A Paleoenvironmental Assessment of the Central Lake Albert Rift Basin - Uganda, East Africa from Exploration Well Geochemical Data*

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Abstract

East Africa has experienced a dynamic history of geological, climatological and ecosystem changes since the middle Miocene, which overlap with emergence of the human lineage. Presently, records of these changes are derived from sparse outcrops of lake sediments and volcanic rocks or from deep-sea cores situated at great distances from the continental interior. Detailed and continuous records of past environmental variability are limited, but the tectonic lakes of the East African rift system hold the promise of revealing such long-term changes. In this study, elemental geochemical data from drill cutting samples of a 3,392 m deep well drilled on the eastern shores of Lake Albert-Uganda, East Africa are used to investigate a long-term paleoenvironmental history and stratigraphic evolution of the central area of the Lake Albert rift basin-Uganda. The Ngassa-2 well was drilled through loose and coarse sands in the upper 300 m, massive mudstone deposits interbedded with siltstones for middle sedimentary section (300 - 3,250 m) and then conglomerate at the base (3,250 - 3,392 m). Results from XRF data and Total Organic Carbon (TOC) are indicative of warm and wet conditions around the late Miocene, later developing into cooler and dryer climatic conditions around the late Pliocene. These dry conditions are possibly related to aridification of East Africa around 3 Ma. Anoxic lacustrine conditions in the early Pliocene are documented by a dramatic rise in TOC and coinciding trends with iron (Fe) for the depth interval 3,000 - 3,250 m of the Ngassa-2 well. Additionally, integration of geochemical data, lithological observations, seismic data attributes and down-hole gamma ray logs provide evidence of a basin that transitioned from fluvial to generally mixed fluvial-lacustrine and subsequently dominantly lacustrine environment before shifting back to fluvial and shallow lacustrine system in the latest Pleistocene and Holocene. Changes in the variability of XRF and

TOC data over the full section may relate to orbital forcing of African climate since the middle Miocene, but confirmation of external forcing on this time scale awaits higher resolution sampling of the Lake Albert sedimentary section.

Introduction

The earth movements that formed the Albert basin probably started in the Miocene (Beadle, 1974) and maximum sediment thickness of the entire Albertine graben has been estimated to be approximately 4.6 km (Karner et al., 2000). The use of geochemical data from the Ngassa-2 well in investigating paleoenvironmental history presents an opportunity to understand stratigraphy, quantify lithological variability and along with seismic reflection data, to assess the facies architecture of the Lake Albert basin. Extensive hydrocarbon exploration of the onshore part of this basin has been carried out by several companies since 2002, resulting in the identification of several hydrocarbon prospects such as the Ngassa prospect first drilled in 2007 (Petroleum Exploration and Production Department, 2008). The Ngassa-2 well drilled on the Ngassa prospect (Figure 1) is the focus of this study, with special emphasis on geochemical aspects.

Methods

Samples used in this study were collected at the Ngassa-2 drill site in 2009. Over 400 samples selected at 10 and 11 m intervals were prepared and scanned for major and minor chemical elements using an ITRAX core-scanning instrument at the Large Lakes Observatory in Duluth, Minnesota. Major and minor elements measured using the ITRAX X-ray instrument include; K, Ca, Ti, Cr, Mn, Fe, Rb, Sr, Zr, Al, Si, P, S, Cl, Ar, Cu, Ni, Zn, Se, Ba, and Pb. The Costech ECS 4010 elemental analyzer at the Heroy Geology Laboratory, Syracuse University was used to determine the abundance values of total organic nitrogen, and total organic carbon in the samples.

Distributions of redox sensitive elements (Fe and Mn) in lake sediments have the potential to enhance our understanding of past climate processes in East Africa, an area of the world where such information remains scarce (Brown et al., 2000). An increase in TOC may indicate increased primary productivity, increased organic matter preservation and/or decreased dilution of organic matter from siliciclastic sediments (Meyers, 1997). Ti and Zr have been widely used as reference elements because they are largely insoluble, immobile and weathering resistant (Koinig et al., 2003).

Results

Of the 336 samples considered for analysis in the Ngassa-2 well, 205 of them have TOC values of 1% and above. Some of these samples, which would be potential source rocks, are from shallow depths of about 450 m. Six major geochemical stratigraphic units (A, B, C, D, E and F) were identified based on trends of all elements. Chemostratigraphic section C was further subdivided into four subsections (C1, C2, C3 and C4) due to dramatic fluctuations in Rb, K, Zr, Ti, Fe, Mn (Figure 3 PC1) and gamma ray, at intervals from 1,500 to 1,640 m and at 2,190 m. Potassium (K) displays very low values for the first 400 m and a more generally constant downward trend thereafter. Fluctuations at 1,400 m may be related to mud contaminants.

Principal Component Analysis

Component coefficients and component scores are visualized in a three-dimensional plot (Figure 2). The first component gives information about variability in Fe, Ti and Rb. High values of Fe especially in an organic rich basin like the Lake Albert rift basin, gives evidence of microbial decay from mainly terrestrial plants. The second component shows that Si, TOC and Compton scattering are the main contributors. Lithological descriptions of the well indicate predominant lacustrine claystone and shales with massive sand beds at the surface and only thin sandstone intercalations at greater depth. The third component provides information on Ca and Sr as main contributors. Sr concentrations are usually interpreted from silicates fractions of lake sediments. This may give an insight into productivity of the basin.

<u>Section A (3,391 to 3,250 m)</u>

This section shows generally low values of TOC, scattering ratio, Fe, Mn and Sr. Si:Ti and Zr are relatively high which suggests alluvial/fluvial deposition system of quartz and heavy mineral under intense physical erosional regimes (Cohen, 2003). Low Rb:K suggests fresh silicate minerals in the sediments, consistent with rapid erosion and transport. Additionally, the basal conglomerate implies high-energy currents or mass flows contributing to strong physical erosion of bedrock in the catchment area. These high-energy currents could have been influenced by rift tectonics that created high erosional gradients. The relatively low values of TOC coupled with evidence of heavy erosional regimes (increasing Ti and Zr) suggest low productivity. The highest C/N ratios of this section are observed in this section with values greater than 30. This trend implies organic matter of terrestrial origin (Meyers and Ishiwatari, 1995), which may indicate fluvial deposition.

Section B (3,250 to 2,520 m)

In section B, trends of Ca, Sr, (Figure 3 PC3) Zr, Ti, TOC and gamma ray (Figure 3) gently decrease upwards, compared to Fe and Mn, suggesting decreasing bedrock weathering and erosional regimes. In contrast, the higher initial values of Rb:K, followed by lower Rb:K in the upper part of this section implies an initial pulse of altered material followed by sustained input of relatively fresh material. The relatively high TOC (up to 9.6wt %) in this section is likely responsible for the tremendous hydrocarbon accumulations in the Lake Albert rift basin and suggests deep lake deposition under anoxic conditions.

Section C (2,520 to 1,410 m)

Patterns observed in geochemical data from this section reveal pronounced fluctuations in all elements with varying intensities. For example, the high variability shown by Fe/Mn ratios suggests changes in mixing regimes of the lake. Similarly, elements originating from silicate minerals such as K, Rb, Ti, Zr and Si show a general increasing trend in this section.

Sub-section (C1) with its enrichment in Fe and Mn suggests reducing environments. Elemental values of Ti, Zr, K, Rb, Ca and Sr are indicative of strong and short-term fluctuations approximately every 30m.

The elevated levels of the elements; K, Ti, Rb, Zr and Si in subsection C2 point to enhanced physical erosion of silicates from the watershed (e.g. Koinig et al., 2003). High Rb/K is suggestive of mobilization of previously weathered material.

The broad-peaked but steep negative spikes of Rb, Zr, K, Ti, Fe and Mn in sub-section C3 are indicative of an abrupt change of environmental conditions, most likely under wet conditions.

The top most sub-section C4 indicates a shift in trends with a sharp rise in Ca and notable decrease in Rb, Zr, Ti, Fe and Mn. Seismic data attributes show relatively continuous, high frequency and moderate amplitude reflectors, which imply lacustrine environments pointing to deposition by suspension in a deep lake.

Section D (1,420 to 650 m)

Resistant elements Zr and Ti are enriched in the top part of the section in contrast to decreasing/constant levels of Fe/Mn, TOC, K and Sr. The enrichment of Ti and Zr in the top part suggests intensified bedrock erosion and/or physical transport (e.g. Cohen, 2003).

Section E (650 to 280 m)

Section E is characterized at the top boundary by an abrupt negative shift in Ti, K and Rb. Fe, Mn and TOC remain almost constant. This shift coincides with a lithological transition from mainly silts and claystone to claystones with significant sand interbeds.

A very high C/N is indicative of dramatic climatic changes at this stage, possibly relating to changes from lacustrine to intensely fluvial deposition. At this depth, there is also a dramatic increase in Rb:K, increase in Ca and decrease in Sr:Ca. This suggests non-carbonaceous sediment deposition of mature reworked sediments.

Section F (280 to 0 m)

The top most section (F) is indicative of the lowest values of Rb, K, Ti, Fe, Mn (Figure 3-PC1) and TOC. Scattering ratio and Si are relatively high in this section with composition of about 80% loose sands. The relatively high Rb:K value is indicative of transport of mature reworked sands. This section mainly represents recent sediments related to river deposition, lacustrine deltas and 140 m in XRF data of all major elements is presented here.

Tectonic Impact

The basal fluvial sand deposits indicated by our data in section A (Figure 3) suggest initial development of low-elevation rift shoulders and possibly accommodation zones during the first stage, but these two structural elements may have limited influence on sedimentation. XRF data analyses and palynological interpretations indicate predominantly humid climatic settings as shown in section B, suggesting a large-deep lake. The deepest lacustrine conditions in Lake Albert are possibly indicated by the high TOC zone at about 3,200 m suggestive of anoxic conditions. Fluctuations shown especially in section B (Figure 3) may suggest changes from overfilled to balanced fill lake conditions.

Climatic Events

Results and discussions from our data show features that may be related to some regional (East African) and global paleoclimatic events. For example, available ages for our data are consistent with the onset of human evolution as investigated from East African fossils. Aridification of East Africa around 3 Ma, 1.8 Ma and 1 Ma may be related to dry conditions suggested in our data notably the boundary between sections C and D. The general lack of volcanic records and datable ash deposits makes age dating challenging, and hence it is difficult to match our data to East African /global climatic events with precision.

Conclusions

The Ngassa-2 exploration well presents the most continuous sampling to date of the sedimentary section from the late-Cenozoic East African Rift System. The cuttings samples recovered from this well represent phases of basin evolution from rift inception through the present. Deep basin hydrocarbon accumulations in the Albertine Graben mostly date back to the Pliocene, a predominantly wet period of tropical African geologic history.

A multi-proxy analysis comprising of lithology, XRF, TOC, gamma-ray and seismic reflection data indicates a general transition from a generally alluvial/fluvial deposition system in section A to a relatively mixed fluvial-lacustrine environment up to about 1,600 m (late Pliocene) and this is associated with a gradual change from very humid conditions to relatively arid conditions. Interpretation of depositional environments in these two sections indicates alluvial plain at the base to delta plain environments.

Analysis of the bulk geochemistry of cuttings samples of the Ngassa-2 well provides insights into major East African paleoclimatic events. Further geochemical analysis on other deep well samples in the basin will provide additional information on the link between regional East African and global climate.

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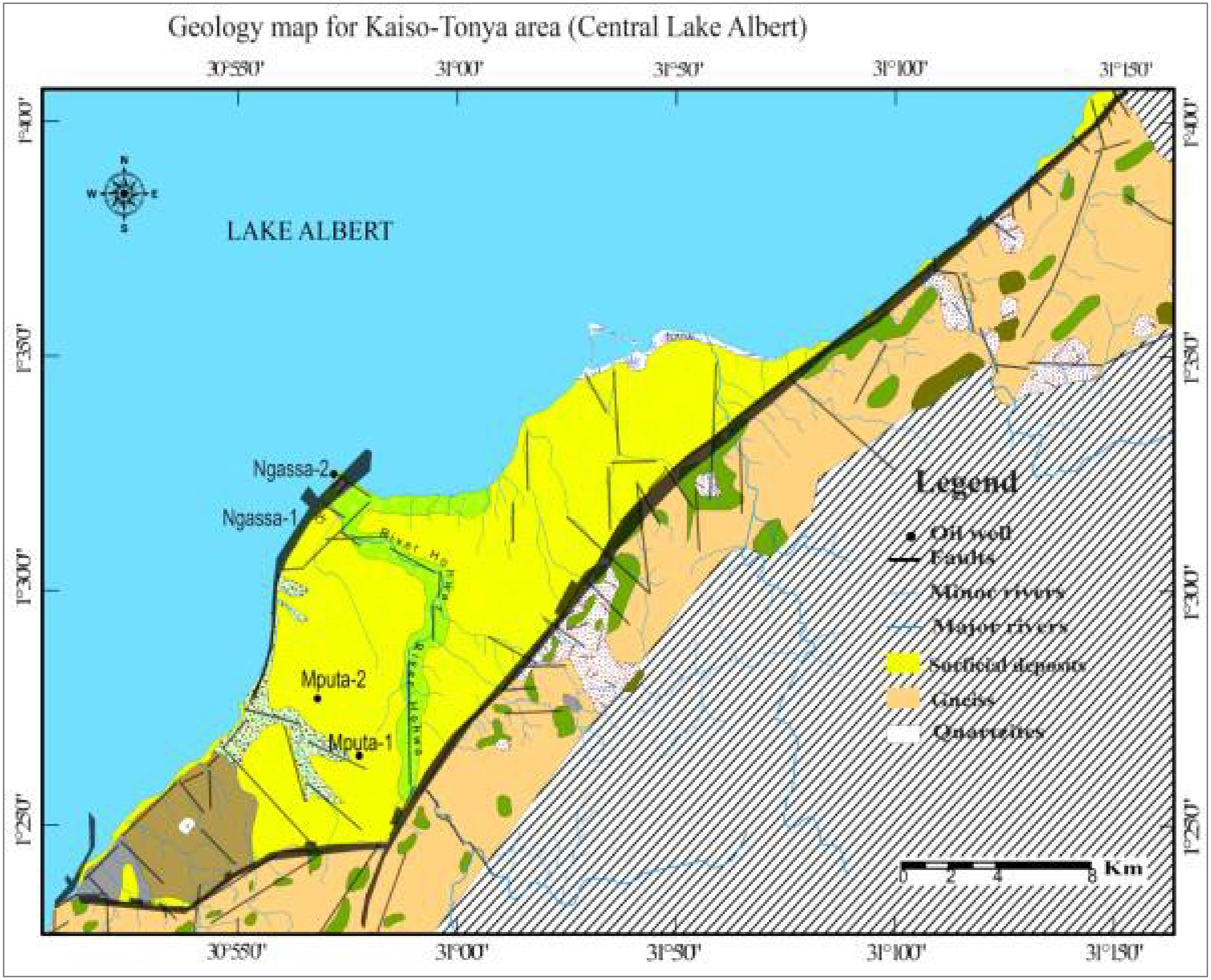

Figure 1. Geology of the Kaiso Tonya area (central Lake Albert) (from PEPD, 2008).

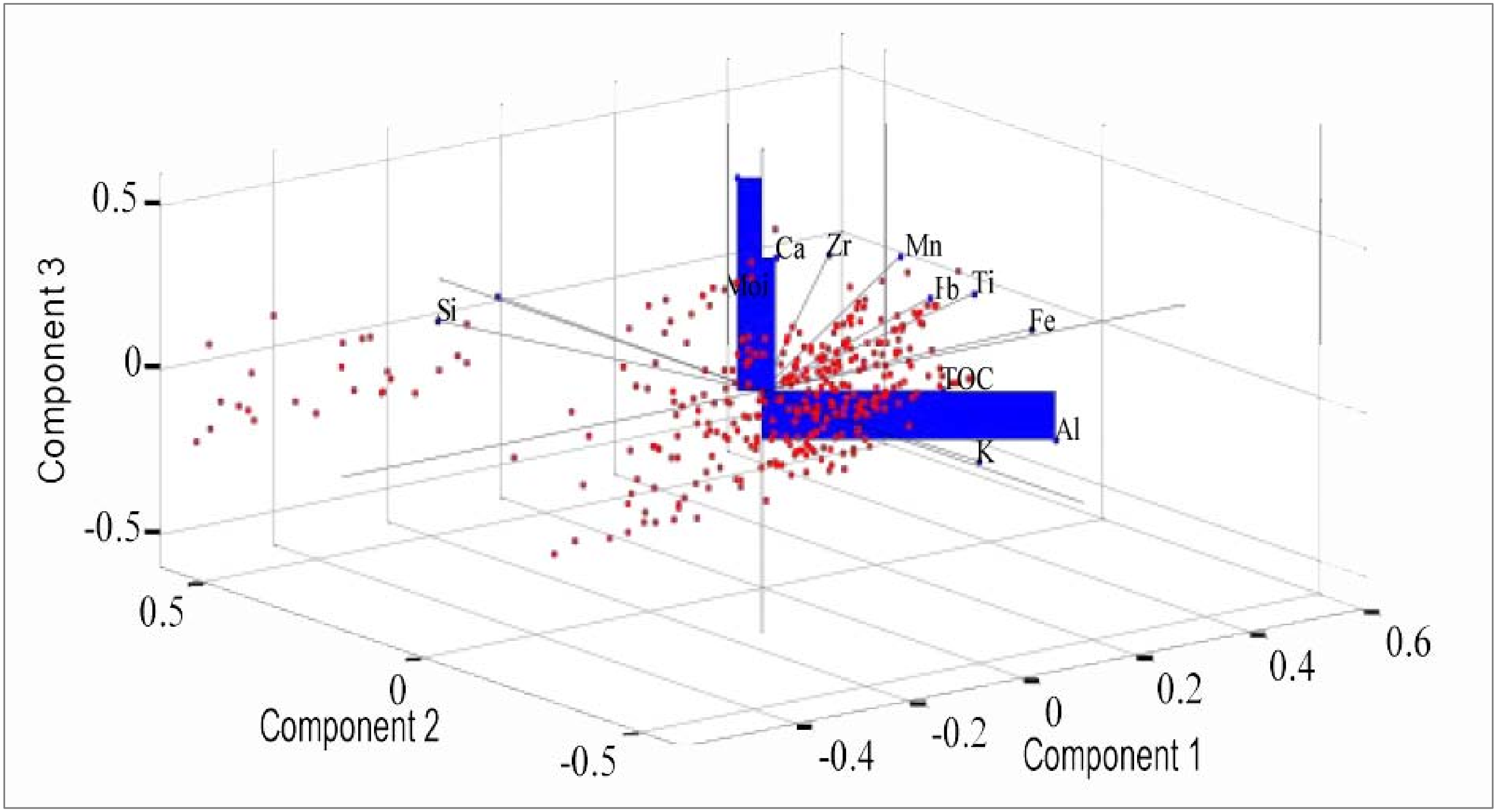

Figure 2. A 3-D visualization plot of principal component coefficients (blue lines) for each variable and principal component scores (red points) for each observation in a single point.

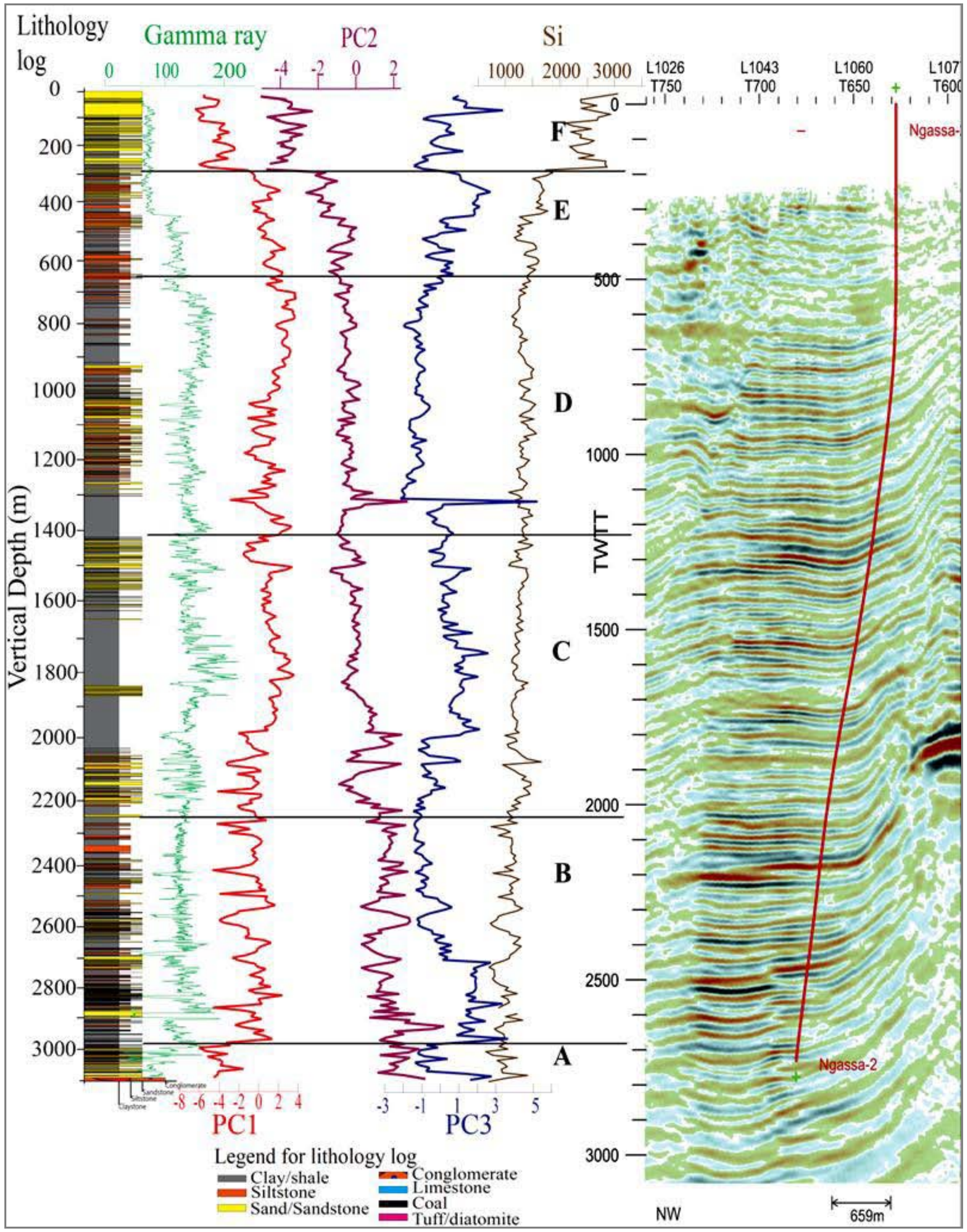

Figure 3. Synthesis panel- lithology, gamma ray, TOC, xrf plots, seismic data. Note that depths have been converted from measured (deviated) to true vertical depth. Note that PC1 has Fe, Ti, Rb, and Zr as main contributors while PC2 has Si, TOC and scattering measure Moinc, PC3 has Sr and Ca.