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Modeling and Interpreting Gravity Anomaly Data in African Great Lakes Region

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Abstract: The Albertine Graben is a promising petroleum area in Democratic Republic of Congo and probably for the neighboring countries, with a length of several kilometers and a width nearly equal 60 km. Geological surface mapping has indicated that mature source rocks are guaranteed, hydrocarbons have been generated and migration has taken place as proved by several substantial oil seeps in the graben. Geological and geophysical mapping have demonstrated typical rift basin block faulting with sequences of reservoir quality sandstones exposed in the graben. The Albertine Graben is a Mesozoic-Cenozoic rift basin formed and developed on the Precambrian orogenic belts of the African Craton. The graben trends NE-SW through most of its length and forms the northern most part of the western branch of the East African Rift System. The effect of isostatic compensation of topography was calculated assuming the local compensation model of Airy-Heiskanen with the following parameters: crustal density, 2.67gcm^{-3} ; mantle density 3.19 gcm^{-3} ; water density 1.02 gcm^{-3} ; crustal thickness to sea level, 40 km.

Key words: Isostasy, filtering, anomaly, field separation, modeling

INTRODUCTION

Gravity and density in the earth: Fortunes are to be made by discovering oil. Our growing industrial economy demands more and more black gold.The question is how to find it. A century ago the search was guided mostly by schemes based on ignorance if not out right fraud. But the chance discoveries provided valuable information about the various natural settings where oil had accumulated. Some fabulous oil fields were situated where layers of sedimentary rock included peculiarly deformed beds of salt. Underground pressures caused the salt to flow plastically into domelike structures. Now we need only remember that they are good places to look for oil. Once this was known, oil drillers began devising methods to locate salt structures buried hundreds or thousands of meters underground. One of the most practical methods was based on minute changes in the gravitational force on the Earth's surface. How can we find salt structures from changes in the gravitational force? The principle is simple. These structures cause density irregularities. We know that the density of salt is about 2.0 gcm^{-3} . Oil has been found in the places where salt domes protrude into overlying rock having a higher density about 2.5 gcm^{-3}. Because of the low density of salt, the gravitational force on the surface directly over a salt dome is not as strong as it is farther away where the underlying rock has higher density.

Geologists are continually asked about the materials that lie hidden underground. These can be fundamental questions about the way the earth is put together. Or we want to know where some useful raw materiel might be located. Density is a property of the materials buried in the earth. We already know that irregular variations in density affect the shape of the sea level and our measurements of elevation. Now we can look into relationships between density in the earth and the gravitational force on its surface.

Regional and residual anomalies: The Bouguer anomaly $|¤g$, observed at any point of the Earth's surface, constitutes the sum of two components: the regional effect or regional anomaly $|¤g_R$ and the residual or local anomaly $|¤g_L$ and can be expresses as below:

$$|¤g = |¤g_R + |¤g_L \tag{1}$$

A regional anomaly is a gravity effect usually of large extent, which has the characteristic features of deep-seated anomalous masses and which does not interest. A residual anomaly is an anomaly which would be observed, if the effect of the anomalous mass generating it were not obscured by deep or extensive sources. The regional anomaly (effect) is determined either graphically, or by computation by transforming the original field in a given region S, or by approximating the anomalous field by a polynomial of the n-th degree, or by filtering using harmonic analysis.

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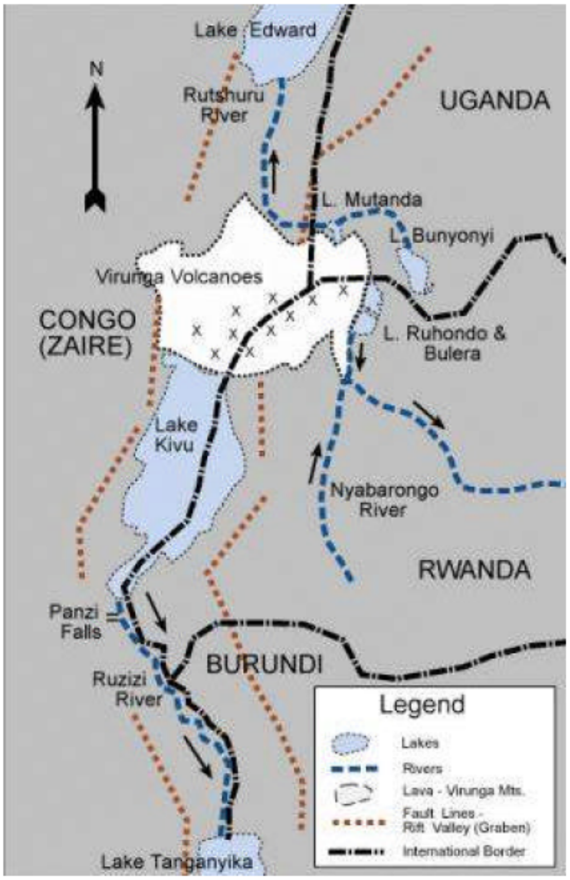

Fig.1: The Albertine graben map

Graphical methods: The principle of the graphical method of determining the regional field consists in smoothing and simplifying the plotting of anomalies on the gravity map. Good results can be achieved by smoothing anomalies curves in a network of profiles in two mutually perpendicular directions, so that the regional field has the same value at their points of intersection. This is a quick and simple method; an experienced interpreter with a good knowledge of regional geology using this method can determine (construct) the regional field very realistically and compute the residual anomaly,

$$\Delta g_L = \Delta g - \Delta g_R \qquad (2)$$

This is also suitable for quantitative interpretation.

Transforming the field in a regional: The regional field is calculated as the mean value of the field in the region considered, the weight of the individual gravity data being dependent on the position of points M to which they correspond relative to the centre of the region in which the point of calculation P is located. This then involves the integral transformation defined by the relation

$$\Delta g_R(P) = \frac{1}{\mu}\iint_S \Delta g(M)\mu(M)\,ds, \qquad (3)$$

where M is any point in a region S, ì(M) is the weighting function at point M for the region S, in the coefficient which normalizes Equation (3) so that the function $\Delta g_R(P)$ is expressed by the weighted mean value in the region S. The anomaly is again defined by equation (2). In most cases we adopt the weighting function $\mu(M) = 1$, i.e., the same weight is assigned to the gravity values at all points. Using (2), the residual anomalies will then read

$$\Delta g_L = \Delta g - \frac{1}{S}\iint_S \Delta g(M)\,ds. \qquad (4)$$

Field measurements and their processing: Gravimetric surveys may essentially be divided into three stages. The first stage covers the preparatory work, the second stage the field measurements and the third the interpretation or the geological explanation of the observed gravity anomalies. As part of the preparation for gravity observations it is necessary to become acquainted with the geological problem to be solved, with the geological structure of the area of interest. We must study in detail the results (including information on the physical properties of rocks) of all geophysical projects which have already been undertaken and prepare proposals for geophysical (gravimetric) measurements. The preparation of gravity observations itself includes the preparation of suitable topographic data, data on the reference points of the national leveling net and gravity acceleration data at points of the national gravimetric net. An important part of the preparatory work is the preparation of geodetic instruments and particularly of the gravity meter, which must be adjusted and calibrated at the beginning and the end of the observation season.

Prior to start field measurements it is necessary to inform the landowners and the appropriate authorities of the types and purpose of the planned geophysical work in the appropriate area and to request permission for access. In field measurements either individual gravity stations (regional survey), or stations on gravity profiles or nets (detailed survey-microgravimetry) are decided upon in the area of interest and their positions are plotted on topographical maps on a scale of 1:10 000, 1:5000, or on even smaller scales. Each point is surveyed for gravity, as well as altitude and sometimes position. The heights of gravity points are determined by leveling. Each leveling

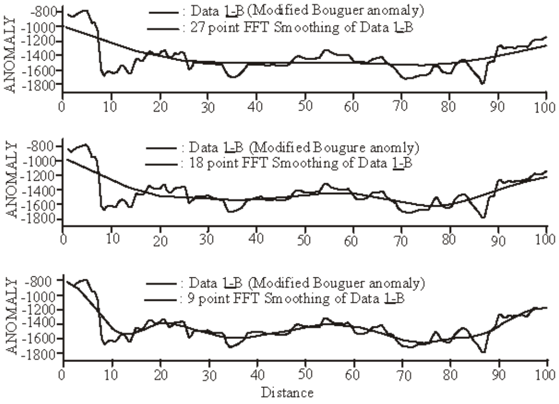

Fig. 2: Upward continuation of Bouguer anomaly field by FFT smoothing

traverse must be connected at each end either to the national leveling network, or to the I points of an auxiliary altitude network, surveyed by accurate leveling. The admissible mean error of altitude measurements in regional gravity survey is m = ± 0.1 m, in detailed survey m = 0.02 m.

Gravity measurements carried out by gravity meters must be connected to points of the national gravimetric network. Each gravity traverse must be connected at the beginning and end of measurements to the same gravity base point. If the measurement is to take longer than 5 hours, it is necessary also to connect the gravity traverse to the gravity base point in the middle of the traverse. Should the density of the points of fundamental (national) gravimetric network be insufficient for the gravity measurements being carried out, it is necessary to survey an auxiliary supporting gravimetric network. In order to keep a record of the gravity meter drift, measurements at 10 to 15 % of the points are repeated at 2 to advisable to repeat these measurements every half hour. In order to determine the mean error of the measurements, independent observations are carried out at the check points (at least at 10% of all surveyed gravity points). This error must not exceed ± 0.5 μm s^{-2} in regional surveys and ± 0.2 μm s^{-2} in detailed surveys.

Data of the gravity measurements are recorded in a gravity log book or on a special form. The heading of each gravity traverse record must give the survey area, the date, the type and manufacturer's number of the gravity meter used its constant and the name of the operator. The number (stationing) of the point, the height of the stand (provided it was measured), the time of the observation and at least two readings of the gravity meter, possible also the average of the readings (in detailed and accurate gravity surveys at least three) must be recorded at each point. By processing of gravity measurements we mean the computation used to convert the initial data recorded in the field, into a graphical representation of the anomalous gravity field (profile or map of complete Bouguer anomalies, or map of derived fields). In the course of the processing, therefore, we covert the reading of the gravity meter, in divisions, by multiplying it by the gravity meter constant into a reading in μm s^{-2} ,we eliminate the effect of tidal variations and of the gravity meter drift and calculate the acceleration of gravity at the individual points. We can calculate the value of the complete Bouguer anomalies |¤g. The processing of gravity measurements is very demanding and the manual processing very tedious. All computational operations we are now being carried out by suitable desk calculators or computers.

GRAVITY ANOMALY INTERPRETATION

Regional-residual separation: A pretty arbitrary process designed to separate anomalies on basis of spatial scale, and hopefully depth. Non uniqueness, an infinite number of subsurface density models can produce exactly the same gravity field, example the point mass of any spherically symmetric density anomaly; Density difference is all that you can determine, for local gravity anomalies measure change from place to place allows only interpretation of lateral density difference. The same is largely true for the global case because spherically symmetric fields do not alter average gravity." inversion" consists usually of hypothesis testing and forward modeling consists of trial and errors and testing models based on others data such as seismic. As a example of estimating the regional anomaly from the recorded data and isolating the local anomaly with this estimate consider using a moving average operator. With this technique, an estimate of the regional gravity anomaly at some point along a profile is determined by averaging the recorded gravity values at several nearby points. The number of points over which the average is calculated is referred to as the length of the operator and is chosen by the data processor. Averaging gravity values over several observation points enhances the long-wavelength contributions to the recorded gravity field while suppressing the shorter-wavelength contributions.The Fig. 2 below shows the 27 points FFT smoothing operation.

Exploration scale measurements of gravity commonly supplement seismic work, as well as regional geologic field work. For example, evidence of basement faults in sedimentary basins may be important in identifying their extension into later sediments, and

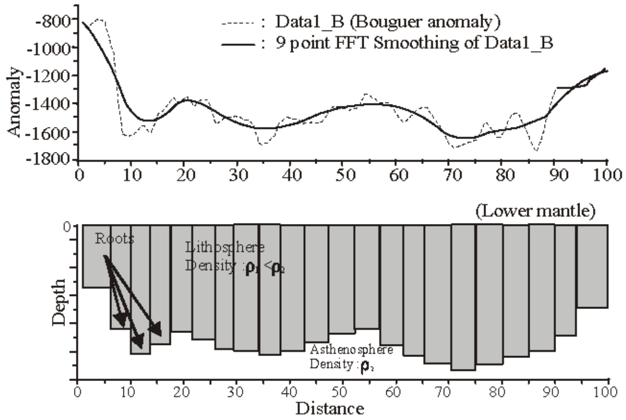

Fig. 3: Below shows the theoretical model for 9 points FFT smoothing

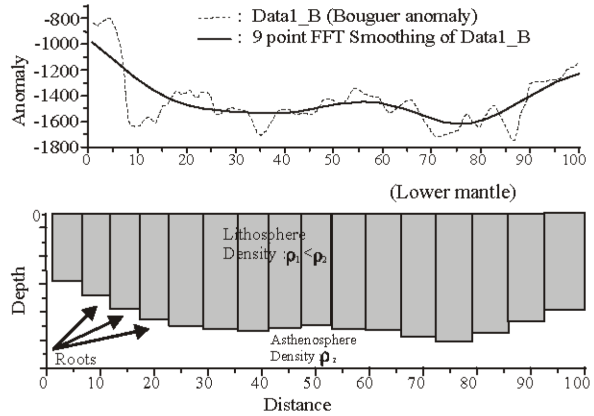

Fig. 4: Below shows the theoretical model for 18 points FFT smoothing

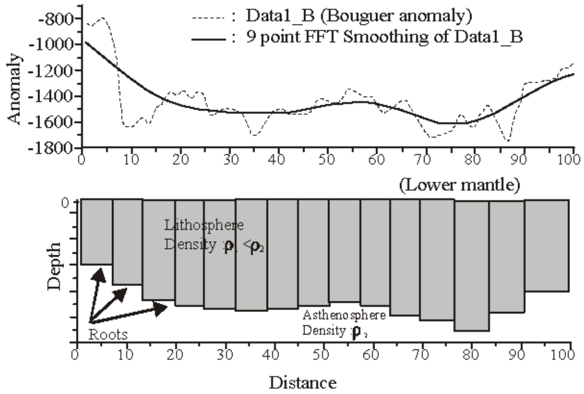

Fig. 5: Below shows the theoretical model for 27 points FFT smoothing

possible fault trapping areas for hydrocarbons. Exploration for salt domes was one of the early applications for gravity exploration, since salt has a low density compared the most sediments. At exploration scales, isostatic compensation is not an issue, we are looking at loads small enough that the crust can support them. Then we need to understand how to quantitatively interpret the size of the anomaly. Actual practice is a forward modeling approach with a computer program and testing hypotheses about subsurface structure. Relation between spatial scale and depth of the source shows that large scale features are generally assigned to deeper depths, though this is not guaranteed.

Conceptually we know that upward continuation produces a smoother field, so smoother fields are generally associated with deeper features. The concept is best illustrated by a buried sphere anomaly; half width is comparable to depth; the depth to the center is 65% of the half width, so we can conclude that the spatial scale of anomaly is comparable to the depth of sources. The anomaly of the buried sphere is not simply the attraction of the mass, but rather the vertical component of this, requiring that we multiply by the factor (z/distance) to get the final result $(4/3)\Delta\pi\rho r^3\ Gz/(z+x)^{3/2}$.

After all corrections we are left with a gravity anomaly (Bouguer anomaly) (or geoid anomaly map). Now we are ready to interpret it. The question is what is the subsurface distribution of density responsible for these spatial variations in gravity anomalies? To proceed, we need to understand generally we can only see effects of density differences, not absolute density. This is because we can add any constant density layer to any model and not change the spatial variation of the gravity field, at least on a local level. What density differences do we expect? We can study the range of density for various lithologies, or try to correlate density with velocity. In some cases, we can estimate density fro Nettleton's method: find the density used in the Bouguer correction which leaves the least signature of topography (suitable for small scale studies). For large scale studies, the Bouguer anomaly mirrors topography, because of isostasy: high topographic features have low density roots, so that the vertical column of mass has about the same weight everywhere, and does not therefore sink into the viscous mantle. At small scales (tens of km or less), the finite strength of the lithosphere is able to support loads. The Fig.3 below shows the theoretical model for 9 points FFT smoothing. Fig.3; expected theoretical model for 9 points fft smoothing

Isostasy implies that the upper mantle behaves like a fluid so that high standing topographic supported by low density roots, as if topographic features were floating on a liquid mantle. The two 'end member' models of

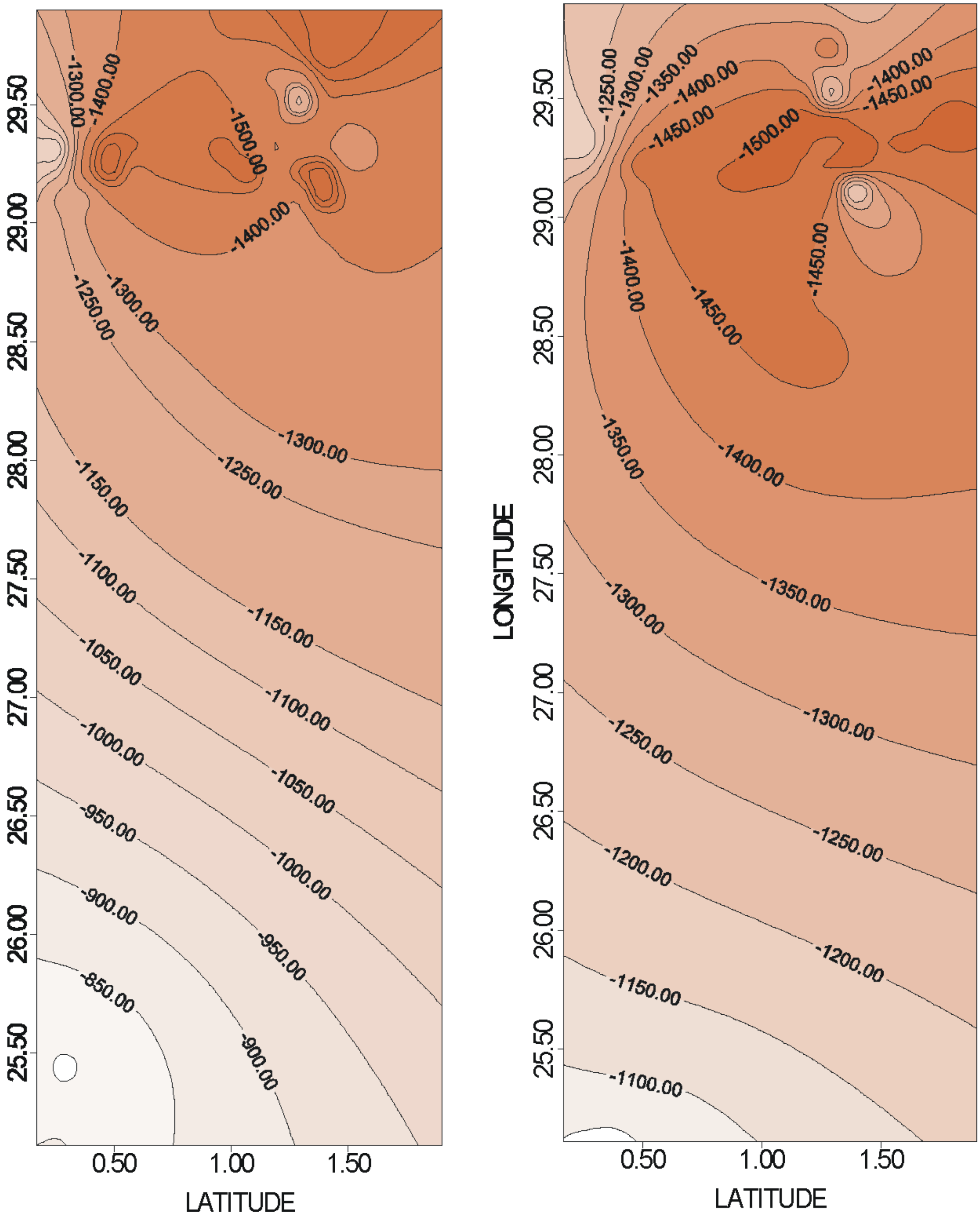

Fig.6: Contours maps of modified Bouguer anomaly (a) Regional and residual contours anomaly map (b) Regional contours anomaly map

isostatic compensation are Pratt (lateral density variations, constant depth of compensation) and Airy (variable root depth). These are conceptual only. The actual situation is more complicated because the lithosphere acts like an elastic plate, partly supporting loads, in addition to the strictly buoyant effects that the Pratt and Airy models include. The Airy- Heiskanen model allows for a deformed plate supporting the load over a fluid lithosphere, thus providing a combination of variable support, and elastic strength. Elastic strength means that small scale are not compensate because the lithosphere is strong enough to support them, and large scale loads completely compensated, and in between scales (depending on the thickness of the lithosphere) are partly compensate by buoyancy forces, and partly by elastic strength. Example of Pratt type compensation: mid ocean ridges where lateral change in density of the crust occurs due to thermal expansion. Example of Airy type compensation: the mountain belts where low density roots support the high topographic. The Fig.4 and Fig.5 show respectively the theoretical model corresponding to the 18 and 27 points FFT smoothing and Fig. 6 shows the contours map of gravity data. Fig .4: Expected theoretical model for 18 points FFT smoothing Fig. 5: Expected theoretical model for 27 points FFT smoothing

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CONCLUSIONS

Interpretation of gravity anomaly data is inherently ambiguous. In the first place there is not single mathematical solution to the determination of a gravity field, no matter show precisely how this field can be mapped. For a given breadth of anomaly there is a maximum depth but the source with an appropriate modification of shape can be shallower and broader.

The system of gravity analysis with calculations of varying degree of detail is sometimes presented as representing the disturbances from a limited band or zone of depths.

Volcanic activity of this graben is mainly limited to the southern part of the graben and becomes mild northwards. Magmatic activity has been localized in the fault-bounded basins where chains of active volcanism are aligned along tips of some border fault segments and along oblique-slip transfer faults crosscutting the rift valley.

Existence of hot springs indicates the thinning of the crust and the closeness of the mantle plumes to the surface, which has facilitated a relatively higher geothermal gradient in the graben. Lacking significant volcanic fill, the western branch consists of narrow, deep and stratified lakes that have been accumulated organic rich sediments. Lake Albert covers the central part of the graben and in some parts it extends to the western escarpment of the graben in Democratic Republic of Congo.

A high degree of petroleum potential is revealed by the large sediment thickness (5000 m), the numerous oil seepages, the potential oil source and good reservoir rocks outcropping in the graben. Geochemical analyses and correlation of the three oil seeps in the graben (Paraa, Kibiro and Kibuku) are poor in steranes relative to hopanes, which is suggestive of a non-marine source.

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