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Subsurface Depositional Systems in Lake Turkana Basin, North-western Kenya: Based on Gravity and Seismic Data Investigations

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ABSTRACT

This study unravels subsurface structural features and further creates a better understanding of sedimentary rock sequences, believed to belong to Cretaceous-Tertiary age, which have been deposited under the vast Lake Turkana Basin (NW Kenya). The gravity anomaly maps and seismic profiles revealed the presence of several horst- and graben-like structural systems. It was also revealed that the basin could have attracted potential petroliferous sedimentary piles (2000-5200m thick) which are deposited on basement rocks of Precambrian age. The basin is known to have evolved through extension tectonics that brought out continental rifting as a part of the major Gondwanaland breakup in the Late Paleozoic time and continued in the Mesozoic and Tertiary. This movement was accompanied by a stupendous outpouring of the lava flows.

1.0 INTRODUCTION

Lake Turkana Basin lies between longitudes 35°45'E and 36 °48'E and latitudes 2°25'N and 4°38'N. The basin was initiated as an asymmetric graben bounded by the N-S fault systems during the Tertiary time. At the centre of the basin lies Lake Turkana (formerly Lake Rudolf), one of the largest lakes in the eastern arm of the East African Rift System (Figure 1).

The Lake Turkana Basin forms a north-south broad depressional Horst-graben feature with an alkaline lake water. It is bounded both to the east and to the west by the north-south trending fault systems of the Kenya Rift (Tertiary). These fault systems are the result of the rifting mechanism, which began in Late Oligocene to Early Miocene time and later gradually progressed eastwards with time to trend NNE-SSW (Barker et al, 1972, Rop, 2002, Wescott et al., 1993). Many of these major basinal faults have been active and have also affected the Upper Oligocene-Lower Miocene to Pliocene volcanics, forming the highlands on both the eastern and western side of the Basin (Figure 2).

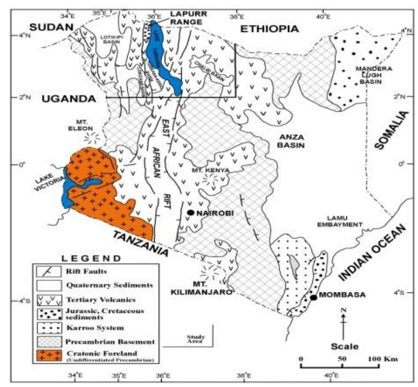

Fig. 1: General Geological map showing present study area

The geology of Lake Turkana Basin consists of the Precambrian basement rocks and the Tertiary volcanics that have covered subsurface sedimentary deposits, which are now considered to be a potential petroliferous block in Northern Kenya (Rop, 2003). The basin is known to have evolved through extension tectonics that brought out continental rifting as a part of the major Gondwanaland breakup in the Late Paleozoic time and continued in the Mesozoic and Tertiary (Figures 2 and 3). The region underwent uplift and subsidence, intermittently, along major boundary faults even in the Miocene period. These movements were accompanied by the stupendous outpouring of the lava flows.

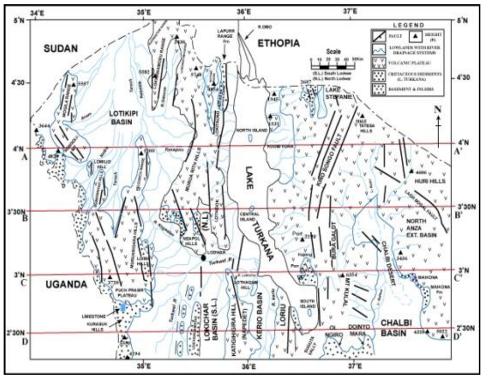

Fig. 2: Physiographical and Geological map of the study area showing major fault systems

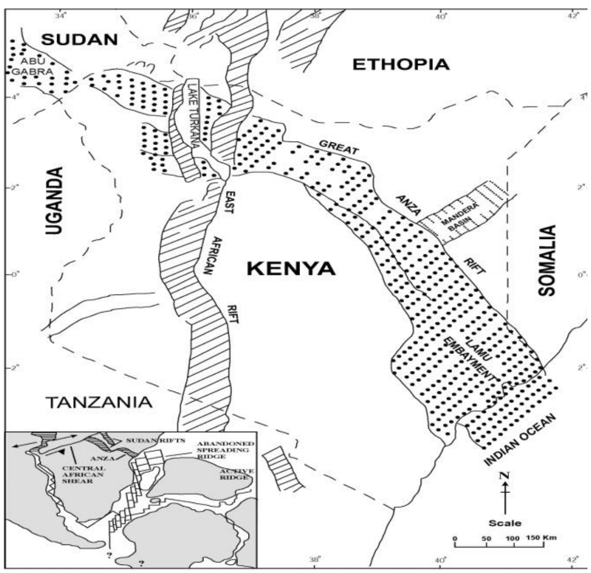

Fig. 3: Map of Northwest-trending Anza Basin rift extension (modified after BEICP, 1984). Inset - Gondwanaland breakup in Late Paleozoic time.

The Mounts Kulal-Porr-Moiti and Loriu-Lothidok-Murua Rith volcanoes (Figure 2), which erupted during the Quaternary, form the eastern and western shoulders of the Lake Turkana basin, respectively. The Chalbi basin (Cretaceous), which forms a part of the Great North Anza Rift, is located some 40km to the east of Lake Turkana. It is assumed that the Anza Graben discontinuously extends north-westwards across (under) the Lake Turkana and Lotikipi basins (Figure 3) into the Abu Gabra Rift of Southern Sudan, where oil discovery has been made (Schull, 1988). The basin and its sub-basins continued as sites of deposition and extension also during the Late Tertiary and even in Quaternary period. Sedimentary rock sequences belonging to the Cretaceous-Tertiary age may have been deposited under the vast and little known Lake Turkana Basin (Rop, 2003).

The physiographical features such as the basement ranges and inliers, Tertiary volcanic plateaus, Lake Turkana and lowlands with alluvial plains as well as drainage systems are present in the study area (Figure 2). The entire area is volcanically and seismically active, even throughout the Quaternary period, shown by the thick alluvial cover concealing the entire eroded surface of the older sedimentary sequences as well as the basement rocks (Barker et al., 1972; Rop, 2002). The landscape consisting of flat alluvial plains and high plateaus and ranges intervening them indicates the control of block faulting. The drainage follows most recent strikes of faulting, north-south direction, but the tilts are asymmetric giving rise to rivers flowing in opposite directions.

2.0 MATHERIALS AND METHODS

2.1 Lake Turkana, Alluvial Plains and Drainage Systems

The Lake Turkana is the largest lake in the eastern arm of the East African Rift Valley. It is a tectonically controlled lake occurring centrally in the present study area. About 240km long and 50km wide, it has a maximum depth of 120m (Johnson *et al*., 1987). The water level in the lake fluctuates with the variations in rainfall and the evaporation rates. The lake is fed by the Omo River (draining the Ethiopian highlands) in the north and the perennial Turkwell-Kerio river systems draining the western part of the present study area (Figure 2). These rivers, which predominantly flow southwards and northwards into the lake trace the north-south-trending major faults. The environment being very hot and arid, the lake has neither a surface outlet nor a subsurface drainage. The water is alkaline (pH 9.2), moderately saline, with total dissolved solids of about 2500 parts per million (Yuretich, 1986).

The Lake Turkana is supposed to have developed tectonically during the Early Miocene-Pliocene time, with major rifting of Pliocene age forming the north-south trending marginal faults on the northwestern and central parts of the lake (Ochieng’ et al., 1988, Wilkinson, 1988). It is bounded by the major N-S trending normal faults and the Kenyan and Ethiopian domes abutting against the northern end of the Gregory Rift Valley of Kenya, the entire depression between these two domes is rift-related; the rifting strongly influenced also the sedimentation history within this region. The Lake Turkana itself is said to be a part of the half-graben structure with intermittent structural highs, deepening progressively to the north because of tectonic subsidence (Johnson et al., 1987). Dunkelman (1986) suggested that the Lake Turkana is intersected obliquely also by some pre-rift structures of the North Anza Basin, which is a NW-SE striking basin filled with Cretaceous sediments, predicted to be 2500m to 4000m thick. The flat lowlands around the lake (e.g. Koobi Fora to the northwest) contain Quaternary sediments of Plio-Pleistocene age (Brown and Feibel, 1986, Wilkinson, 1988, Ochieng' *et al*, 1988). These areas are distinctly transected by the east-west flowing small rivulets. These rivers do not follow the main north-south drainage trend of this physiographic region.

The low-lying alluvial areas with Plio-Pleistocene sediments occur intermittently amongst the Tertiary volcanic plateaus and the basement ranges. The rivers flowing through these lowlands have sudden major bends that are also tectonically controlled. The regional rifting and faulting systems have imposed restraint upon the courses of the rivers. The lowlands are more dominantly seen along sections drawn at 3°N and 3°30'N latitudes (Fig. 2). Further south at 2°30'N section line there are no mounts of very high altitudes like Mount Kulal. The terrain is low but highly undulatory. On the whole, the steep escarpments are seen along the northernmost section and on both sides of Mount Kulal along the section at 3°N latitude. The Turkwell and Kerio rivers, draining the predominantly metamorphosed basement source area, subsequently converge and form a delta on the central southwestern shores of Lake Turkana. The Precambrian basement rocks are sparsely exposed as inliers and ranges, particularly at the Lapurr Ranges to the northwest, Kajong-Porr area to the southeast and at the north Loriu Plateau to the southwestern shores of Lake Turkana (Figure 2). These basement rocks are probably extension of the Precambrian rocks of Samburu gneissic groups to the south of the lake (Key et al., 1987).

2.2 The Lapurr Range Sedimentary Sequences

The basement rocks in the Lapurr Ranges (the 'type' section for the surface geology in the present study) are seen to be unconformably overlain by sediments initially termed "Turkana Grits" by earlier workers. This term denotes generally coarse-grained siliciclastic sediments between the basement and the Tertiary volanics. These sedimentary sequences have yielded wood and dinosaurian fossil remains (Savage and Williamson, 1986, McJGuire and Serra, 1985) in the Lapurr Ranges, to the immediate northwest of the Lake Turkana (Figure 2). These have been described as continental fluvial-lacustrine and fluvial-deltaic deposits (up to 600m thick) consisting of fine- to coarse-grained sandstones, pebble-to-cobble-conglomerates and siltstones or shales interbedded between the sandstones and conglomerates. They have been designated as the Lapurr Range Formation (Rop, 2003).

The sediments to the east of Lake Turkana Basin (around Kajong-Porr area) have been described as admixtures of both siliciclastic and volcaniclastic strata termed as Sera Iltomia and Kajong Formations, respectively (Savage and Williams, 1986, Rop, 1990, Wescott et al, 1993). The siliciclastic Sera Iltomia sediments are believed to be of Upper Cretaceous to Miocene in age, while the Kajong sediments and volcanics are of Miocene age. The voluminous basalts (Upper Oligocene-Miocene to Pliocene) overlie the Lapurr Range and the Kajong-Porr sediments and, in turn, are overlain by the post-volcanic sediments of Plio-Pleistocene to Holocene age, particularly in the horst-graben like Koobi Fora sub-basin to the northwest of Lake Turkana Basin. The depositional environments within the margins of Lake Turkana basin provided suitable life conditions for a prolific vertebrate fauna during the Tertiary and Quaternary times resulting in high potential for preservation in the hominids fossil records (Brown and Feibel, 1986, Harris et. al., 1988).

3.0 RESULTS AND DISCUSSIONS

3.1 Subsurface Structures and Tectonics

The Lake Turkana Basin lies along the Kenya Rift Valley, which forms the eastern arm of the East African Rift System (Figures 1 and 3). The rifting period in the Turkana basin occurred between the Late Mesozoic to Early Tertiary during which the sub-basins that formed extended in the north-south directions; the rifting being mostly in the east-west direction. During this rifting, there was stupendous outpouring of basaltic lavas which extensively covered the entire northern Kenya. These lavas have hidden under them a large terrain of older rocks comprising the Precambrian basement rocks and sediments filled in the rift basins (Rop, 2002; 2003). Thus direct observations on the possible Mesozoic and Tertiary sedimentary sequences are not possible.

The Lake Turkana basin forms a part of the Early Oligocene-Miocene rifting. The Chalbi Basin to the east of Lake Turkana and the Lotikipi Basin to the west of the lake are not a part of this Tertiary rifting. They belong to the Late Paleozoic rifting (Key et al., 1989, Winn et al., 1993) and are supposed to extend subsurface in the NW direction towards Sudan, where oil discoveries have been reported (Schull, 1988). The study of intracontinental rifting and its associated subsurface structural features caused by extensional tectonic stresses is critical for effective hydrocarbon exploration province (Rop, 2003, Harding 1984). It is proposed therefore to examine in this paper the tectonic structure of the Lake Turkana subsurface basin in the light of basement depth contours and gravity anomalies from BEICIP, 1987 regional structural contour maps (Figsures 4 and 5). The gravity anomaly maps and seismic profiles were most useful for the interpretations of subsurface structural features, thus unravelling the depositional province of the (2000–5200m thick) sedimentary rock sequences, believed to belong to Cretaceous-Tertiary age, which have been deposited in the vast lake. The gravity values both to the east and west of Lake Turkana basin are mainly positive, to the order of 20 to 40 mgals (Figure 4). Over the Koobi Fora and Moiti areas, to the east of the basin, the gravities are positive (+40 and +20 mgals, respectively). Some negative gravity anomalies are seen in areas around the North Island (-90 mgal) within the lake, Eliye Springs (-70 mgal) to the southwest of the lake, and South Island (-70 mgal) within the south part of the lake.

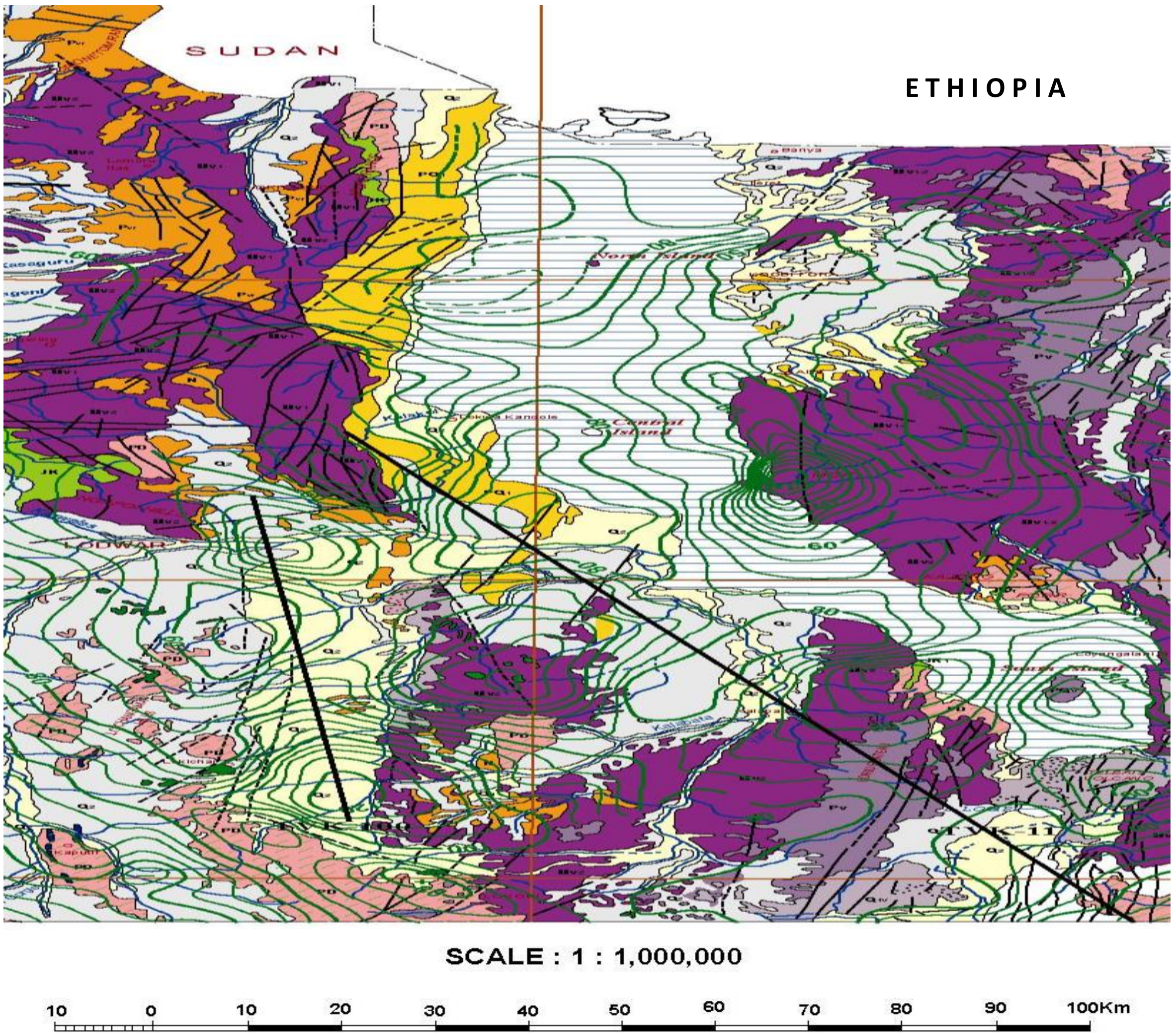

Figure 4: Bouguer gravity contour map over the Lake Turkana basin (Adopted from BEICIP-Ministry of Energy Geological Map, 1987)

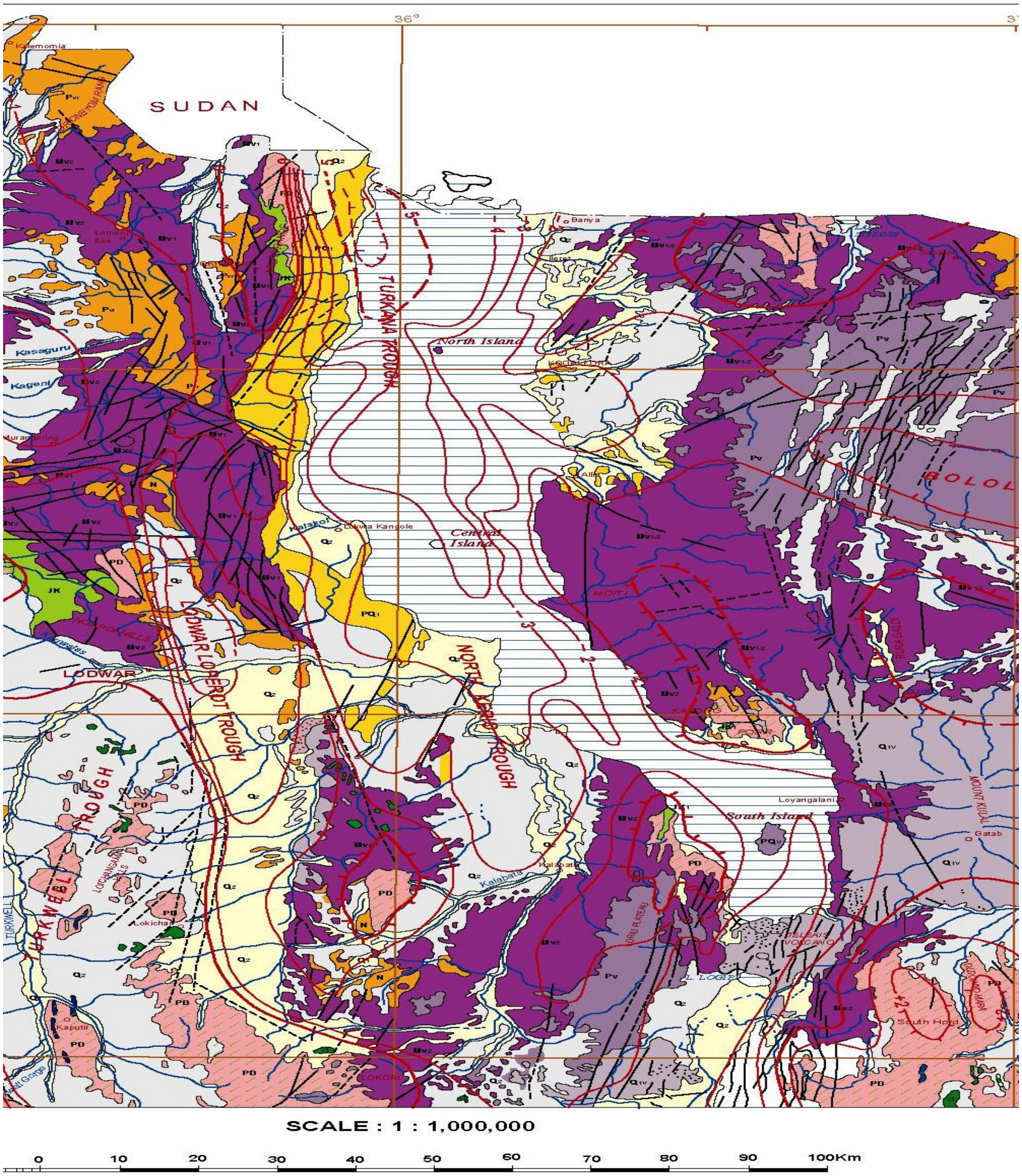

Figure 5: Basement contour map showing basement depths in Lake Turkana (Adopted from BEICIP-Ministry of Energy Geological Map, 1987)

3.1.1 Gravity Cross-Section Along 4°N Latitude

The strike of the Bouguer gravity anomaly contours is mostly north-south. A cross-section along latitude 4°N (Figs. 2, 4, 6) through Lake Turkana basin reveals a couple of sharp anomaly variations, which indicate subsurface features such as the thickness of sediments, basement depth, and direction of shallowing and deepening (Rop, 2002, 2003). To the east of longitude 35°30'E the gravity anomalies become steeply negative (ranging from -60 to -90 mgal). This is the area extending from the western margins of the N-S trending Murua Rith–Lokitaung volcanic Hills (point X) towards east up to the immediate southwest of the North Island (point R). From point R eastwards the gravity anomalies become only gently positive from -90 to -80 mgal up to point T. The anomalies show a jump and become positive (-75 mgal to +75 mgal), representing horst structure covered by volcanic under point U on the section.

From the basement depth contour map (Figures 5 and 6), the basement is also seen to be deepening (from -1 km to -4km) towards the centre of the lake, west of North Island. This deepening is seen to have been accomplished in two stages. From point X the basement rises from -2km to -1km up to point P and then steeply deepens to -2km at point Q. The basement deepens further eastwards, first gently up to point R and then steeply to -4.2km at point S. From point S the basement also steeply rises first from -4.2km to -3km at point T and then gently to about -2km at point U.

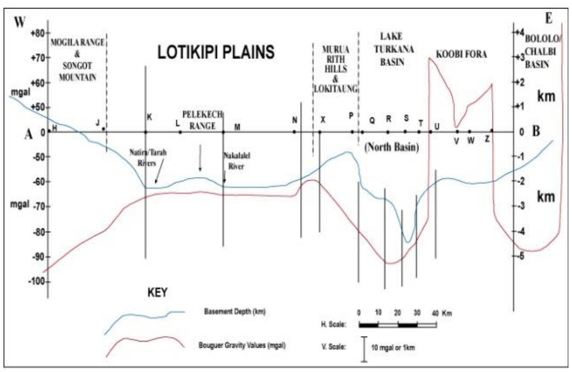

Figure 6: W-E Section of Bouguer Gravity and Basement Values profile along Latitude 4o00'N. Between Longitudes 34o25'E and 36o30'E through Lotikipi and Lake Turnana Basins

From the above variations in the basement depth and the steep negativity of the gravity anomalies, one can conclude that 1) the area has undergone vertical active tectonic and 2) the upper mantle in this region has steeply downwarped. There are a series of faults, some of them are deep and have affected the basement also. The sense of movement between point P and point S is that of a downthrow. It can thus be concluded that the basin here represents a graben structure bounded by faults underneath points X and U. Other intrabasinal faults underneath points P, Q. R and S can also be marked. The magnitude of the deepening, west of the North Island, is far less than towards the east. The region to the east of the shoulders of the basin beyond point U represents an upthrown horst structure, while the Turkana Basin itself seems to be half-graben.

The basement contours (Figure 5) also indicate a deeper half-graben structure towards the north-western edge of the lake (depth contours increasing from -3km to -5km). It implies that the sediment fill progressively deepens not only eastwards under points R and S but also northwards. The gravity picture of the Lake Turkana basin is in sharp contrast with that towards the immediate eastern and western region. In the Lotikipi plains to the west, the gravity anomalies showed hardly any variations along this latitude, while to the east under the Koobi Fora region, highly positive anomalies are seen. Thus the faults in the Turkana basin seem to be even mantle-reaching, bringing about a downwarp of the mantle. In comparison, the mantle has been upwarped under the Lotikipi plains and has been sharply thrown upwards under the Koobi Fora area. Between points X and P, faulting has upthrown the basement but has affected the mantle also.

3.1.2 Gravity Cross-Section Along 3°30'N Latitude

The cross-section along latitude 3°30'N (Figures 2, 4 and 7) through the central part of the Lake Turkana Basin, at the Central Island area (long. 36°05'E) reveals, more or less, similar subsurface features as those to the north (cross-section 4°N latitude). The positive gravity anomalies (+50 to +70 mgals) between longs. 35°40'E and 35°45'E over the Lothidok volcanic hills (points C and O) mark the western margin of the basin. From point O eastwards the anomaly suddenly dips to -75 mgal at point E. Further eastwards the negativity varies gently towards the central part of the lake up to longitude 36°E (-85 mgal) at point F, which is to the immediate west of the Central Island. It becomes gently positive from point F to point G (-85 to -75 mgal), where it suddenly (point H) becomes highly positive (from -70 to +70 mgal) in the Moiti area forming the eastern margin of the basin (Figure 4).

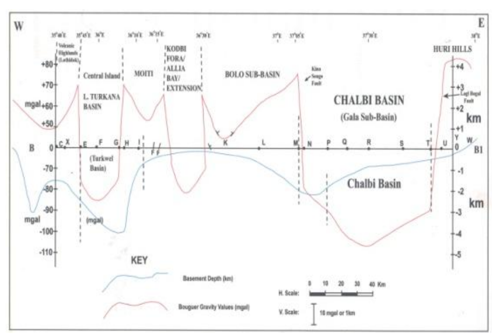

Figure 7: W-E Section of Bouguer Gravity and Basement Depth Values profile along Latitude 3o30'N. Between Longitudes 31o15'E and 37o30'E through Lake Turkana north Chalbi Basin

From the basement depth contours map (Figure 5 and 7) the basement is also seen to be gently deepening (from -1.5km to -4km) from the western margin (point C) of the basin to the eastern margin (point H). It is seen that the basement deepens nearer the eastern margin of the basin from -1km to -4km (points C and H). From the above it can be concluded that the basin is bounded by faults that have affected the basement, and have even downwarped the upper mantle also. One can also demarcate a series of faults striking north-south. Among these, the faults under point C and point H form the western and eastern margin, respectively. Within these two major marginal faults lie intra-basinal faults under points O, E, F and G. The western margin faults (under points O, E and F) gently dip eastwards while the eastern margin faults (under points G, H and I) steeply dip westwards. Both marginal and intra-basinal faults have subsequently contributed to the formation of half-graben structure at the centre of the basin.

From the basement depth contours map (Figures 5 and 7) a half-graben structure can be interpreted, which is deeper to the immediate east of the Central Island (-4km). The graben structure strikes in the N-S direction and appears to deepen towards the north. Similar to the earlier section (3.1.1) the magnitude of deepening, east of the Central Island, is far more than towards the west. The regions both to the western and eastern shoulders of the basin beyond points O and H represent horst structures while the Lake Turkana Basin is a half-graben.

3.1.3 Gravity Cross-Section Along 3^{o}N Latitude

The cross-section along latitude 3^{o}N (Figures 2, 4, 8) cuts across the two subsurface basins: North Kerio and Turkana basins. The North Kerio basin joins the Lake Turkana basin at around longitude 36^{o}E and extends southwards. The section reveals a N-S striking Bouguer anomaly contours and similar subsurface features as those of the latitude $3^{o}30'$N cross-section (Section 3.1.2). To the immediate east of longitude 36^{o}E (Figure 4) the gravity anomaly dips at the Lokichar River from a low of -70 mgal to -80 mgal toward east, forming the western margin of the Turkana basin (points C/B to point J in Figure 8). The gravity anomaly then becomes gently positive eastwards (from -80 mgal to -75 mgal) up to point K then suddenly varies steeply to become positive (-75 to +75 mgal) under points M and A on the section. From point A to point E, which is the eastern margin of the basin, the positive gravity anomalies gently decrease from +75 mgal to +45 mgal.

From the basement depth contours map (Figure 5) and Figure 8, the basement is also seen to be gently deepening from -1.8km at point H, at the eastern margin of the Lokichar basin towards the east up to point K (-3.2km)) and gently rises to -2km at point L. From point L it takes another gently dip through point M (-2km) to point N (-2.2km) where it suddenly becomes steep and positive up to point B (+0.5km) on longitude $36^{o}30'$E; in the Kajong/Porr area, forming the south-eastern shore of the Lake Turkana Basin (Figures 2 and 4). The rifting and faulting in this area has been active in the Tertiary up to Quaternary time thus controlling also the river drainage system in this part of the basin.

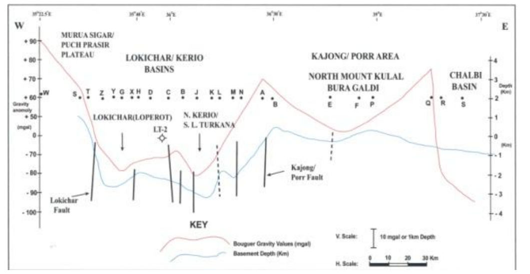

Figure 8: W-E Section of Bouguer Gravity and Basement Depth Values profile along Latitude 3o00'N. Between Longitudes 35o25.5'E and 37o30'E through Lokichar/Kerio, Lake Turkana and Chalbi Basins

Comparing the sections across latitudes 4^{o}N and $3^{o}30'$N, it can be concluded that the basemen depth shallows towards the south and deepens northwards (Figures 5, 6 and 7). It can be said that the sedimentary sequence in the Lake Turkana basin becomes thicker from south to north. The region to the west of the shoulders of the lake (point H) represents another graben structure (Lokichar/Kerio sub-basins) while that to the east of the fault under point N represents a horst (Kajong/Porr area). The Lake Turkana Basin itself is a half-graben.

3.1.4 Gravity Cross-Section Along $2^{o}30'$N Latitude

The cross-section along latitude $2^{o}30'$N (Figure 9), further to the south resembles those drawn on the northern latitudes (Figures 2, 6 - 8). Both the Bouguer gravity anomalies and the basement depth dip eastwards from point A to point E. East of point E both the basement and gravity anomalies gently rise; the basement rises from -2.2km to the surface at the southern margin of Mount Kulal (Figure 2) and the gravity anomaly rises from -80 mgal to -65 mgal. At the eastern margin of the basin the gravity anomaly rises to +65 mgal (point M). It can be concluded that the basinrepresents a simple graben bounded by faults at points A and M. Some intra-basinal faults can also be interpreted between points H and C. The central part of this graben is the deepest region but the basement depth is the shallowest when compared to sections along the northern latitudes. It seems the Lake Turkana deepens from south towards the north. The faults interpreted have certainly affected the sediments, basement and perhaps also the upper mantle. On both the eastern and western sides of this basin, horst structures can be interpreted on which the surface outcrops of basaltic flows are located.

This study of the intracontinental Lake Turkana rifting and its associated subsurface structural features caused by extensional tectonic stresses is critical for effective probable petroleum prospective target areas (Figure 10) identified from the gravity profiles of the cross sections above. The Turkana basin revealed the presence of several horst- and graben-like structural systems. It was also revealed that the basin could have attracted potential petroliferous sedimentary piles (2000–5200m thick) which are deposited on basement rocks of Precambrian age and later covered by Tertiary/Quaternary volcanics.

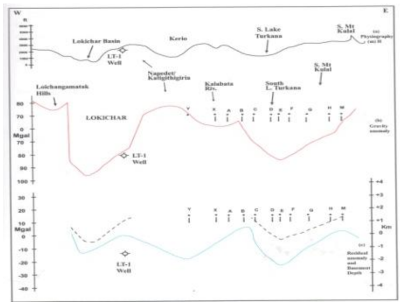

Figure 9: W-E Section of Bouguer Gravity anomaly values profile along Latitude 2o30'N. Between Longitudes 35o30'E and 37o00'E through Lokichar-Kerio, and Lake Turkana Basins

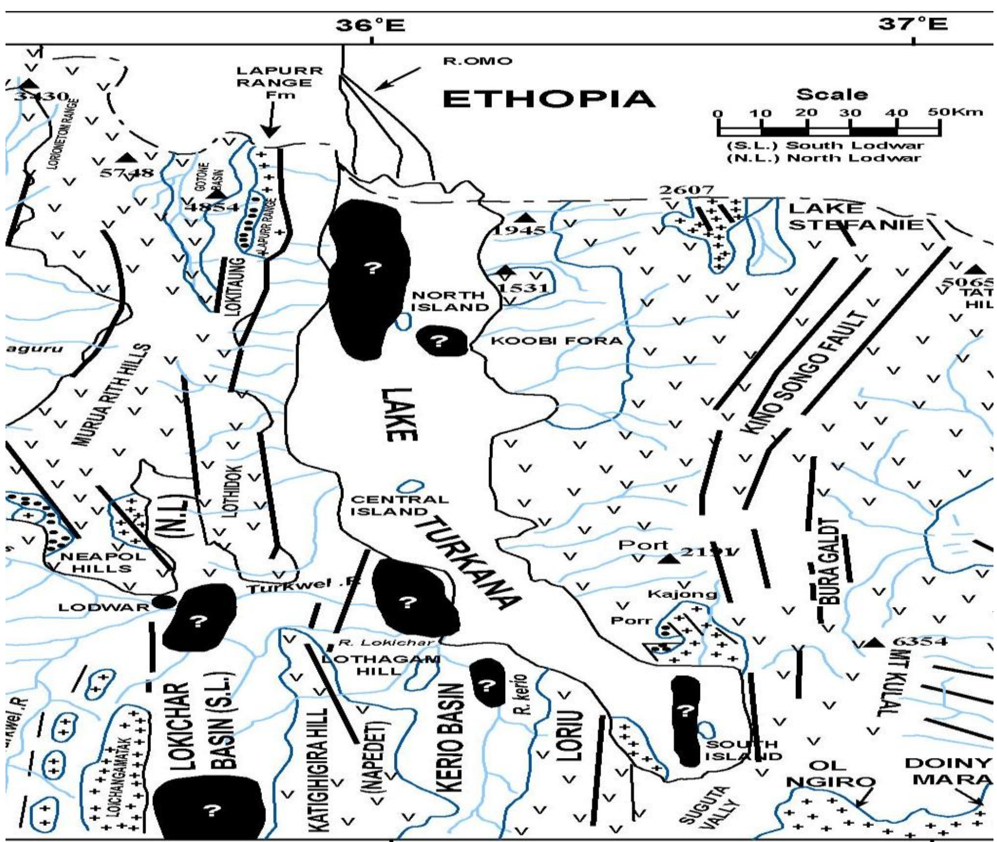

Figure 10: Map showing probable petroleum prospective areas (shaded black) in the Lake Turkana rift-related asymmetric and half-graben sub-basins

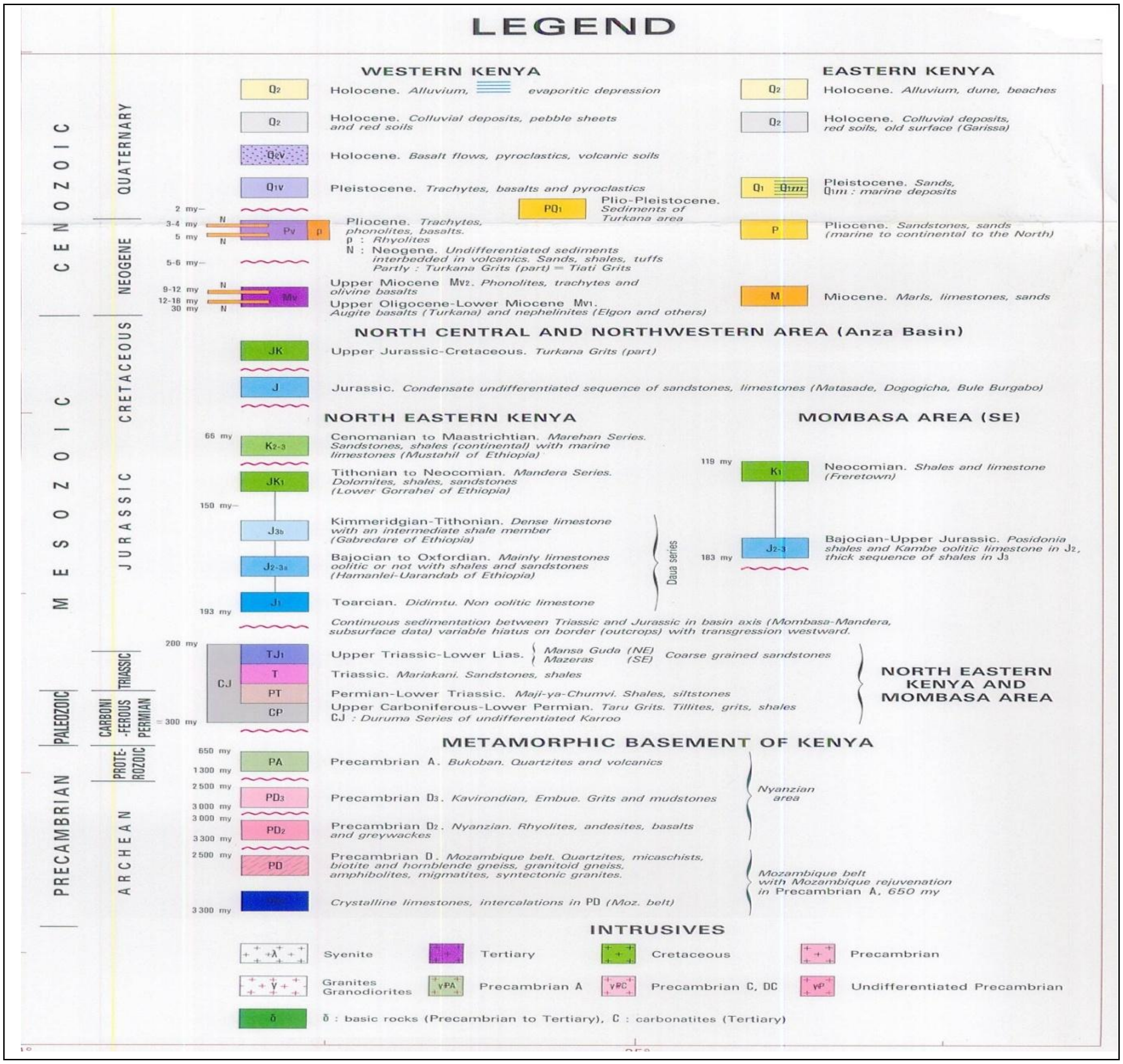

Figure 11: Explanation for Geological Coloured Maps in Figures 4 And 5 (Adopted from BEICIP-Ministry of Energy Geological Map, 1987)

4.0 CONCLUSIONS AND RECOMMENDATIONS

From the above four cross-sections, it can be concluded that the entire Lake Turkana subsurface basin is bounded by N-S striking faults and the thickness of the sediments seems to be maximum to the north and less to the south, since the basin seems to be deepening

northwards. The nature of the subsurface basin is like half-graben, which deepens and becomes more complex from south to north. There seems to be variations in the depth of the basement in this part of the basin from lats. 2°30'N to 4°30'N. It can be seen that between lat. 2°30'N and 3°N the basement shallows and is exposed to the surface. This is a horst-like structure which seems to be controlled by E-W faults. Beyond latitude 3°30'N, the basement deepens suddenly as has been interpreted earlier; it becomes deepest between latitudes 4°N to 4°15'N. The subsurface structure between latitudes 2°50'N to 3°45'N, based on gravity profiles and basement depth, showed that the basin also deepens towards the east; deepest towards the north between latitudes 3°30'N to 4°30'N. The subsurface structure is therefore very complicated, characterised by irregular downthrows and upthrows related first to the E-W faulting and later to the N-S faulting in the basin.

The gravity profiles of the Lake Turkana Basin present terrain have indicated that within the basin are sub-basins, which are asymmetric half-grabens bounded only on one side by a major fault and on the other side by a set of faults. The major faults define the boundaries with either a horst of basement rocks without volcanic cover or with a huge volcanic cover. The asymmetric rifts or half-grabens are intracontinental and the gravity profiles reveal that they characteristically occur over the crests of regional arches of the basement and the mantle, or, only on the continental crust with a trough-like mantle profile.

The infilled sediments are predominantly non-marine but it is possible that there is some marine influence during the initial sediments filling of the Lapurr Formation (Cretaceous) part of the basin. The geothermal gradients of the Cretaceous basins and those of the Tertiary should have been different, consequent to the non-uniform mantle upwarping as revealed by the gravity anomaly profiles. The structural profiles also revealed that the basin could have attracted potential petroliferous sedimentary sequences which are deposited on basement rocks of Precambrian age underneath the vast Lake Turkana Basin. Future drilling and fossil finds will provide additional stratigraphic attributes to these seismically defined sediments in the Turkana Basin.

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