ZIBELINE INTERNATIONAL™ PUBLISHING

ISSN: 2521-0890 (Print)
ISSN: 2521-0491 (Online)
CODEN: GBEEB6

Geological Behavior (GBR)

DOI: http://doi.org/10.26480/gbr.02.2024.106.117

CrossMark

RESEARCH ARTICLE

TECTONOSTRATIGRAPHIC RESPONSE TO FAULTING IN RED BED ENVIRONMENT USING LIDAR DATA: THE ABU ZENIMA FORMATION SINAI

Auwalu Yola Lawan[a], Abdullah Musa Ali[a*], Byami Andrew Jolly[b]

[a] *Department of Geology, Bayero University Kano*
[b] *Department of Geology, Ahmadu Bello University, Zaria*
**Corresponding Author Email: amali.geo@buk.edu.ng*

ARTICLE DETAILS

Article History:

Received 23 May 2024
Revised 15 June 2024
Accepted 19 July 2024
Available online 23 July 2024

ABSTRACT

This study investigates the tectono-stratigraphic response of the continental red beds of Abu Zenima Formation, Sinai using digital outcrop modelling to the evolution of the intra-block Nukhul fault zone during the Oligo-Miocene initial rifting phase in the Suez Rift, Egypt. Nukhul fault zone is one of the several intra-block fault zones from a 500 Km^2 area of the Hammam Faraun fault block and is interpreted to have evolved from two isolated fault segments trending NW-SE. Abu Zenima Formation represents the early fluvio-lacustrine syn-rift stratigraphy and documents an early phase of basin fill in the hanging-wall of Nukhul fault zone. The stratal geometries are characterised by considerable along-strike variability in thickness and onlap relationship. The thickest stratigraphy developed towards the centre of the fault segments. This shows variation in displacement along the strike from maxima at fault centre to minima at fault tip produced as a result of temporal and spatial evolution of normal fault growth. Fault-propagation folds that form due to the growth of extensional faults, in particular fault-parallel syncline and fault-perpendicular anticline control the structural style of the early syn-rift basin. The observed onlap relationship of the lower stratal geometries and the subsequent pronounced thinning of the upper stratal geometries towards the fault-perpendicular anticline from the two NW-SE segments, indicates that the two fault segments interacted at an early age during the initial rifting and were subsequently linked as a normal fault zone. The implication of this study could be related to hydrocarbon exploration of early syn-rift play in many rift basin within the passive (Atlantic type) continental margins. Such basin contains excellent fluvial reservoirs with thickness variation, truncation and onlap relationship across the basin. Thus, understanding the tectonic control and other synorogenic sedimentation and resultant depositional geometries of syn-rift sedimentary rocks will substantially reduces hydrocarbon exploration risk.

KEYWORDS

fluvial reservoirs; syn-rift sedimentary rocks; Abu Zenima Formation;

1. INTRODUCTION

Many workers have recognised that fault segments growth, propagation and linkages in a typical extensional setting that form a continues basin-bounding normal fault zones is the first order control on the size and shape of rift sedimentary basin (e.g. Gawthorpe et al., 2003; Sharp et al., 2000; Gawthorpe and Leeder, 2000). The Stratigraphy and the geomorphology of the hinterland portrays the evolution of such normal fault zones (Gawthorpe and Leeder, 2000). The importance of syn-rift sedimentary rocks in rift basin should not be overemphasized. Their sedimentary fills are attractive but challenging hydrocarbon reservoirs. They are attractive because large volumes of coarse clastic syn-rift sediments can be transported into the basin, creating high quality reservoirs (Pivnic et al., 2003). Also their bounding tectonic structures provide: sink with high preservation potential for sedimentary and fossil records of past change in climate, sea/lake level and sediment/water supply, information on the growth, activity, decay and death of normal faults (Gawthorpe and Leeder 2000).

Normal fault evolution models show that faults grow by systematic increases in maximum displacement and length, and also shows that faults within a fault population become linked with time (e.g. Gawthorpe et al., 2003; Young et al., 2003; Roche et al., 2017). The rate of displacement "vary spatially along the strike from maxima at fault segment centre to minima at fault tips which result in an asymmetric half-graben configuration" (figure 2) (Gawthorpe et al., 2000). Also observation from a variety rift basins indicate that fault propagation folds are an important element in the development of normal fault zone which also exerts control on the evolution of rift basins and the associated early syn-rift sedimentary fills. (Gawthorpe and Hardy,2002). In particular "transverse folds at high angle to fault strike are associated with along-strike displacement gradient in hanging wall of normal fault while transverse anticlines are associated with displacement minima at segment boundaries" (Gawthorpe and Hurst, 1993). Other folds associated with normal faults zone lie parallel to the fault zone and were form due to ductile deformation ahead of the propagating fault tip. These fault propagating folds are commonly preserved as monoclines in the footwall of normal faults and as hanging wall synclines (Gawthorpe and Hardy, 2003).

This study was undertaken incorporating the tectonostratigraphic analysis using a digital outcrop modelling approach to study the normal fault array evolution; growth, propagation and linkages in controlling the stratigraphy of the early syn-rift fluvio-lacustrine Abu Zenima Formation

Quick Response Code	Access this article online	
	Website: www.geologicalbehavior.com	**DOI:** 10.26480/gbr.02.2024.106.117

Cite The Article: Auwalu Yola Lawan, Abdullah Musa Ali, Byami Andrew Jolly (2024). Tectonostratigraphic Response to Faulting in Red Bed Environment using Lidar Data: The Abu Zenima Formation Sinai. *Geological Behaviour 8(2): 106-117.*

in the hanging wall of the Nukhul fault zone. This study analyses the control of fault propagation folding in the evolution of stratal geometries and architecture of the early syn-rift deposits of the Abu Zenima Formation. The spatial and temporal variability of the fluvio-lacustrine Abu Zenima Formation facies was analyzed in terms of thickness and depositional environments. This way, the controls on the deposition and facies of the early syn-rift Abu Zenima Formation can be determined. The results will have an implication for sequences stratigraphic model and hydrocarbon exploration of subtle syn-rift hanging wall plays within extensional basins.

This study focuses on the control of normal fault evolution; growth, propagation and linkage of the intra-block Nukhul fault zone located in the central dip province of the Hammam Faraun fault block Sinai, Gulf of Suez (Figure 1) using the early syn-rift fluvio-lacustrine red beds of Abu Zenima Formation. The Nukhul fault zone is one of the several intra-block fault zones from a 500km^2 area of the Hammam Faraun fault block located in the eastern side of the Suez rift. It anticipated that the modelling results presented in this thesis could serve as an analogue for predicting syn-rift play using subsurface information such as high-quality seismic and wells, so as to constrained and reduced exploration effort in many rift basins across the globe that characterised passive (Atlantic-type) continental margins e.g. the North Sea basins, Gulf of Suez, the Jeanne d'Arc basin, the brazillian rift basins e.t.c.

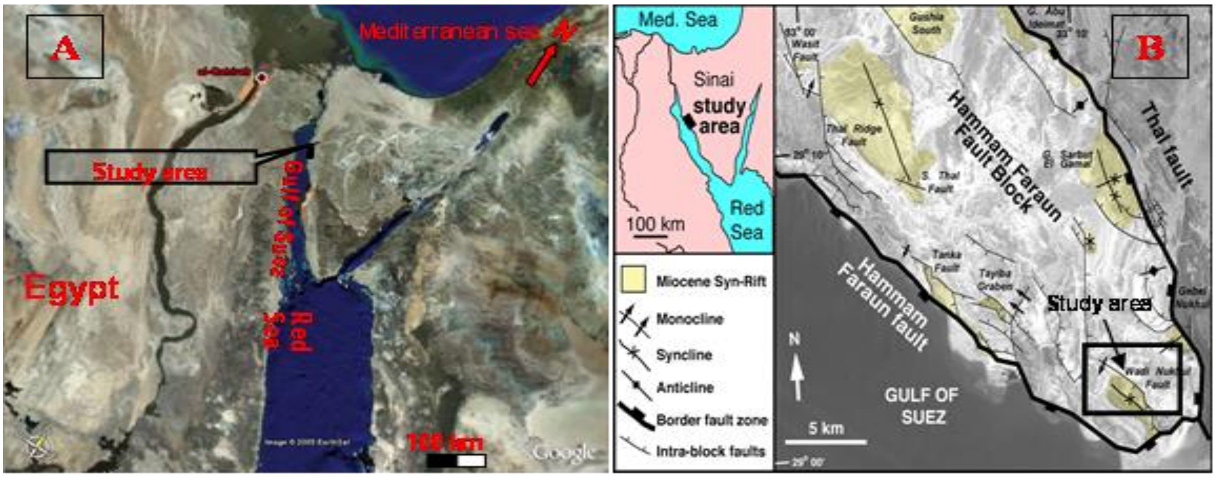

Figure 1: Location map of the study area (A); with the satellite image of the Hammam Faraun fault block (B). Note the study area is indicated in a box.

2. Geological Setting

The Suez rift has been described by many researchers as a northern continuation of the Red Sea, which developed during the separation of the African plate from the Arabian plate in the late Oligocene (figure 1) (e.g. Said, 1962: Moustafa,1993; Gawthorpe et al., 2003; Sharp et al.,2000; Young et al., 2003; Jackson et al., 2005; Gupta et al., 1999; Montenanat et al., 1988; Pivnic et al., 2003; Sharp et al., 2000). The rift has a northwest-southeast trend and is 300km long as wide as 80 km. Normal fault strike parallel to the length of the modern gulf and are linked by shorter, slightly oblique transfer faults. A group researcher recognised that "the combined fault trends result in a classic extensional zigzag fault pattern in plan view" (figure 1), while in cross section, the rift is characterised by large tilted fault blocks 10-20 km across, the dips of which subdivide the rift into three asymmetric dip province along strike (Sharp et al., 2000). A group researcher stated that in the three distinct structural provinces of the rift, "in each province, the dip direction of major normal faults is constant; however the dip direction reverses 180^0 between provinces" (Pivnic et al., 2003). Also, structural complex transfer zones separate these provinces (Moustafa, 1993).

The dominant rift-parallel faults strike NW-NNW and were linked by subordinate NNE, E-W and N-S trending faults. In cross-section the NW-NNW trending faults bound major half-graben and rotated the fault blocks up to 40 km long and 25 km wide (Young et al., 2000).

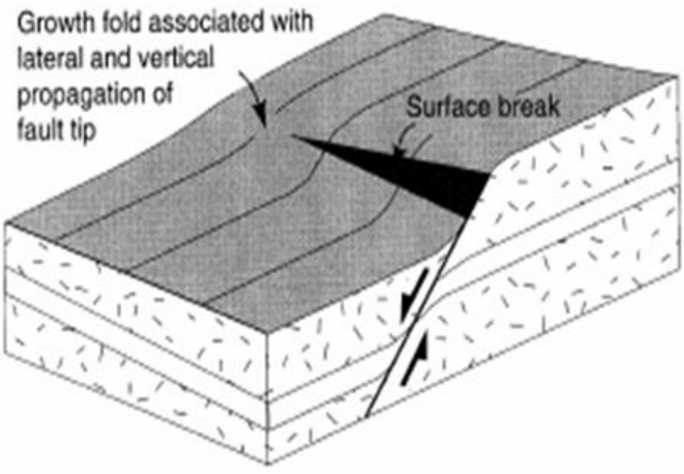

Figure 2: Schematic three-dimensional block diagram illustrating the manner in which surface-breaking normal fault pass along-strike into monoclinal fold (Adapted from Gawthorpe and Hardy, 2002)

2.1 Stratigraphic framework

The Stratigraphic framework of the eastern side of Suez rift was described, which can be divided into three sedimentary megasequences that unconformably overlies Precambrian Pan-African metamorphic basement (Figure 3) (Sharp et al., 2000). Here they described megasequences 1 comprises predominantly non-marine Nubian sandstone of Cambrian to Early Cretaceous age, megasequences 2 is made up of mixed carbonate and clastic marine dominated succession of Mesozoic to early Tertiary age and megasequences 3 comprises the syn-rift and post rift sediments that unconformably overlies the pre-rift strata (Sharp et al., 2000). This megasequences "has traditionally been divided into two groups; 1. The basalt clastic-dominated Ghrandal Group, and 2. The overlying, predominantly post-rift evaporitic Ras malaab" Group (Sharp et al., 2000). This study focuses on the Abu Zenima formation fluvio-lacustrine sediments of Ghrandal Group deposited during the period of rift initiation in the late Oligocene.

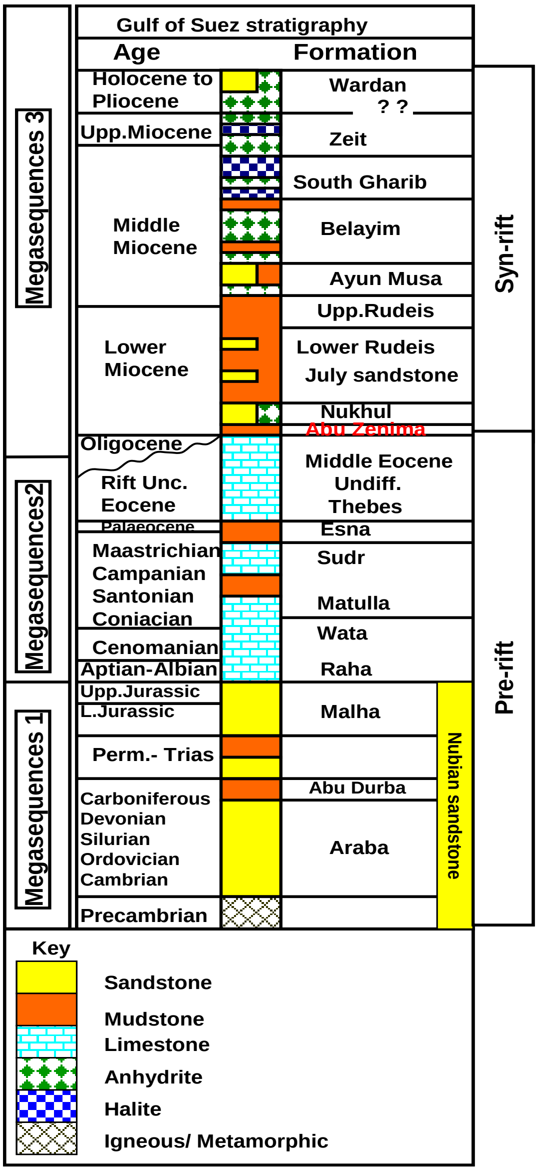

Figure 3: Composite stratigraphy of Gulf of Suez (modified from Pivnic et al., 2003)

2.2 The Abu Zenima Formation

Abu Zenima Formation is facies association 1 situated at the base of the syn-rift succession (Figure 4) and represent the initial syn-rift depositional unit in the hanging wall of Nukhul fault and has a thickness ~ 80 m with a lateral continuity of more than 3 km along the fault zone strike (Young et al., 2003). The formation as described by Sharp consists of conglomeratic facies (facies 1a) that constitute more than 90% of the facies association and mudstone facies (facies 1b) (Sharp, 2000). Based on detailed analyses of the deposits in terms of grain size, sedimentary structures and absent of fossils, the depositional setting of the facies association 1 was interpreted to be continental (Young et al., 2003).

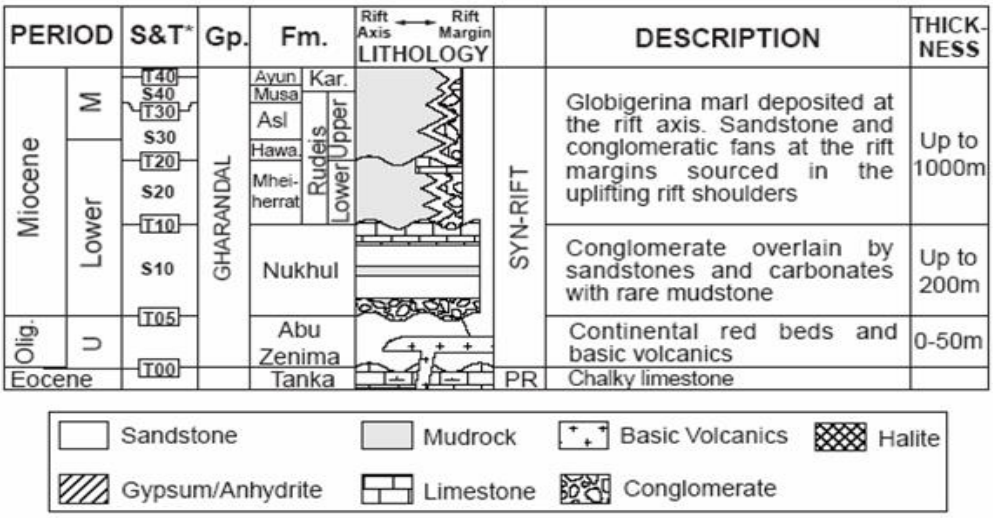

Figure 4: Stratigraphic column for the syn-rift of the Gulf of Suez. Biostratigraphic sequences (S) and Terraces (T) (Krebs et al., 1997; Adapted from Wescott 1996)

Cite The Article: Auwalu Yola Lawan, Abdullah Musa Ali, Byami Andrew Jolly (2024). Tectonostratigraphic Response to Faulting in Red Bed Environment using Lidar Data: The Abu Zenima Formation Sinai. *Geological Behaviour 8(2): 106-117.*

2.3 Structural evolution and style of Hammam Faraun fault block

The structural characteristics and tectonic evolution of Hammam Faraun was documented from the work of (Moustafa, 1992; Gawthorpe et al., 2003). Moustafa defined a fault block "as an area several tens of kilometres in length and width that includes a group of second-order (relatively small, several kilometres wide) fault blocks and is separated from adjacent rift blocks by major faults that have throws on the order of several hundreds of meters to a few kilometres" (Moustafa, 1992). Thus, Hammam Faraun is one of the main eastern margin fault blocks exposed on the Sinai Peninsula in the central dip province of the Suez rift (Figure 1), the Suez rift is the NW extension of the Red sea rift which developed in the Oligo-Miocene due to the separation of the Arabian plate from Africa (Gawthorpe et al., 2003; Young et al., 2000).

The fault block has typical half-graben geometry, dipping moderately to the east (12-15^0) and is up to 25 km wide and is bounded to the east and west by major normal fault zones; the Thal and Hammam Faraun fault zone respectively (Gawthorpe et al., 2003; Sharp et al., 2000; Moustafa, 1993). These major border fault zones are in excess of 25 km long, dip slightly to the west (60-80^o), and have displacement up to 5 km. The border faults have a zigzag pattern; the dominant fault strike is NW-SE with subordinate N-S, NNE-SSW and E-W trending segment (Figure 1). The southern boundary of the fault block is marked by the prominent E-W trending Baba-Markha fault.

The Thal fault zone bounded the block to the east and is a rift border fault that evolve by the progressive linkage of four fault segments namely: Nukhul, Sarbul El Gamal, Abu ideimat and Gushea segments (Figure 1). The four segments linked up in a "clysmic" pattern and trend NW-SE along the 8 km long fault zone "and have a doubly-plunging fault parallel synclines in their hanging walls" (Gawthorpe et al., 2003). Fault displacement was documented to be "greatest in the south (ca. 2 km) where the Thal and Baba-Markha faults branch, and decreases northward to 1.3 km at Gebel Sarbut El -Gamal,600-700m at Gebel Abu Ideimat, and ultimately to zero at the fault tip over 30 km to the north of the branch point" (Gawthorpe et al., 2003). Also, Gawthorpe pointed out that "the northward decrease in displacement is accompanied by the progressive northward younging of pre-rift strata exposed in the footwall of the fault zone suggesting decreasing footwall uplift to the north (Gawthorpe, 2003).

The Hammam Faraun faults zones bounded the block to the west also link up in a zigzag pattern like the Thal rift-bounding faults but have larger amount of throw ∼4800 m (Moustafa, 1993). The fault zone evolve relatively at late age during the Rudeis times (Lower Miocene-early Middle Miocene) and the faults segments linked up in the Late Belayim (Middle Miocene-Recent) and is still active (Gawthorpe et al., 2003).

The Hammam Faraun fault block is dissected internally by a series of mesoscale synthetic and antithetic fault zones termed as intra-block fault zones and have displacement of < 1 km and have a similar orientation and zigzag pattern to the border faults (Figure 1) (Gawthorpe et al., 2003). These faults zone are marked by fault propagated fold features which is an important deformation mechanism adjacent to the fault zones, with fold axes oriented both parallel and perpendicular to the fault zones. Fault–parallel anticlines and synclines occur within the footwall and hanging wall respectively, and can be traced laterally, parallel to fault strike, into unbreached monoclines located at the fault tips e.g. Tanka and Nukhul fault in the study area (Figure 1) (Sharp et al., 2000; Jackson et al., 2002). Fault-perpendicular folds are also pronounced in the immediate hanging wall of fault zones and die out within several hundred metres to 1-2 km of the fault zones (Sharp et al., 2003). Jackson observed that Stratigraphic relationships around these folds provide important information on the style of surface deformation around the fault zones and the timing of linkage of adjacent fault segments (Jackson, 2002).

In the evolution of Hammam Faraun, as documented by a group researchers, revealed that "the initial fault activity was distributed across the fault block on short, typically < 4 km long, low displacement (several hundred metres) fault segment that were isolated or interacted with their neighbours (Figure 5), the presence of the Abu Zenima Formation at the present tips of these fault segments suggest that the fault attained their final lengths very early in their growth (Gawthorpe et al., 2003). Interaction between segments occurred throughout Abu Zenima to Lower Rudeis times (24-18 Ma) with locus of fault activity migrating as some fault zones grew by segment linkage whilst others died (Figure 5 a and b). During this rift initiation phase, many of the intra-block fault zones (e.g. Nukhul fault zone) were surface- breaking and had greater displacement than the faults segments that became the Thal border fault zone".

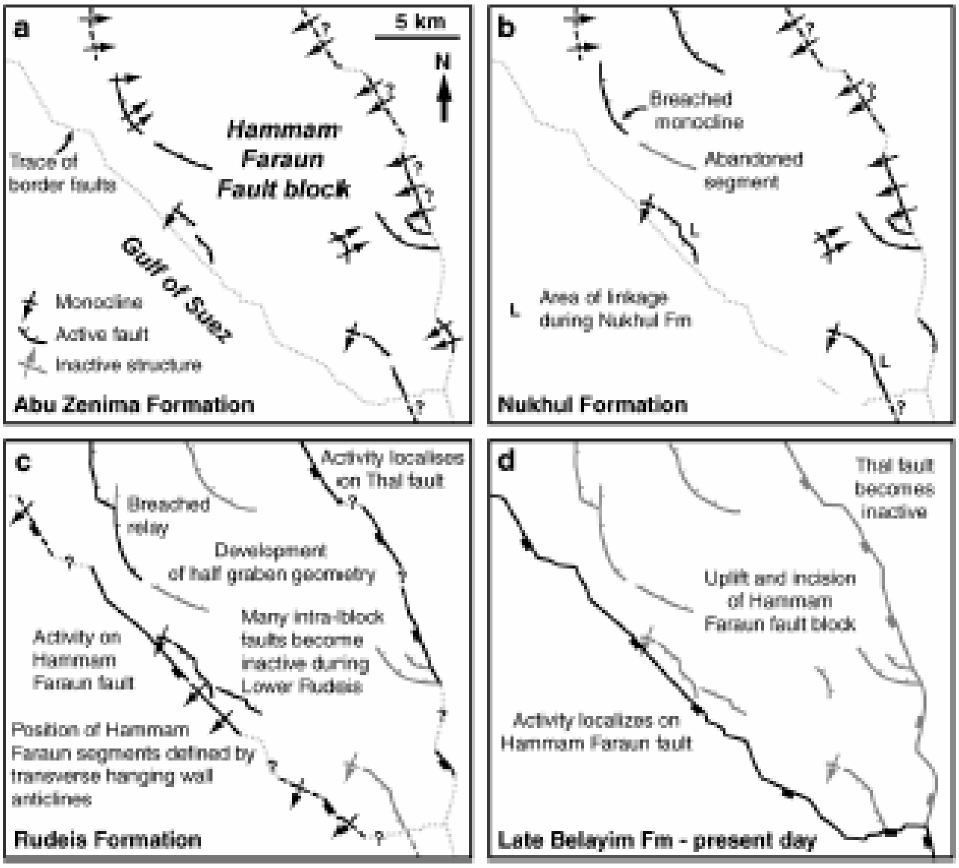

Figure 5: Evolution of the Hammam Faraun fault population (a) Abu Zenima formation (late Oligocene-earliest Miocene). (b) Nukhul times (lower Miocene). (c) Rudeis times (lower Miocene-early Middle Miocene). (d) Post Late Belayim Formation (Middle Miocene-Recent) (Adapted from Gawthorpe et al., 2003)

From Figure 5 above, the two border faults bounding the Hammam Faraun block "were not surface breaking normal fault during the rift initiation stage. Several synthetic and antithetic intra-block fault zones such as the Nukhul fault zone (of the study area), had the highest displacement during deposition of the Abu Zenima and Nukhul Formation, but died during, or soon after localisation of displacement on to the Thal fault zone during Rudeis times" (Gawthorpe et al., 2003).

2.4 Tectono-stratigraphy

The early syn-rift stratigraphy of fluvio-lacustrine Abu Zenima Formation, Sinai consist predominantly of inter-bedded reddened mudstone/marl and conglomerate with minor fluvial sandstone sub-facies and biostratigraphically correspond to S_{05} sequence of (Krebs et al., 1997). The Formation overlies major angular unconformity (T_{00}) in the pre-rift Tanka Formation and is erosionally overlain by tidally influenced Nukhul Formation (Krebs et al., 1997).

Abu Zenima Formation was deposited during rift initiation stage in the Acquitanian when a broad downwarping of Eocene surface occurred accompanied by normal faulting due to separation of African plate from the Arabian plate (Wescott et al., 1996). The initial rifting leads to distributed deformation within numerous small scale isolated fault segments having < 1km displacement (Sharp et al., 2000).

This initial episode is characterised by slow subsidence as the fault started to grow from the blind monocline fault tip to a surface breaking fault. Continual growth and propagation of the fault segment leads to varied displacement rate along the strike from maxima at fault centre to minima at fault tip resulting in an asymmetric half-graben basin configuration (Gawthorpe and Leeder, 2000). This invariably dictates the basin architecture that defined the depocentre and the drainage catchments from the foot wall derived, hanging wall dip slope and fault tip axial drainage. Normal fault growth is associated with fault-propagated folding, in particular, transverse folds at high angle to strike are associated with along strike displacement gradient, and in the hanging wall of normal fault, transverse anticlines are associated with displacement minima at segment boundaries, and fault-parallel syncline are associated with displacement maxima in the hanging wall (Sharp et al., 2000).

During the Abu Zenima time, two NW-SE normal fault grow and the associated fault-propagated folds comprising transverse anticline and fault-parallel syncline developed due to spatial displacement along the fault strike, which is the precursor to basin formation where fluvial river flow from fault tip towards the syncline and eventually terminated to form a lake at the depression. Continual growth of the isolated fault segments means continual distribution of deformation and this leads to segments interaction and eventual linkage. Fault interaction features are marked by a relay ramp indicating the two hanging-wall highs at the fault tip.

3. METHODOLOGY

This study focuses on the eastern onshore fault block; the Hammam Faraun which dip moderately 20°-30° toward the east and are bounded by large displacement in excess of 4 km; Thal fault zone (THZ) and Hammam Faraun fault zone (HFFZ) to the east and west respectively. The study area is the intra block Wadi Nukhul fault zone; one of the numerous meso-scale fault zone within the Hammam Faraun fault block and is located in the southern end of the block bordering Baba-Markha fault zone (Figure 6).

This study is based on the structural and stratigraphic analysis of terrestrial LIDAR (light detection and ranging) scan data sets acquired from the Oligo-Miocene early syn-rift outcrop deposits of red bed environment; the fluvio-lacustrine Abu Zenima Formation, along the NW-SE strike of the intra-block Nukhul fault zone. The system is linked with a differential global positioning system (DGPS) for the location of scans stations. The dataset from eleven (11) scan locations with a total number of fifty-four (54) 3D scan images along the strike of the NW-SE intra block Nukhul fault zone (Figure 1) were interpreted for the study.

The 3D scan datasets were acquired using the Riegl LMS Z420i laser scanner, and the Trimble Pro XR differential global positioning system (DGPS) for scan locations. All the data from the ground-based LIDAR surveys were processed with Innovmetric Incorporated Polyworks software. Here individual scans were "merged on the basis of feature matching from one scan to the next" (Bellian, 2005). Stratigraphic interpretation of the stratal surfaces within the Abu Zenima Formation was done in Riscan Pro. Software and the picked surfaces (Polylines) were exported into Schlumberger's Petrel; a PC based modelling package where the final digital outcrop modelling was carried out.

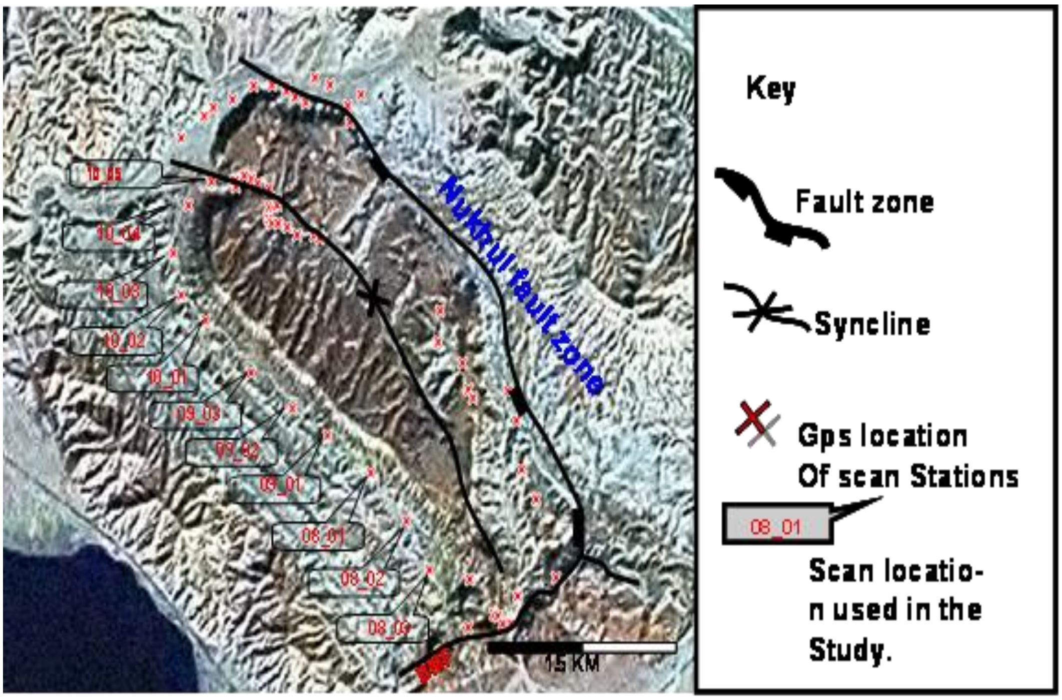

Figure 6: Satellite map of the intra-block Nukhul fault zone (see Figure 1 for location), showing landsat image of the GPS location of LIDAR scan stations indicated used in the study. Note the scan stations lies along the strike of the Nukhul fault zone to the west (Modified from Hodgetts, 2005).

3.1 LIDAR

The LIDAR technique is applied in complex 3D earth models from outcrops for stratigraphic modelling (Digital outcrop modelling), and for improved reservoir modelling as conditioning data (Bellian, et al., 2005). Digital outcrop modelling is built from the "triangulated irregular network of points commonly known as triangular mesh files. These files have explicit point defined in 3D space (X, Y and Z) with the option to add attributes such as colour, laser intensity, to each random point. In stratigraphic modelling, horizons are digitized directly on the 3D point cloud and exported to modelling software as ASCII format 3D line or irap classic point file for the construction of 3D Geocellular model. These horizons defining the top and base of each stratal unit, becomes the bounding surfaces for the grid cells of the model (Bellian et al., 2005). Although no substitute to field work, LIDAR no doubt provides 3D visualisations and perspective view which aid extraction of both qualitative and quantitative geological information (Figure 7).

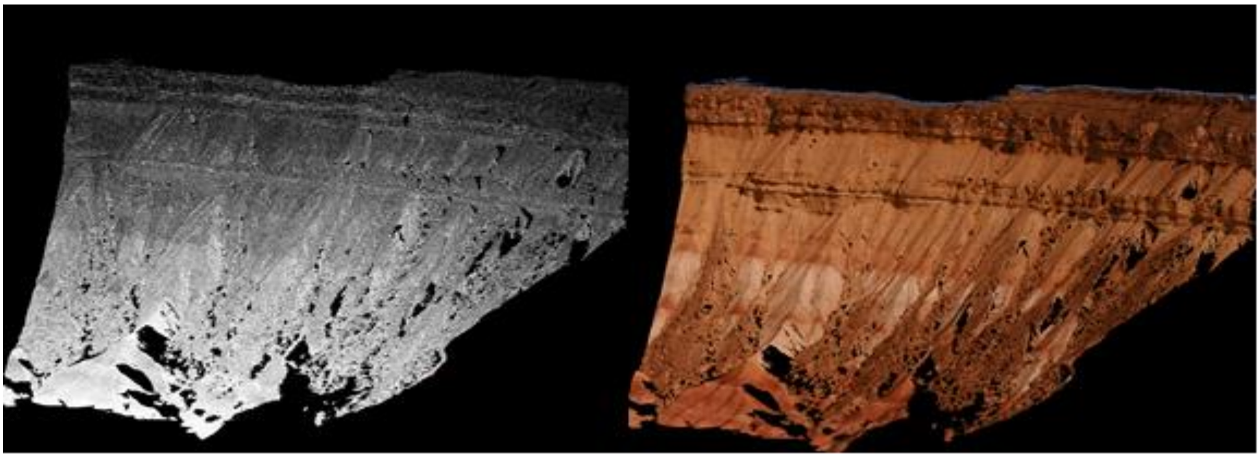

Figure 7: Laser Scanner above and scans images showing high resolution image (left) colour coded for reflection intensity and image (right) colour coded with RGB values from the digital photographs of the study area.

3.2 Modelling work flow

3.2.1 Data interpretation

The data based used in this study comprises fifty-four (54) high resolution scan acquired from eleven scan stations along the strike of Nukhul fault zone (Figure 8). The scan data sets were processed with Innovmetric Polyworks Software where the various scan were merged. Data interpretation was done in Riscan Pro. Software where the high-resolution images colour coded for reflection intensity was colour coded with RGB values from the digital photographs of the study area. Interpretation of stratal surfaces within the Abu Zenima Formation was done by merging two or three scan images from a scan station and the surfaces were interpreted by picking them with Polylines. Such surfaces were interpreted and correlated across the scan datasets and sorted out according to each stratal surface.

Eleven stratal surfaces were interpreted within the early syn-rift Abu Zenima Formation defining the Top/Base Nukhul and pre-rift/-syn-rift contact. Five zones were identified – made up of inter-bedded mudstone and conglomerate facies and a minor sandstone subfacies associated with the conglomerate facies. Interpreted surfaces from these zones in the form of Polylines and in dxf format were exported out from the Riscan Pro. Software into an in-house developed application where the dxf format was "stripped" to ASCII format and imported into Schlumberger Petrel software where the final digital outcrop modelling was done. The imported data in Petrel representing same surface was merged/ appends as one dataset using setting command. Problems encountered due to inversion of the data points was resolved by using Z=Z- functions in the general function tab. Structural modelling commenced by defining the model as Abu Zenima.

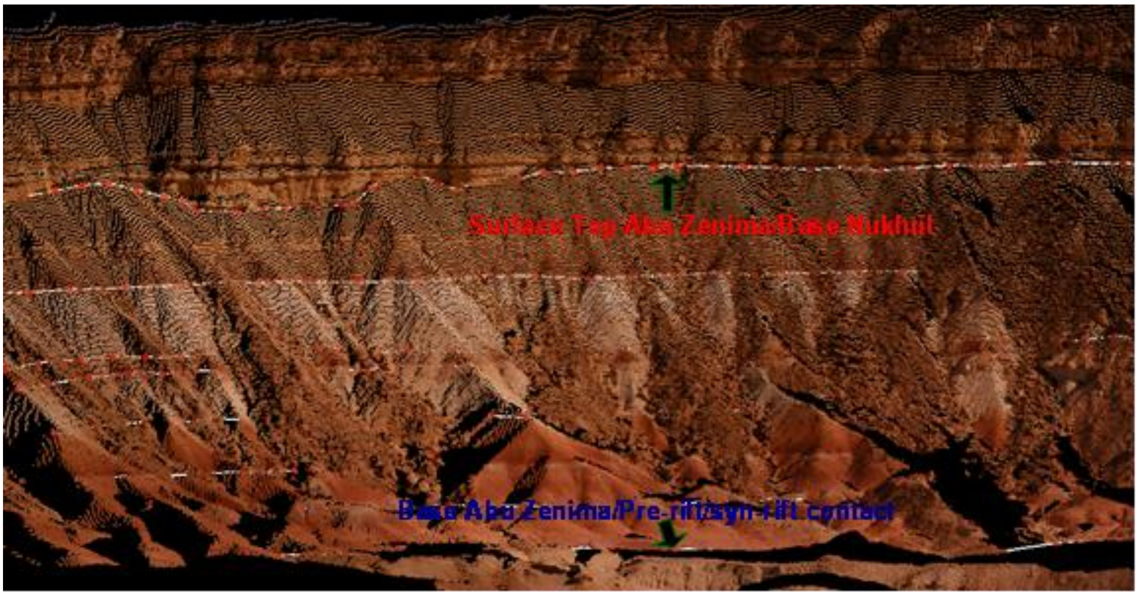

Figure 8: Scan image showing the interpreted surfaces from Polyworks software.

3.2.2 Fault modelling from outcrop data

Normal Fault was discovered toward the SE in the syn-rift succession and was interpreted with the point data. The fault is dipping NE with an approximate 80 m throw. Fault modelling is the first stage adopted in building the model so as to define the structural framework. The fault point data representing the fault plane was used to create the key pillars for pillar gridding. This fault defined the breaks in the grid; lines along which the horizons inserted later may be offset. Pillar gridding was done which defines the framework of the horizons and was done by approximately following the shape of the model outcrop from the input data.

3.2.1 Make horizons and zone modelling

"'Horizons' are surfaces within the model that define the overall Stratigraphic structure, while 'Zones' are the intervals within the model that represent genetically related units" (Hodgetts et al., 2004). This method was adopted to allow making the model building easier by subdividing the model into geologically meaningful interval based on facies association and key geological relationship such as onlap.

In the Abu Zenima model, the zone definition was based on the inter-bedded major facies association of reddened mudstone and conglomerate. Five zones were delineated composed of eleven key horizons that bounded the Abu Zenima Formation from the Top Abu/ Base Nukhul to Pre-rift/Syn-rift contact, as shown in Figure 9. This was achieved through correlation within the high-resolution scan data sets. Map of these horizons were produced showing the variation of topography. Layering was done to inserts the fine scale grid cells which will describe the vertical variation within each geological zone. Proportional zone division was used so as to have constant number of cell layers at every pillar of the grid. The cell layering conforms to both top and base of the zone.

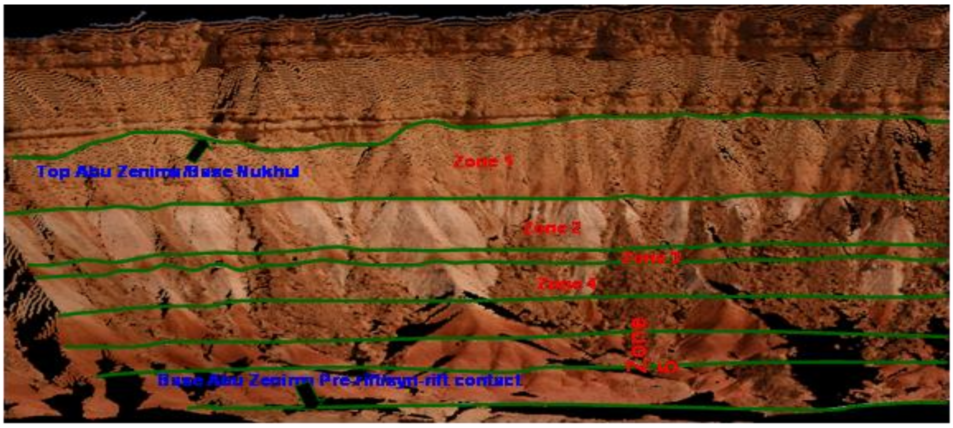

Figure 9: Scan image showing interpreted zones within Abu Zenima Formation.

4. RESULTS AND INTERPRETATIONS

The description and interpretation of facies association 1 of is given below (Young et al., 2003).

4.1 Facies Association 1: Continental

4.1.1 Facies 1a: pale grey conglomerate with minor sandstone

Facies 1a occurs immediately above pre-rift strata and above/inter-bedded with reddened mudstone (Facies 1b). The facies has an erosional base and consist of poorly sorted, clast-to matrix-supported conglomerate that has fine sandstone to mudstone matrix. The clast are typically rounded to subrounded in shape, range in size from <1cm to 1m, and are predominantly composed of white Eocene Tanka Formation (95%),with rare brown muddy limestone and bio-clastic limestone clasts of the Thal/Khaboba or Darat Formation (5%).The facies is crudely bedded on a metre scale, marked by a clast size variations. Individual beds are generally planar, ungraded, lack primary sedimentary structures (e.g. cross-bedding or clast imbrications) and have sheet-like geometries. A minor sandstone sub-facies occurs inter-bedded within the conglomerate, but comprises <5% of the facies unit as a whole. The sandstone is fine-grained; centimetre-decimetre-scale planar bedded and is generally eroded into by the conglomerate beds.

4.1.2 Facies 1b: variegated mudstone

Facies 1b consists of massive mudstone that has a variegated red/brown to purple colour and occurs immediately above the pre-rift strata, where it varies from < 1-10 m in thickness. It is inter-bedded with, and typically incised into by conglomerate (Facies 1a). The mudstone commonly contains pale grey carbonate nodules that generally occur at specific horizons. They have two main forms: irregular patches or nodules that are up to 20 cm in diameter and vertical streaks that are a few centimetres in width and up to 30 cm long.

Generally, the lack of any marine indicators such as fauna or trace fossils, together with the presence of pedogenic carbonate within facies 1b, suggests that these facies are non-marine. The clast/grain size, generally planar, sheet-like internal bed geometries, lack of cross-bedding and lack of upward finning motifs indicates that facies 1a was deposited as gravel sheets or low relief longitudinal bars within a fluvial setting, where the lack of slip-face deposits (cross-bedding) suggests that gravel-bed streams were shallow with gravel rapidly deposited. The fluvial system probably consisted of wide, shallow ephemeral river beds, similar to the present – day wadis in Sinai, Egypt. The mudstone facies 1b and also the minor sandstone in facies 1a were most likely deposited from suspension/waning flow during channel abandonment following a flooding event. Mudstone was also probably deposited in playa lakes adjacent to the wadis. During intervening non-depositional periods, evaporation, oxidation and pedogenic processes occurred, resulting in the precipitation of calcrete nodules within soils, and also preferentially around rootless (vertical streaks). During unconfined flash flood events, gravel was frequently transported across the mudstone (facies 1b) into which it incised (Young et al., 2003).

4.2 Data Modelling

The model build using Schlumberger's Petrel is hereby used to presents the description of the stratal surfaces that defined the zones, and then the description and interpretation of the zones using their thickness maps. Eleven stratal surfaces that bounded five zones were interpreted and modelled based on facies association and key stratigraphic elements such as onlap (Figure 10). Some of these surfaces are described and interpreted below using bottom-up approach.

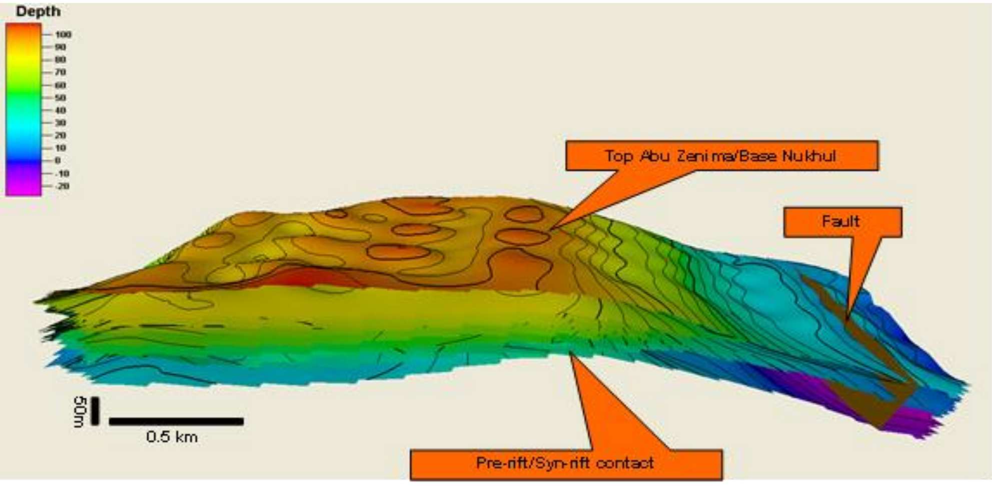

Figure 10: Display of interpreted surfaces displayed as horizons from Petrel software.

4.2.1 Prerift/synrift contact (Base Abu Zenima Formation) surface

The surface trends NE-SW and is characterised by topographic variation from low at the NW separated by high at the centre and was proceeded by gently dipping low towards the SE, with subtle variation of undulating nature. The surface is also faulted at the SE with a normal fault dipping towards the North (Figure 11). The considerable topographic variation from low to high and then low of the surface suggests the surface to be erosional. This surface represents the Pre-rift/syn-rift contact that equally defines the base of Abu Zenima Formation and was interpreted based on boundary between the reddened mudstone facies of Abu Zenima and the Eocene Tanka white limestone.

4.2.2 Top Abu Zenima/Base Nukhul Formation surface

This surface trends NW-SE and is characterised by considerable topographic variation with undulating nature of low and high topography. The surface progressively gets low towards the SE (Figure 11). This surface was interpreted to represents the Top Abu Zenima Formation/Base Nukhul. The undulating nature at the NW is due to erosion of the top most mudstone facies eroded by fluvial channel system. The surface is markedly delineated by mudstone facies and lower sandstone of Nukhul Formation

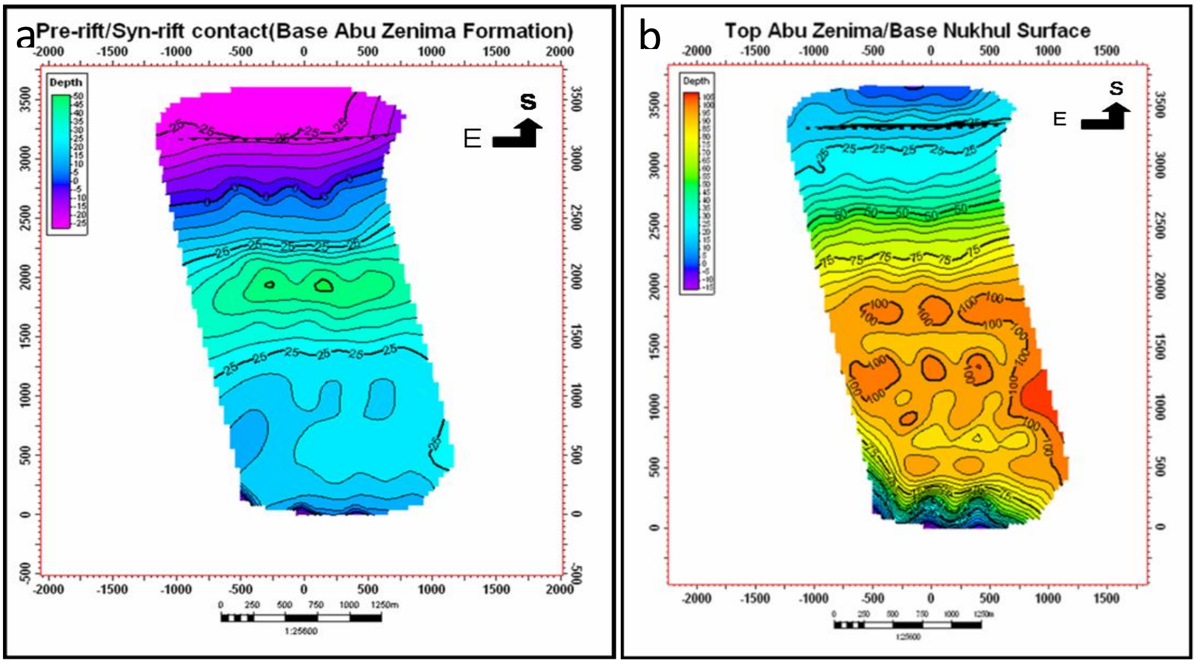

Figure 11: (a) Map of horizon base of Abu Zenima Formation showing topographic variation from relatively high at NW separated by high at the centre then low at the SE (b) Map of horizon Top Abu Zenima/Base Nukhul showing undulating nature of the topography from the NW towards the SE and gently sloping towards the SE.

4.3 Model interpretation

From the modelling of eleven stratal surfaces that bounded the Abu Zenima Formation, five major zones defined the genetically related facies association of inter-bedded reddened mudstone and white conglomerate displaying stratal thickness variation and stratigraphic elements such as onlap, truncation along the strike of the fault zone. It can be seen from Figure12 below, the lower mudstone facies in zone 5 comprising Sub-Zones 2,3 and 4 (coloured red, blue and brown) onlap at the pre-rift/syn-rift contact, and the thickness from the whole zone thins toward the centre with maximum thickness of approximately 170 m at the NW trend, as shown in Figure 13.

The Zone 5 (Mudstone Facies1) also thins towards the centre and get thicker away from the centre. This location is interpreted to be the fault perpendicular anticline associated with normal fault growth and propagation that divide the two lows hanging wall syncline in the NW and SE respectively. Zone 4 is a white conglomerate facies that trends NW-SE and is also characterised by thinning toward the interpreted fault-perpendicular anticline and eventually on lap on the Zone 5 mudstone facies. Zone 3 is the thinnest mudstone facies modelled with an average thickness of 8-10 m and this zone traversed? the whole model and also characterised by thinning towards fault-transverse anticline (Figure 13).

Zone 2 represents conglomerate facies and is divided into three with the middle one containing conglomerate and minor fluvial sandstone sub-facies (shown with green colour, Figure 12). The Zone also displays variable thickness along strike, and thinned towards the interpreted fault-transverse anticline and progressively gets thicker towards the SE (Figure 12). Zone 1 represents the last mudstone facies with minor fluvial channel overbank deposits and sandstone. This zone capped the Abu Zenima Formation and is bounded by two surfaces. The upper surface is erosional that incised part of the Abu Zenima Formation and the erosional scours can be seen in Figure12. This zone ultimately onlap on zone 2 towards the SE.

Based on the tectono-stratigraphic analysis above, using stratal thickness variation, and onlap within the model of Abu Zenima Formation, the evolution of Nukhul fault zone can be assumed to have evolved from two NW-SE trending faults segments that were subtly linked by a basinward relay ramp during the initial rifting period. The analysis also indicates that the NW fault segment is longer – approximately 2.2 km than the SE fault segment which is approximately 1 km long along the strike (Figure 14).

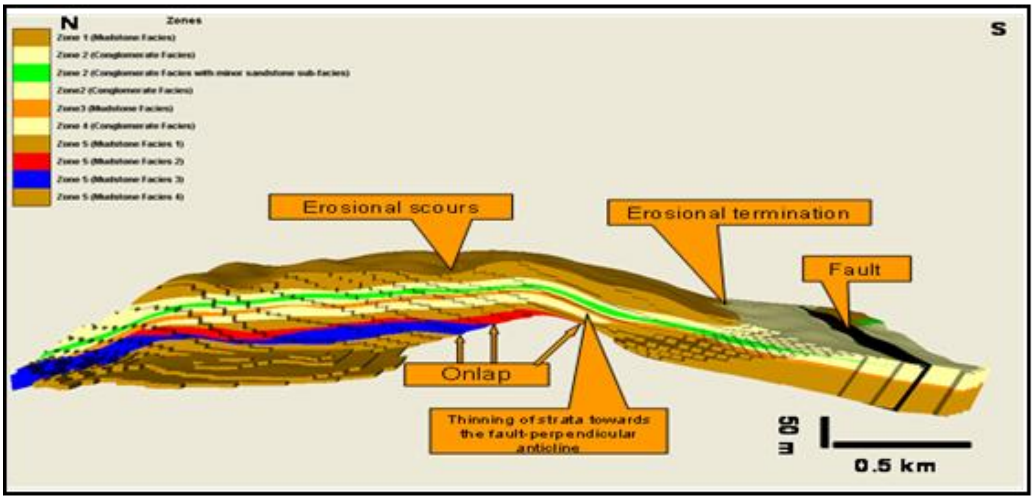

Figure 12: Model of the five zones within the Abu Zenima Formation.

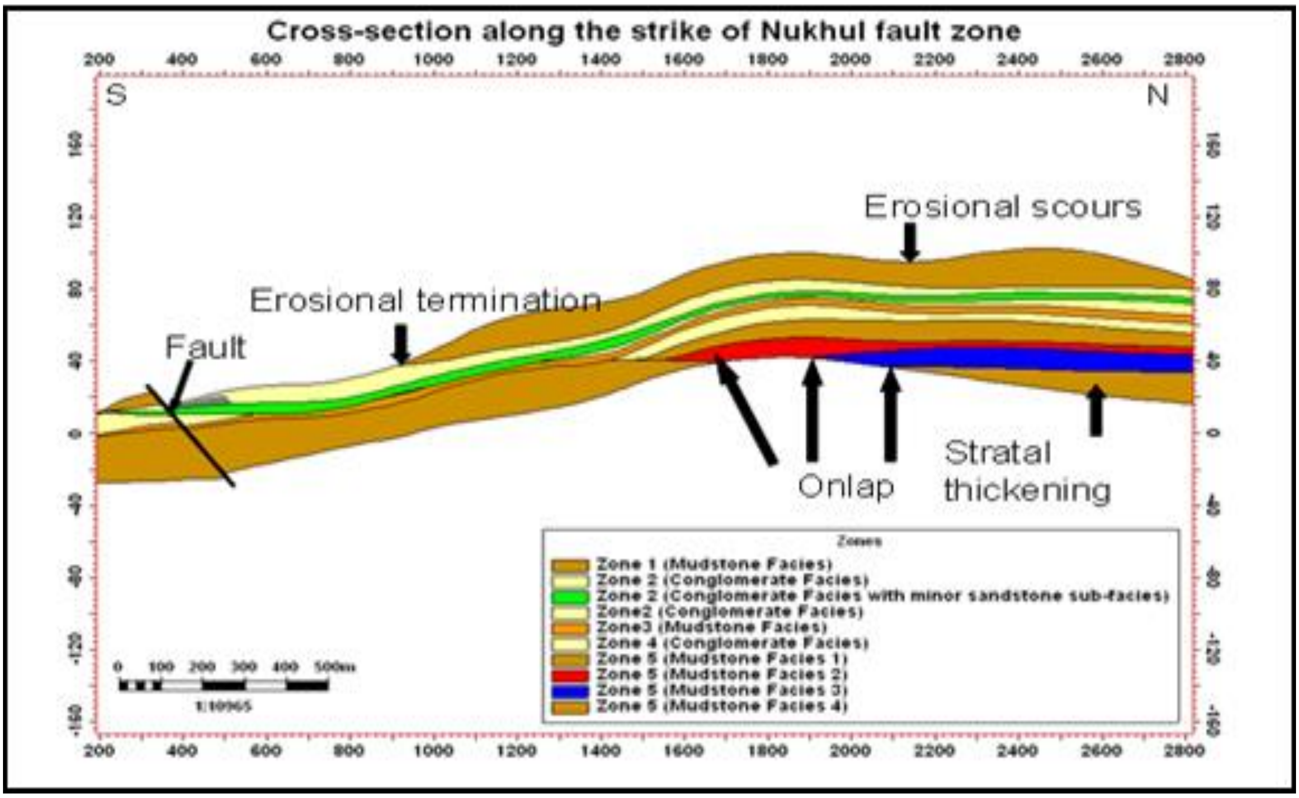

Figure 13: Cross-section of the five zones showing stratal thickness variation and onlap.

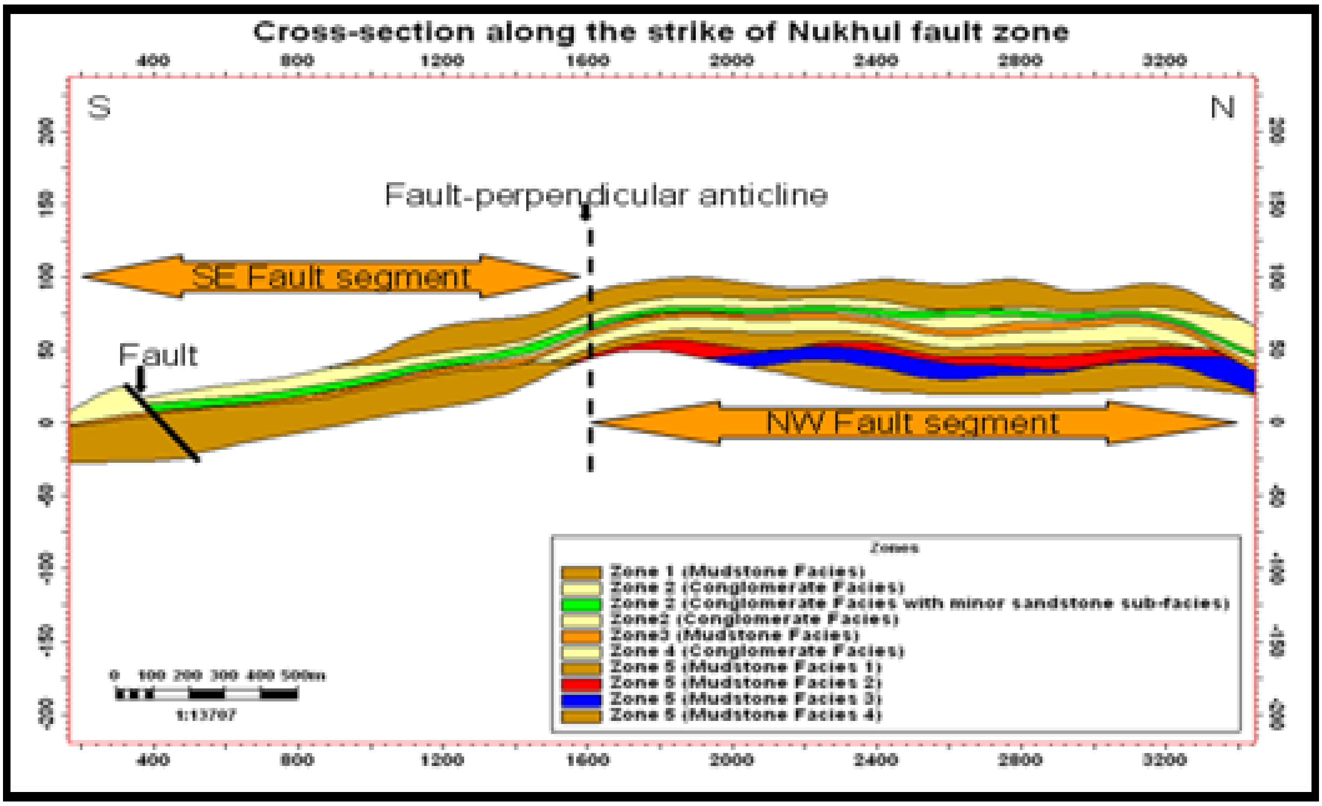

Figure 14: Cross-section 2 showing segmentation of the SE and NE fault trends

From the above interpretation, we can deduce the following:

- The structural style of the basin indicated by two syncline-shaped depocentres separated by high fault-transverse anticline was produced as a result of fault-propagation folding during the initial extensional phase.

- The stratal geometries characterised by thickness variation and stratal onlap is an indicative of the spatial and temporal evolution of normal fault in extensional setting characterised by variation in displacement along the strike from maxima at fault centre to minima at fault tip.

- These analyses indicate that Nukhul fault zone evolved from two initially isolated fault segments that do not conform to the present day structural configuration.

- Thus, normal fault evolution together with the fault-propagation folds in a typical extensional setting can be regarded as major control on the basin structural style and stratal geometries.

4.4 Depositional model

Depositional model of any system and their sedimentary products should reflects the integration of autogenic (internal) and allogenic (external) controls, and they are responsible for basin sedimentary fill geometry and architecture (Allen and Allen, 2005). The Abu Zenima Formation represents the initial syn-rift non-marine continental deposits in the Nukhul fault zone. The tectonic evolution of Nukhul fault zone started with the growth and propagation of two isolated small displacement fault segments trending NW-SE. This leads to generation of depositional basin through the evolution of associated fault-parallel syncline and the development of drainage network that has an orthogonal relationship to local tectonic grain (Allen and Allen, 2005). The main drainage system from surrounding source areas descends a paleoslope oriented perpendicular to the main controlling tectonic element (Miall, 1986).

Three drainage systems are envisaged for the deposition of Abu Zenima Formation from the Miall, basin fill model (Miall, 1986). The model is characterised by transverse, longitudinal rivers and lake (Figure 15). Proximal part of the basin is dominated by transverse river from the foot wall derived source, medial part is dominated by longitudinal /axial river from the relay ramp dip slope, while the distal end is the lake margin where the longitudinal rivers ends as ephemeral channel dying out on lake margins. Thus, the basin is envisaged to have a through drainage dominated by well established river system and perennial lake.

The facies association of Abu Zenima reflects the pattern of such drainage system where the predominantly mudstone/marl are deposited in the lake system, while the conglomerate facies reflects the tectonically controlled drainage system were increased in relief leads to over supply of coarse sediments. The minor fluvial sandstone reflects the interplay of base level change/fluctuation associated with the lacustrine and fluvial system.

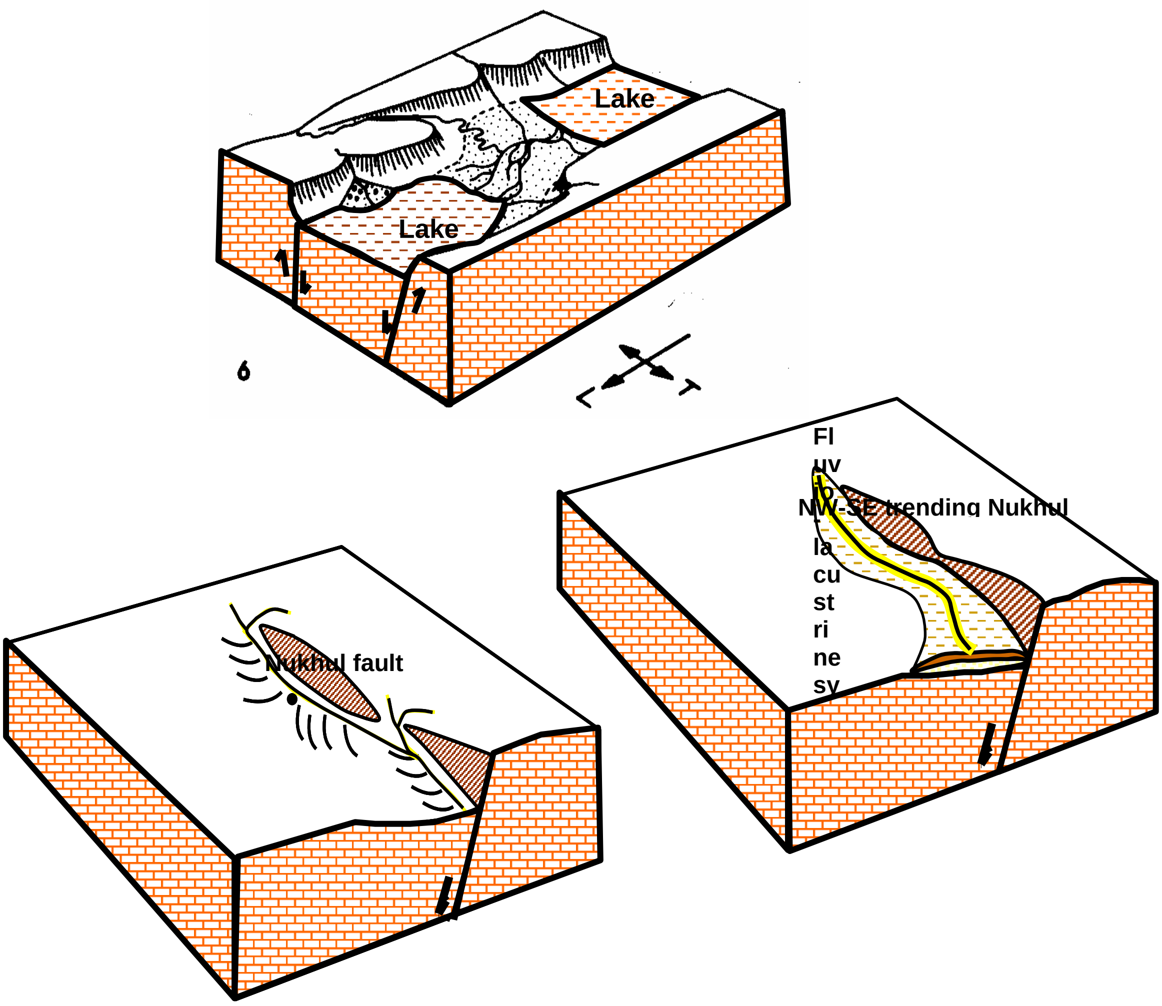

Figure 15: Schematic basin fill model of Abu Zenima Formation showing the interplay of proximal drainage, medial drainage and distal lake (modified from Miall, 1986)

5. DISCUSSION

The early syn-rift stratigraphy of fluvio-lacustrine Abu Zenima Formation documents an early phase of basin fills in an extensional setting that characterised variation in stratal thickness and onlap of syn-rift strata on pre-rift rock. The structural style of the basin is a direct reflection of the evolution of normal fault in extensional setting that produce a typical rift basin; a fault-bounded feature known as half-graben. The half-graben has a triangular geometry and the three sides of the triangle comprise the border fault, the rift onset unconformity between pre-rift and syn-rift rocks and the post-rift unconformity between syn-rift and post-rift. This fanning geometry, along with thickening of syn-rift units toward the boundary fault, is produced by syn-depositional faulting (Schlische and Withjack, 1996).

The half-graben geometry produced is controlled by the varied displacement surrounding the boundary fault system. In particular, the displacement is greatest at the centre of the fault and decrease to zero at the fault tip resulting in syncline-shaped basin in longitudinal section (Figure 16a), also in transverse section, the displacement of an initially horizontal surface that intersects the fault is greatest at the fault itself and decrease with distance away from the fault. This produces footwall uplift and hanging-wall subsidence, the latter of which creates the sedimentary basin (Schlische and Withjack 1996). Continual displacement on the boundary fault cause the basin to deepens through time. More so, the width of the hanging-wall deflection increases with increasing fault displacement, the basin widen through time. Also increase in fault displacement results in increase in fault length and thus the basin lengthens through time and the growth of the basin through time produces progressive onlap of syn-rift strata on pre-rift rocks (figure 16 and 17) (Schlische and Withjack, 1996).**Figure 16:** Schematic diagram showing fault-displacement geometry of a half-graben. (a) perspective diagram before (left) and after faulting showing how normal faulting uplifts the footwall block and produces subsidence in the hanging wall block.(b) Transverse section before faulting (left) and after faulting and sedimentation showing footwall uplift and hanging-wall subsidence. The latter produces a wedge-shaped basin (half-graben) (Adopted from Schlische and Withjack, 1996).

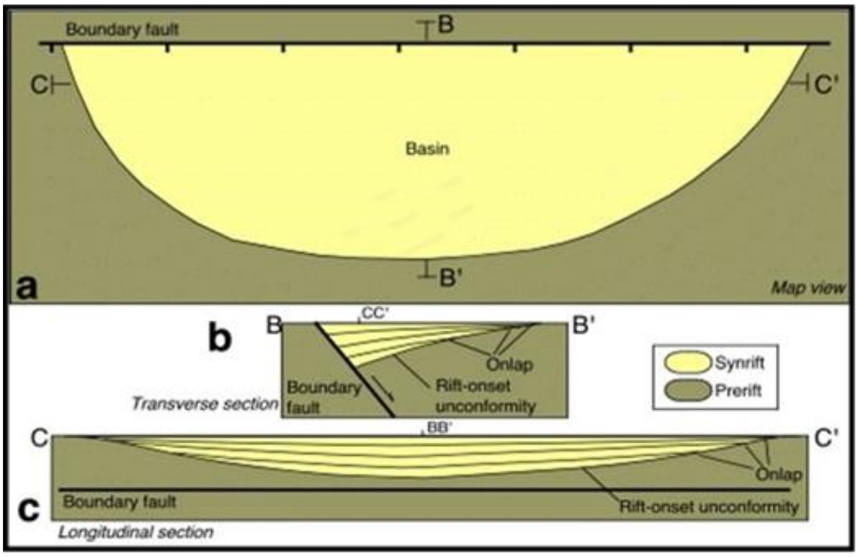

Figure 17: Geometry of a simple half-graben. (a) Map-view geometry. (b) geometry along a cross section oriented perpendicular to the boundary fault, showing wedge-shaped basin in which syn-rift strata exhibit a fanning geometry, thicken toward the boundary fault, and onlap pre-rift rocks. (c) Geometry along a cross section oriented parallel to the boundary fault, showing syncline-shaped basin in which syn-rift strata thin away from the centre of the basin and onlap pre-rift rocks (Adopted from Schlische and Withjack, 1996).

The above model is tenable to a half-graben produced by single normal fault, however the architectural style and stratal geometries of two or more fault segments that spatially and temporally linked to form a fault zone is markedly different, though the initial isolated fault segments that grow prior to interaction and eventual linkage have similar geometry described above, however the onset of linkage will change the architectural style of the basin characterised by two or more syncline-shaped basin separated by fault-propagated transverse anticline were the two fault meet. This represents the relay ramp and this scenario will result in two or more isolated depocentre to interact and communicate. Hence, in this setting the lower most strata from hitherto isolated depocenters will onlap the pre-rift rock, but the topmost growth strata will only thin toward the relay ramp and extend down the basin without onlapping. Thus, the depositional patterns such as thickness and onlap within the syn-rift tectonic stratal units gives us insights into the spatial characteristics of fault zone at particular stage of evolution.

The discussion is based purely on the interpretation of the modelled early syn-rift fluvio-lacustrine Abu Zenima Formation and the structural style of the basin, thickness variation and onlapping of strata along the strike of Nukhul fault zone. During the Abu Zenima (24.1 ma), the sequence of event started with the initial rifting and fault growth was “characterised by rapid lateral propagation, and thereafter, fault segments grew by accumulation of displacement with minimal lateral propagation” (Gawthorpe et al., 2003). This idea can be supported from the observation in the model where only few lowermost stratal surfaces from the two linked fault segments onlap on the pre-rift rock (Figure 36) while the remaining only thin towards the fault-perpendicular anticline that separated the two depocentres. This unequivocally suggest that the linkage of the two fault was rapid, and the fact that rift initiation is characterised by slow subsidence, the conventional fault growth models, where faults grow by systematic increase in both displacement and length with time (D/L relationship) should be revisited.

As highlighted before, the systematic evolution of the normal fault arrays control the structural style of the basin, they equally control the drainage catchments within the basin resulting in “contrasting transverse drainage catchments to evolve on newly created footwall and hanging wall uplands” (Gawthorpe and Leeder, 2000). Axial drainage system that runs parallel to tectonic grain evolved from the fault tip where the displacement is low to hanging-wall syncline where the displacement is high. In the case of Abu Zenima this scenario occurred where such axial drainage system terminated at the lake margin in the syncline resulting in the deposition of the term “Fluvio-lacustrine Abu Zenima Formation”.

The evolution of normal fault arrays to form a fault zone as highlighted before is the major control on the architectural style of rift basins and the stratigraphic geometries of the basin fills. Since such basins are being explored for hydrocarbon in many passive (Atlantic type) continental margins, the implication of such spatial and temporal evolution is worth studying since the architecture of these basins and the basin fill are strongly influenced by the displacement geometry on the bounding normal fault systems.

The broad features of the initial deposits of rift are that they are predominantly non-marine to shallow marine. Such basins fills contains lacustrine sediments that can serve as a source, while the fluvial and shallow marine sands can generate an excellent reservoirs. The implication of such basin structural style, stratal thickness variation and onlap pattern of syn-rift deposits from the analysis of subsurface seismic reflection data can be use in hydrocarbon exploration in sitting drill wells. Subtle stratigraphic traps associated with stratal onlap can be constrained. Also areas of greatest net pay associated with fault segment centre can be constrained.

6. CONCLUSION

This paper examined the stratigraphic response of the fluvio-lacustrine Abu Zenima Formation to the evolution of Nukhul fault zone using LIDAR data technique for digital outcrop modelling. Firstly, the stratal surfaces that bounded the Formation between Base Nukhul Formation and the pre-rift/syn-rift contact was interpreted and modelled using Schulumberger’ Petrel. The stratal geometries exhibits thickness variation and stratigraphic element of onlap along the strike of the Nukhul fault zone. These give an insight to the structural style of the basin and response of the depositional systems to the spatial and temporal evolution of the fault zone.

Some broad conclusions of this research are stated below:

- The early syn-rift stratigraphy of the Abu Zenima Formation in the hanging-wall of Nukhul fault zone documents an early phase of basin fills, characterised by onlap, thinning/thickening of stratal surfaces.

- The model of the syn-strata depicts a considerable topographic variation characterise by two lows separated by high is an indicative of spatial and temporal evolution of normal fault with variation in displacement along the strike from maxima at fault centre to minima at fault tip.

- Fault-propagation folds that form due to the growth of the extensional faults are responsible for the fault-parallel syncline and fault-perpendicular anticline that define the structural style of initial syn-rift basin as observed in the Abu Zenima.

- These folds grows during fault propagation and significantly impacts on the depositional geometries and stacking patterns of the synorogenic sediments as indicated by onlap relationship and growth strata.

- Also the fault-propagation folds control the drainage catchments of the basin, where transverse drainage developed from the uplifted foot-wall and hanging-wall dipslope while axial/longitudinal depositional system preferentially developed adjacent to overlap or relay zones between the propagating fault segments.

- The above analyses was incorporated to interpret the Nukhul fault zone to have evolved from two isolated NW-SE trending fault segments and were spatially and temporally linked by a basinward relay ramp that do not conform to the present day structural configuration.

- The spatial and temporal evolution of normal fault and fault-propagated folds is the major control that determined the structural style of syn-rift basin and the stratal geometries of the basin fill. However other control on the facies distribution, sediment supply and dispersal can be recognised to include: climate, bed rock lithology and base/ sea level change.

The implication of this study is directly related to hydrocarbon exploration of syn-rift play in many rift basins in passive (Atlantic-type) continental margins. Such basin contains excellent fluvial reservoirs with thickness variation and varying onlap relationship across the basin. Thus, understanding the tectonic control and other synorogenic sedimentation and resultant depositional geometries of syn-rift sedimentary rocks will substantially reduces hydrocarbon exploration risk. It is therefore recommended that further work should incorporate ground penetrating rada (GPR) and borehole drilling to constrain more on the surface, this will significantly improve future model.

DECLARATIONS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Alexander, J., Bridge, J.S., Leeder, M.R., Collier, R.E and Gawthorpe, R.L., 1994. Holocene meander-belt evolution in an active extensional basin, south western Montana: Journal of Sedimentary Research, B64, 4. Pp. 542-559.

Allen, P.A., and Allen, J.R., 2005. 'Basin stratigraphy': Basin analysis: Principles and application, Oxford, Blackwell.

Bellian, J.A., Kerams, C., and Jennette, D.C., 2005. Digital outcrop models: application of terrestrial scanning LIDAR technology in Stratigraphic modelling: Journal of Sedimentary Research, 75 (2), Pp.166-176.

Eliet, P.P., and Gawthorpe, R.L., 1995. Drainage development and sediment supply within rifts, examples from the sperchios basin, central Greece: Journal of the Geological Society, London, 152, pp. 883-893.

Gawthorpe, R.L., and Fraser, A.J., 1994. Sequence stratigraphy in extensional basins: Implication for the interpretation of ancient basin-fills: Marine and Petroleum Geology, 11 (6), Pp. 642-658.

Gawthorpe, R.L., and Hardy, S., 2002. Extensional fault-propagation folding and base level change as controls on growth-strata geometries: Journal of Sedimentary Geology, 146, Pp. 47-56.

Gawthorpe, R.L., and Leeder, M.R., 2000. Tectono-sedimentary evolution of active extensional basins: Basin Research, 12, Pp. 195-218.

Gawthorpe, R.L., Hardy, S., and Ritchie, B., 2003. Numerical modelling of depositional sequences in half- graben rift basins: International association of Sedimentologists, 50, Pp. 169-185.

Gawthorpe, R.L., Jackson, C.A.L., Young, M.J., and Sharp, I.R., 2003. Normal fault growth, displacement localisation and the evolution of normal fault populations: The Hammam Faraun fault block, Suez rift, Egypt: Journal of structural Geology, 25, Pp. 883-895.

Gupta, S., Underhill, J.R., Sharp, I.R., and Gawthorpe, R.L., 1999. Role of fault interact-ion in controlling synrift sediment dispersal patterns: Miocene Abu Alaqa Group, Suez rift, Sinai, Egypt: Basin Research, 11, Pp. 167-189.

Hodgetts, D., Drinkwater, N.J., Hodgson, J., Kavanach, J., Flint, S.S., Keogh, K.J., and Howell, J.A., 2004. Three-dimensional geological models from outcrop using digital data collection techniques: an example from the Tanqua Karoo depocentre, South Africa: The Geological Society of London, special Publication, 239, Pp. 57-75.

Jackson, C.A.L., Gawthorpe, R.L., Carr, I.D., and Sharp, I.R., 2005. Normal faulting as a control on the stratigraphy of shallow marine syn-rift sequences: The Nukhul and Lower Rudeis Formation, Hammam Faraun faut block, Suez rift, Egypt: International association of Sedimentologists, 52, Pp. 312-338.

Krebbs, W.N., Wescott, W.A., Nummedal, D., Gaafar, I., Azazi, G., and Karamat, S., 1997. Graphic correlation and sequence stratigraphy of Neogene rocks in the Gulf of Suez: Bulletin Societe Geologique de France, 168 (1), Pp. 63-71.

Montenat, C., Sperber, F.O., Plaziat, J.C., and Purser, B.H., 1998. The sedimentary record of the initial stages of Oligo-Miocene rifting in the Gulf of Suez and the northern Red Sea': Sedimentation and tectonics of rift basins: Red Sea-Gulf of Aden (ed) by Purser, B.H and Bosence, D.W.J, London: Chapman.

Moustafa, A.R., 1993. Structural characteristics and tectonic evolution of the east-margin blocks of the Suez rift: Tectonophysics, 223, Pp. 381-399.

Moustafa, A.R., 1997. Controls on the development and evolution of transfer zones: The influence of basement structure and sedimentary thickness in the Suez rift and red Sea: Journal of Structural Geology, 19 (6), Pp. 755-768.

Moustafa, A.R., 2002. Controls on the geometry of transfer zones in the Suez rift and northwest Red Sea: Implication for the structural geometry of rift system: American Association of Petroleum Geologist Bulletin, 89 (6), Pp. 979-1002.

Pivnic, D.A., Ramzy, M., Steer, B.L., Thorseth, J., El sisi, Z., Gaafar, I., Garing, J.D., and Tucker, R.S., 2003. Episodic growth of normal faults as recorded by syntectonic sediments, July oil field, Suez rift, Egypt: American Association of Petroleum Geologist Bulletin, 87 (6), Pp. 1015-1030.

Ravnas, R., and Bondevik, K., 1997. Architecture and controls on Bathonian-Kimmeridgian shallow-marine syn-rift wedges of the Oseberg-Brage area, northern North Sea: Basin Research, 9, Pp. 197-226.

Roche, V., Homberg, C., van der Baan, M., Rocher, M., 2017. Widening of normal fault zones due to the inhibition of vertical propagation: Geological Society, London, Special Publications, 439 (1), Pp. 271 – 288.

Said, R., 1962. Geology of Cairo-Suez district': The Geology of Egypt, Newyork: Elsevier.

Schlische, R.W., and Withjack, 2002. Rift basin architecture and evolution: Tectonics of rifting and drifting: Pangea Breakup, American Geophysical Union monograph.

Schumm, S.A., Dumont, J.F., and Holbrook, J.M., 2000. Tectonics and fluvial sedimentation': Active tectonics and alluvial rivers, Cambridge: Cambridge University press.

Sharp, I.R., and Underhill, J.R., 2000. Fault-propagation folding in extensional settings: examples of structural style and synrift sedimentary response from the Suez rift Sinai, Egypt: The Geological Society of American Bulletin, 112 (12), Pp. 1877-1899.

Sharp, I.R., Gawthorpe, R.L., Armstrong, B., and Underhill, J.R., 2000. Propagation history of and passive rotation of mesoscale normal faults: Implication for Synrift stratigraphic development: Basin Research, 12, Pp. 285-305.

Wescott, W.A., Krebs, W.N., Dolson, J.C., Karamat, S.A., and Nummedal, D., 1996. Rift basin sequence stratigraphy: some examples from the Gulf of Suez: GeoArabia, 1 (2), Pp. 343-358.

Young, M.J., Gawthorpe, R.L. and Sharp, I.R., 2000. Sedimentology and sequence Stratigraphy of a transfer zone coarse-grained delta, Miocene Suez rift, Egypt: International Association of Sedimentologists, 47, Pp. 1081-1104.

Young, M.J., Gawthorpe, R.L., and Sharp, I.R., 2003. Normal fault growth and early Syn-rift sedimentology and sequence stratigraphy: Thal fault Suez rift, Egypt: Basin Research, 15, Pp. 479-502.

Cite The Article: Auwalu Yola Lawan, Abdullah Musa Ali, Byami Andrew Jolly (2024). Tectonostratigraphic Response to Faulting in Red Bed Environment using Lidar Data: The Abu Zenima Formation Sinai. *Geological Behaviour 8(2): 106-117.*