown on the bouguer gravity anomaly map, i.e., Southern Lake Albert-Semliki, Northern Lake Albert and Pakwach Basin northward (Figs. 1 and 2).

The Southern Lake Albert-Semliki Basin is mainly located in EA 3; its principal strike is NE, width 40 km, length 80 km, and area 3,000 km<sup>2</sup>. The maximum amplitude of the Bouguer anomaly is  $-65$  mGal. The maximum sedimentary thickness is probably over 5,000 m. This basin is an asymmetrical half-graben, with the border fault at its northwest side.

The Northern Lake Albert Basin lies in the northern part of Lake Albert, EA 2; it strikes NE, width and length 35 km and 50 km, respectively, area 2,000 km<sup>2</sup>. The sedimentary center is located at the central part of Lake Albert. The amplitude of the Bouguer anomaly is  $-70$  mGal. The maximum sedimentary thickness is about 5,000 m.

The Pakwach Basin is located at the northernmost research area. It consists of two secondary depressions, trending nearly NS and covering an area of 1,000 km<sup>2</sup>. The southern one is approximately 300 km<sup>2</sup>, exhibiting a triangular morphology with the typical features of a rift basin. The maximum sedimentary thickness is over 3,500 m.

### 3.2 Boundary fault and accommodation zone

Each of the rift basins in the Albertine Graben is bounded by steep border faults and broad, uplifted flanks, which correspond to the gravity and aeromagnetic anomalous steep belts. The anomalous steep belts are not consistent with the current basin boundaries. This perhaps indicates the reactivation of the border faults. Sets of en echelon border-fault segments (Fig. 3) are linked by small oblique-slip transfer faults and relay ramps, which show that the boundaries between basins are discontinuous.

Structural accommodation zones link main basins and depressions. The latter might have been formed during a regional structural inversion in the Late Cretaceous, which basically corresponds to gravity highs and separates to various extents the early rift segments.

Upcott et al. (1996) pointed out that there are almost E-W-trending accommodation faults separating the main basins. The detailed analysis of gravity data, such as general horizontal gradients and the analyses of the images of the fault structure, explicitly reflects the accommodation faults (Fig. 4). There exist also some large-scale faults trending nearly ENE, which separate the graben into isolated blocks, e.g., to the north of Mount Rwenzori, and the central and northern parts of Lake Albert in EA 3. The analysis based on the limited seismic data of EA 3 supports the presence of a nearly EW fault which was not active later.

### 3.3 Local gravity high

There are several gravity highs in EA 1/2/3 as shown in the residual gravity anomaly map (Fig. 5). One local gravity high exists in the northern part of EA 2. The local gravity high (G1) present mainly in the Congo is long-axis-like with an anomaly amplitude of 5 mGal and an area of 400 km<sup>2</sup>. This gravity high is controlled by faults on both northern and southern sides; to the south is the depocenter of the Northern Lake Albert Basin.

The local gravity anomaly zone trending NE in the southeast slip of the asymmetrical depression of Lake Albert can be inferred as part of the central uplift zone of the Lake Albert Basin. The uplift is located on the southeastern slope of Lake Albert. Three local gravity highs in the central uplift zone are controlled by faults' pull stress on both sides of the central uplift zone to form fault uplift on the slope, as indicated on the residual gravity anomaly map (Fig. 5). The local gravity anomaly ranges usually from 4 to 10 mGal with an area of about 160, 240, and 280 km<sup>2</sup>, respectively.

After the analysis of the basin structure and distribution of the fault system, it is inferred that the several anomalies in the basin are controlled by the nearly E-W trending faults.

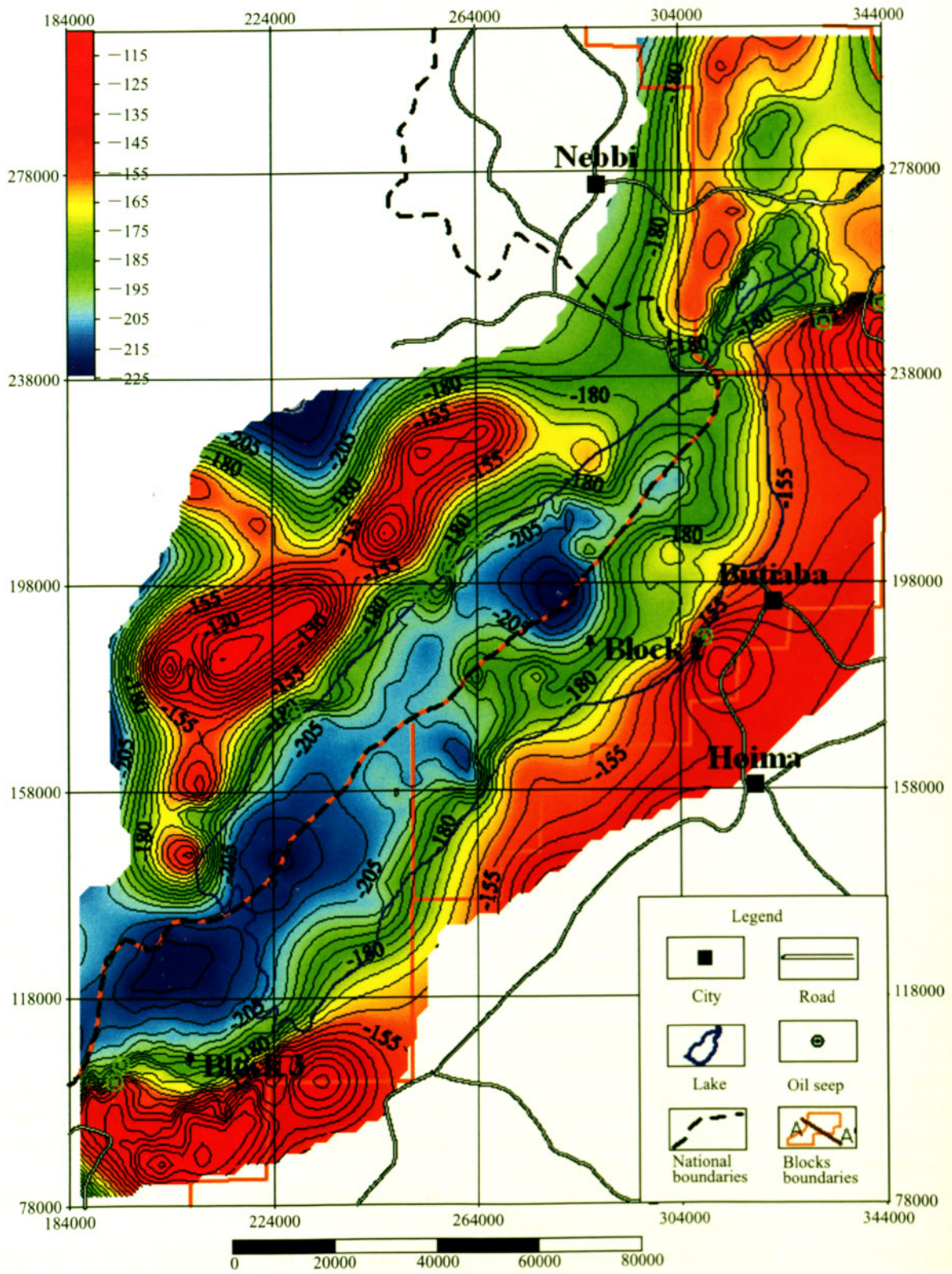


Fig. 2. Bouguer gravity anomaly map of Uganda EA 1/2/3.

**Table 1** Organic matter abundance and composition of chloroform extract of oil seepages and bituminous sandstones

Sample No.	Formation	Description	Location	Extract weight (%)	Saturates (%)	Aromatics (%)	Polars (%)	Asphaltenes (%)	Saturates/Aromatics	Polars/Asphaltenes
01-1228		Oil seepage	Paraa		23.65	25.96	32.17	18.22	0.91	
01-1229		Oil seepage	Kibiro		18.55	38.6	26.86	15.98	0.48	1.68
01-1230	Kisegi	Oilsand	Kibuku	0.0260	36.32	25.94	29.67	8.07	1.40	3.68
01-1237	Kisegi	Bituminous	Kibuku	0.0052	14.86	6.07	46.74	32.33	4	1.45
01-1238	Kaiso	Sandstone	Tonya	0.0055	13.52	4.48	56.48	25.52	1.98	2.21

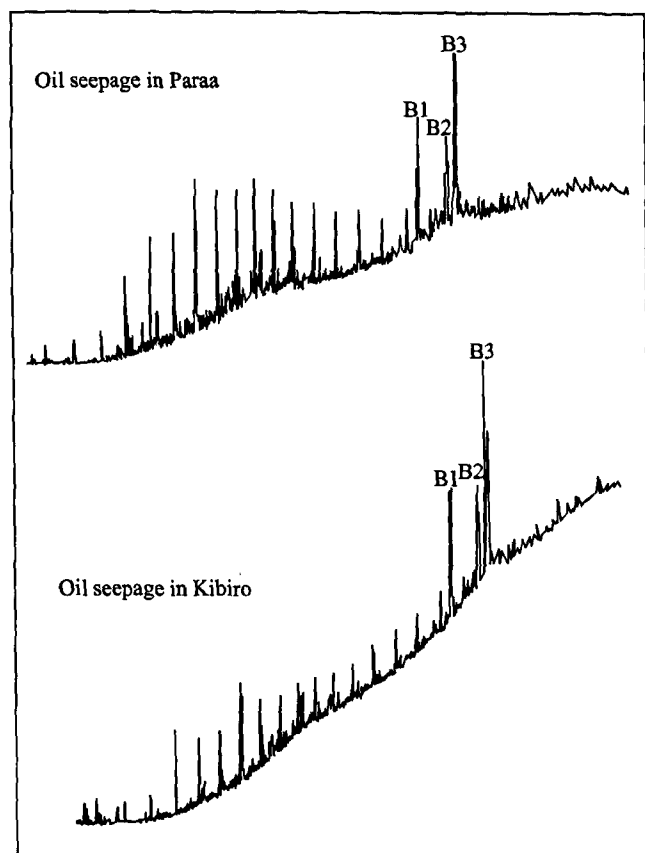


Fig. 7. Botryococanes detected in M/Z85 mass chromatogram. B1: C<sub>33</sub>-Botryococanes; B2: C<sub>34</sub>-Botryococanes; B3: C<sub>34</sub>-Botryococanes.

### 3.4 Magmatic activities

The igneous activity prevailed in the southern part and to the south of EA 3, and usually occurred along the boundary faults and accommodation fault zones. The Cenozoic magmatic activity of this area began approximately around 12 Ma. The activity became mild northwards, and gradually got younger (Morley, 1989). The banded aeromagnetic anomalies on the east bank of Lake Albert extend northwards, which implies that magmatic activity along the boundary is relatively obvious. The geomagnetic data also show that there are three lumpy anomalies, located on both sides of the boundary fault, in the east bank of EA 2, which is also proven by aeromagnetic data. Moreover, the

existence of hot springs nearby indicates further, recent movement of the NE trending boundary faults.

### 3.5 Integrated analysis of seismic and gravity/magnetic data

2-D seismic data of 170 km in EA 3 acquired by the Heritage Company of Great Britain provided reliable evidence for evaluating the exploration potential of this area. We came to the following conclusions from the integrated analysis of the seismic and gravity/magnetic data:

#### 3.5.1 Thick sediments filled in the depression

On the cross-line, the two-way travel time is over 4 seconds, which shows a thickness of over 6000 m and so it is concluded that the calculated thickness of the sediments is reliable based on gravity and magnetic inversion of the depressions in northern EA3 and EA2.

In view of the gravity and magnetic analysis, three relatively isolated depressions with almost the same thickness of sediments separated by NW-SE trending fault belts or uplift belts exist in EA 2 and 3. Based on the seismic analysis (Fig. 6), the thickness of Neogene formations exceeds 4,000 m in EA 3, becoming thinner northwards.

#### 3.5.2 Double-layered framework developed

The basin is characterized by a two-stage development and double-layered framework separated by an unconformity. On the seismic profiles of EA3, there is an obvious strike-slip fault in the center. There are many half-flower structures (Fig. 6) to east of this fault and one suite of 1–2 s thick sequences to the west. This may indicate that the syn-rifting depression is faulted in the west and overlapped eastward, controlled by a buried WSW-ENE strike normal fault in the basin. The syn-rifting faulted-depression is filled by pre-Kisegi formations. Later, the faulted-depression shifted eastwards and linked the early independent depressions. After that, the Kisegi-Kaiso formations developed.

## 4 Analysis of Petroleum Geology Characteristics

The many oil seepages in the graben show that petroleum

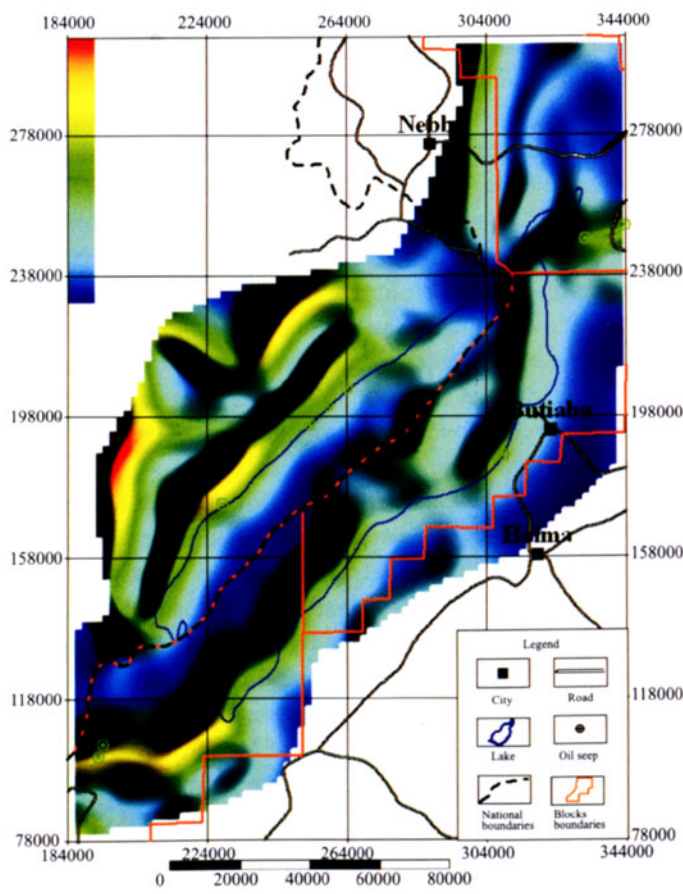


Fig. 4. Line image map of Uganda EA 1/2/3.

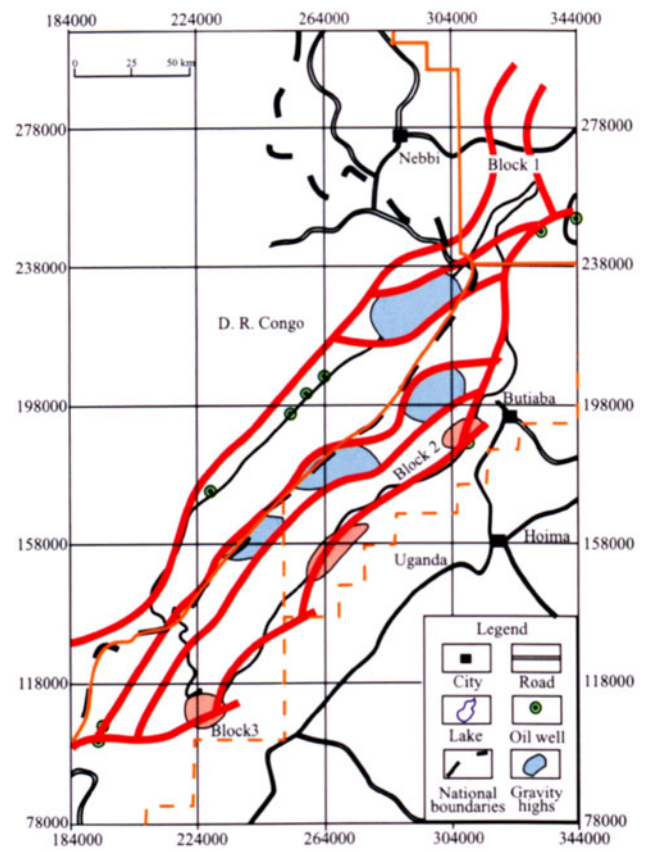


Fig. 5. Local gravity highs indicated by residual gravity anomaly of Uganda EA 1/2/3.

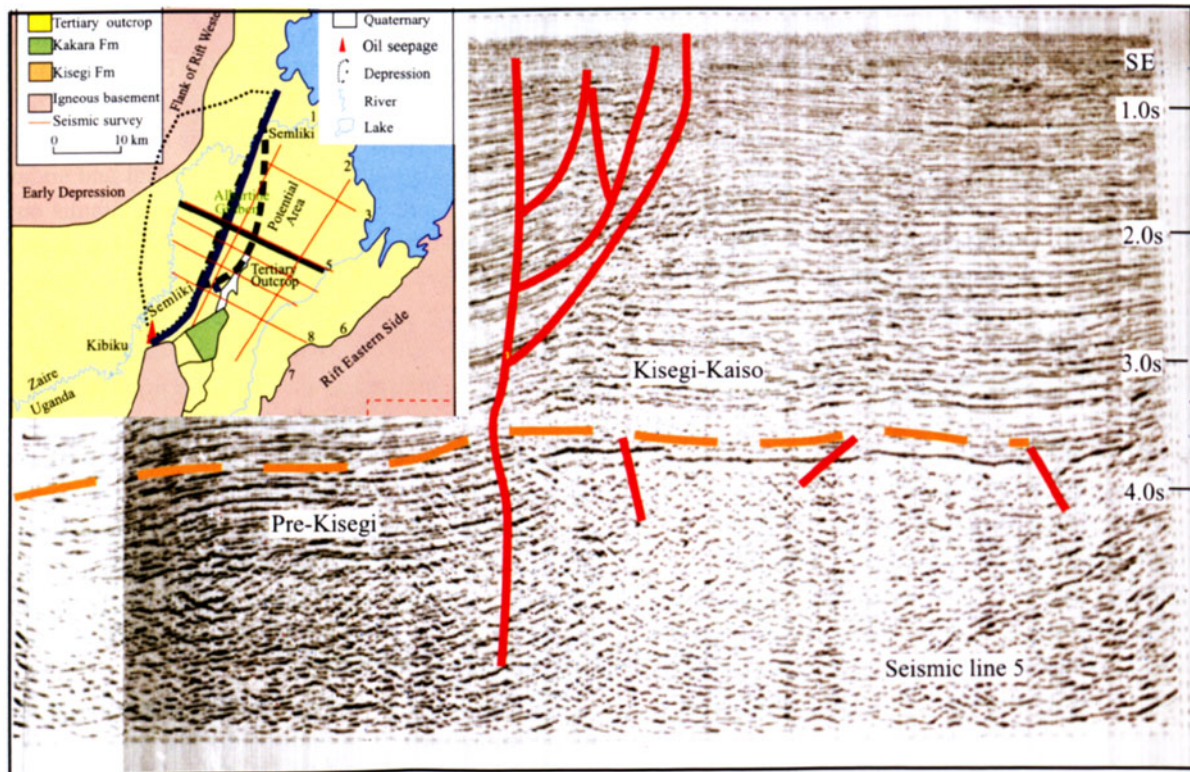


Fig. 6. Interpretation of seismic line 5 of EA 3.

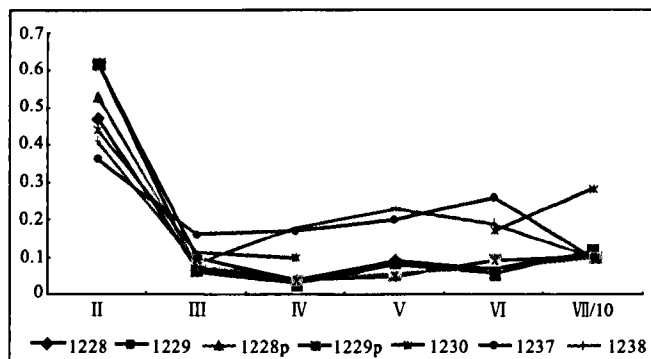


Fig. 8. Biomarker parameters for oil-oil correlation.

II. Diasteranes/Regular steranes- $C_{27}$ ; III.  $(C_{21}+C_{22})/(C_{27}+C_{28}+C_{29})$  steranes; IV. steranes/hopanes; V. gammacerane/hopane; VI. Tricyclic/Pentacyclic Terpanes; VII.  $C_{24}$ -Tetracyclic/ $C_{26}$ -Tricyclic Terpanes.

systems exist. Because of the low degree of exploration in the Albertine Graben, a first assessment of the elements of the petroleum systems in the graben can be studied using the data obtained from outcrop survey and samples.

#### 4.1 Source rock and hydrocarbons

##### 4.1.1 Constituent and chromatographic characters of the oil seepages and bituminous sandstones

Oil seepage samples of Paraa and Kibiro are of poor organic matter type with low hydrocarbon content. The total hydrocarbon content of the Kibuku oil seepage is up to 62.26%, with the saturates/aromatics ratio more than 1 (Table 1), so it is of a good organic matter type. The biodegradation degree of the Kibuku oil seepage is low and the organic matter has a contribution of original hydrophilic creatures. All the oil seepages and bituminous sandstones have a higher polars/asphaltene ratio ( $>1$ ) and exhibit immature characteristics.

The original organic matter is mainly of original hydrophilic creatures in the bituminous sandstones of the Kisege and Kaiso formations (Cheng et al., 2002). These were formed in an oxidic terrestrial sedimentary environment. The  $R_c$  (calculated vitrinite reflectance) is 0.70% by  $MPI_1$  (methylphenanthrene index). This shows that the organic matter is mature, and the bituminous sandstones are probably the remnants of immature oils, which are known from various oil seepage samples.

##### 4.1.2 Special biomarker constituent

Botryococanes have only been detected from the Paraa and Kibiro oil seepages (Fig. 7), which demonstrates that the oil seepages come from lacustrine mudstones enriched in *Botryococcus brannui* (Cheng et al., 2002). Many or a trace of oleanane was founded in the Kibuku, Paraa and Kibiro oil seepages, which indicates that they are from Cretaceous or Tertiary formations, and no oleanane was found in the bituminous sandstones.

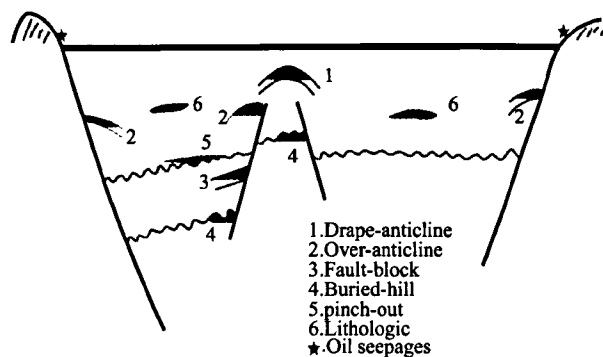


Fig. 9. Trap types in the Albertine Graben.

1. Drape-anticline; 2. Over-anticline; 3. Fault-block; 4. Buried-hill; 5. Pinch-out; 6. Lithologic.

The Kibuku oil seepage has a high abundance of  $C_{24}$ -tetraterpanes while the Paraa and Kibiro oil seepages have lower abundance (Fig. 8). The original organics show that the oil seepages of the Paraa/Kibiro and Kibuku have different sources.

Gammacerane usually indicates a hypersaline environment (Peters and Moldowan, 1993). As shown in Fig. 8, the ratio of gammacerane/hopane is of 0.1 or lower for the Kibuku, Paraa and Kibiro oil seepages, revealing a freshwater lacustrine sedimentary environment for their source rocks. However, it is of 0.2 or higher for bituminous sandstones and mudstones, indicating the influence of a hypersaline terrestrial environment for their source rocks.

##### 4.1.3 Geochemical significances

The comprehensive geochemical analysis indicates that the oil seepages and bituminous sandstones are incomparable. The Paraa and Kibiro oil seepages have similar and a good type of organic matter for their source rocks, which were enriched with freshwater algae. The Paraa and Kibiro oil seepages were generated during the peak stage of oil generation. Thus, they are more mature.

In contrast, the Kibuku oil seepage was derived from poor source rocks, the organic matter of which is dominated by terrestrial higher plants. The Kibuku oil seepage occurred before the oil-generating peak. It is immature. The source rock is undoubtedly from the Cretaceous and Paleogene.

The two bituminous sandstones that have the same organic source are dominated by terrestrial materials, which are the remnants of the low-maturity oils. They perhaps come from a certain Neogene source rock. There are mature or immature source rocks in the graben, which greatly increases the exploration potential of the graben.

#### 4.2 Reservoir rock

Generally, like most Meso-Cenozoic basins in Africa, the Albertine Graben is rich in reservoir rocks. Interpreted from the present data of outcrops and several drilled wells,

two types of reservoirs exist in the study area. One is the basement rock including magmatic and metamorphic rocks, and the other is conglomeratic sandstone.

#### 4.2.1 Basement rock reservoirs

In the eastern part of the graben, basement rocks occur widely in outcrops along the cliff of displacement and the flank of the graben, comprised mainly of gneiss, granite gneiss and quartzite. They were broken and fractures generated due to tectonics. Weathering and solution by organic acid would have caused pores and cavities. In the Kibuku area of the Semliki Basin, two groups of fractures developed in the outcrop basement rocks, some of which had been filled with quartz veins.

Medium grained and sorted sandstones are also found within the basement rocks. Pores, mainly intergranular and intragranular solution pores, can develop slightly within various types (Dou et al., 2001). The sizes of pores as seen under the SEM are between 20 and 30  $\mu\text{m}$ , and are not homogeneous.

These in situ observations and laboratory analyses show that the basement rocks of the Albertine graben are potential reservoirs.

#### 4.2.2 Sandstone (conglomerate) reservoirs

A wide range of sandy sediments occurs in the graben outcrops, including the Kisege, Nyaburogo and Kaiso formations.

A ferrous oolitic sample obtained from the lakeside Kaiso area was reported to be of Oligocene lacustrine sediment formed under an arid environment (Peters et al., 1993). Ooids have a diameter range between 0.40–0.80 mm and are composed of limonite, and mainly point contacted. A few solution pores can be found in the cement. The porosity distribution is not homogeneous with mainly intergranular solution pores, mold pores and super pores.

In the Kibuku area, the Kisege Formation consists of loose sandstones with a thickness of about 150 m in outcrop. The sandstones consist mainly of well-sorted fine sands. The cement type is pore filling. Granules are mainly point contacted. The matrix and cement content is 10%, containing argillaceous and ferrous materials. Pores are well connected with sizes up to 50  $\mu\text{m}$  and the porosity is over 15% as seen under the scanning electron microscope. The pore type is mixed with coexisting primary and secondary pores. Microfissures are also developed, with no fillings.

The sandstone of the Nyaburogo Formation in the Semliki area is heterogranular calcareous sandstone. It is fine and tight. The porosity is poor. The estimated porosity as seen under the SEM is about 2%–3%. Therefore, this sandstone is of extremely low-porosity and low-permeability reservoir.

Based on outcrop observations, reservoirs could develop

in the graben. Since rock composition is mainly quartz, of more than 75% in content, their resistance to compaction is relatively strong. This would have contributed to the development of underground primary porosity, and therefore provide good reservoir potential for oil and gas accumulation.

#### 4.3 Traps and seals

Earlier rift basins reverted to a large extent at the end of the Mesozoic. The expression of the EARS wandered from west to east, forming relatively large-scale structural traps. The pre-Kisege formations were mainly deposited in the western part of the graben. The eastern part of the graben where there are several gravity highs was the most favorable area for oil and gas migration and accumulation.

Based on the interpretation of the limited seismic lines in EA 3, a great variety of traps might have been developed in the study area, such as flower structures, drape-anticlines, faulted-blocks and buried hills (Fig. 9). The flower structures are mainly developed in the footwall of buried faults. These, however, were not favorable places for oil and gas accumulation because of their later forming and top faults probably linking to the surface. The drape-anticlines on the hanging-wall of faults can form oil and gas pools if they link down to the deep hydrocarbon source rocks. Buried hills developed in the basin center are also favorable for oil and gas accumulation, because basement fractures are well developed according to the outcrops in EA 3. A probable exploration risk may be efficient seals covering the buried hills.

## 5 Geological Risk Analyses

The above analyses were based on the recently collected data. Because of absence of drilling data, there are several risks during exploration in this area:

(1) The absence of stratigraphic correlation, undercompaction and overpressure resulting from high sedimentation rates will lead to engineering risks of drilling.

(2) Because of the few scattered magnetic and gravity data points, we now know well about the whole basin framework, sedimentation distribution, and basin evolution.

(3) The distribution and thickness of the source rocks are not distinct. A high sedimentation rate might cause lack of regional seals.

(4) The strike-slip effects could have destroyed the faults and the seal of the trap, and scatter the oils in the field.

Thus, we should pay attention to finding small- to medium-sized oil fields.

## 6 Conclusions

The Mesozoic-Cenozoic rift basin of the Albertine Graben in Uganda has petroleum exploration potential. The double-layered framework with thick sediments exhibit many oil seepages showing that petroleum systems exist in the graben. The gravity highs recorded in the residual anomaly map might indicate central uplift zones. At least two sets of mature or low-maturity source rocks exist corresponding to Cretaceous or Paleogene and Neogene strata. The graben has basement rock potential reservoirs and Tertiary sandstone reservoirs.

## Acknowledgements

Besides the authors, this work was carried out with the supervision and guidance of Mr. Li Qingping, chief engineer of CNODC, Mr. Tong Xiaoguang, Chief Geologist of CNODC, and Mr. Zhang Xing and Zhu Xiangdong, Deputy-directors of the New Venture Department of CNODC. The People's Republic of China Embassy in Uganda guaranteed the completion of this project. Profs. Wang Tieguan and Chen Lihua reviewed the geochemical and reservoir research results. CNODC and the Petroleum Exploration and Production Department of Uganda provided favorable conditions for this project. Miss Gong Qiuxia, Miss Li Shaohua and Miss Qi Shumei scanned the maps and digitized them. We therefore would like to acknowledge and appreciate their input to this project.

Manuscript received July 7, 2003

accepted April 14, 2004

edited by Susan Turner and Xie Guanglian

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