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3D seismic interpretation in a deep-water depositional environment from Lower Congo Basin

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Abstract

This Master of Science (M.Sc.) thesis focuses on the detailed characterization and interpretation of deep-water depositional system within Lower Congo Basin, offshore Angola. The application of seismic geomorphology has helped decipher and characterize complex sedimentary architectures, and identify a rage of geomorphic elements including channel complexes, sedimentary waves and mass transport deposits. Mapping these features using 3D visualization techniques and workflows facilitates a more detailed understanding of how depositional geometry responds to spatial and temporal variations in tectonic deformation, and subsidence and the creation or destruction of accommodation and sediment supply. Ultimately, this approach illustrates how in data limited environments, the effective integration of seismic stratigraphy and geomorphology is key to the reduction of uncertainty with respect, to reservoir prediction and connectivity in exploration.

Keyword: Channels, deep-water depositional environment, Lower Congo Basin, 3D seismic interpretation.

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Chapter 1 -Introduction

1.1-Introduction

The evolution of Angolan margin started with the Early Cretaceous rifting of Gondwanaland (Stark 1991). The Angola margin consists of three basins, the Lower Congo Basin in the north, Kwanza Basin in the center and Namibe Basin in the south. The Lower Congo Basin is one of the most competitive and successful oil provinces in West African, where my study focus is based.

This project provides an overview of the Lower Congo Basin and gives a regional perspective of the deep-water turbidite depositional environment. The 3D seismic data has significantly helped our understanding of deep-water depositional environments due to its higher data quality. The aim of my 3D seismic interpretation is to undertake detailed geological analysis of the recent deposits in the deeper-water part of the basin. Also, the main focus of the work is to identify and interpret the interplay between channel development and seafloor geomorphology. The impact of Salt movements on seafloor topography, as the submarine sediments are affected by gravity flow processes. Seismic visualization and attribute based techniques were used alongside the main seismic interpretation to characterize geomorphologies of the channels and also to define internal architecture of the seismic based units.

The seismic section was divided by units. The unit I is bounded by Horizon A and Horizon B. Unit II is bounded by Horizon B and the Seabed. The Seabed surface geomorphology with channel imprints was important in the study with other surface Seabed features which were also considered. The internal properties of the units with channel development is the main focus of study in this project

1.2- Aims and Objectives

This aims of this project is to understand the profile of seismic interpretation in deep-water depositional environment of the Lower Congo Basin in West African-Angola, Which mainly involves:

- ✓ To perform seismic interpretation of the Oligocene to Miocene strata in the seismic sections.
- ✓ Use 3D seismic data with different seismic based techniques in Petrel software.
- ✓ To interpreting features of both internal and external morphologies in the seismic, related mainly to salt influence and channel development within the seismic units.
- ✓ Analyse the channel features in the units to their different sub facies units.

Objectives

Firstly, I need to have a brief overview of the regional geology of the Lower Congo Basin within the study area. Understand the main sediment forming processes of submarine fan development that is common in the Lower Congo Basin. Also to be able to relate this study regionally to finitely identified/interpreted features in the seismic sections. The objectives include:

- ✓ Interpret the seismic units in both Inline and Xline sections of the seismic volume.
- ✓ Use available techquines from Isopach maps, RMS and Time slice to analyze features.
- ✓ Analyses the internal seismic features to geologic characterizations. This is mainly related to the channel and associated facies.
- ✓ Analyses other features identified with pockmarks, polygonal faults within the seismic sections.
- ✓ Relate these morphologies and features to the regional geologic forming processes.

1.3- Data available for study

The study work was performed in Statoil Center in Rotvol (Trondheim). The work was available using workstation as presented by Statoil.

Data presented for work:

- ✓ Seismic 3D volume in time Pre stacks time migration (PSTM).
- ✓ Location map of the study area in the Lower Congo Basin
- ✓ Interpretation PC workstation
- ✓ Software-petrel

Time of work:

- ✓ 4 week of interpretation
- ✓ 8-12 week of report writing
- ✓ 1-12 week of supervision

Data not available:

- ✓ Wells
- ✓ Velocity data
- ✓ Depth converted seismic Pre stack depth migration (PSDM)

1.4- Location of the basin

The Lower Congo Basin is located in the West of Africa, in the north part of Angola passive margin between 5˚S and 8˚30’of latitude (Valle et al., 2001). The study area is located in the Western part of the Lower Congo Basin (Figure 1-1).

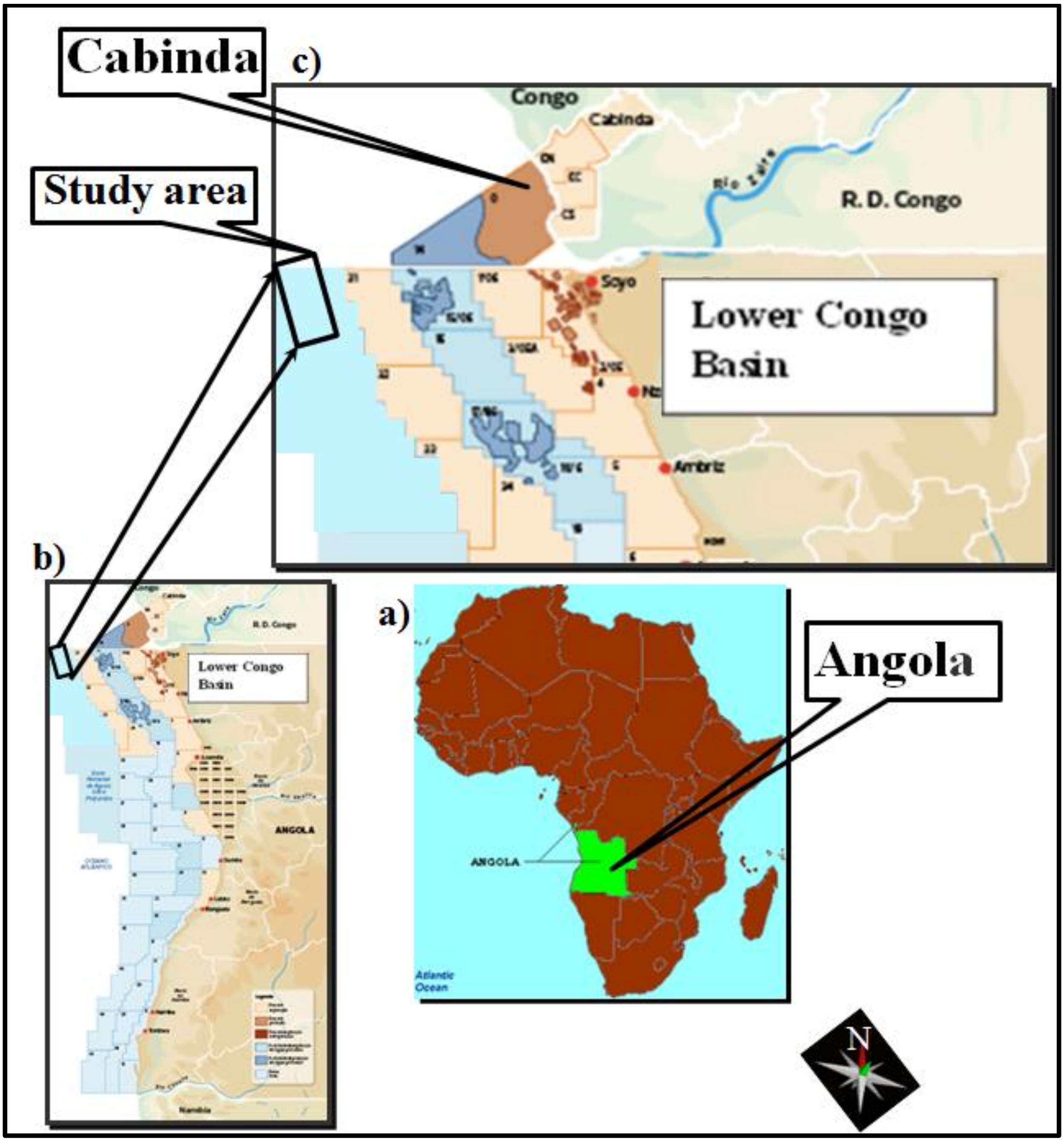


Figure 1-1: The location of the Lower Congo Basin offshore Angola: a) Showing the African continent and Angola is in the South, b) Showing the coast of Angola and the blocks, c) Illustrating Lower Congo Basin and the study area marked by a black rectangle (Sonangol report, 2003).

Bathymetry of northwest Congo Basin and depositional environment

Figure 1-1 illustrates the position of the study area in the Lower Congo Basin, which shows the Congo River as the main supplier of sediments with associated geologic features identified as submarine fan, canyons, channels and lobes etc. (Droz et al., 2003) The channels are developing from the main Congo River, which flows from the Northern hinter part of the Angolan margin toward the Western section of the submarine fan deposits. The channels are direct feeders of the marine fan systems as sediments are supplied during the base level changes in lowstands .The channel developed in response to sea level changes to adjust current shelf level to current sea level profile, during lowstand or drop in sea level with river incisions, thereby producing canyons. My prospect area lies in the upper sections of the channels systems as seen in the (Figure 1-2).

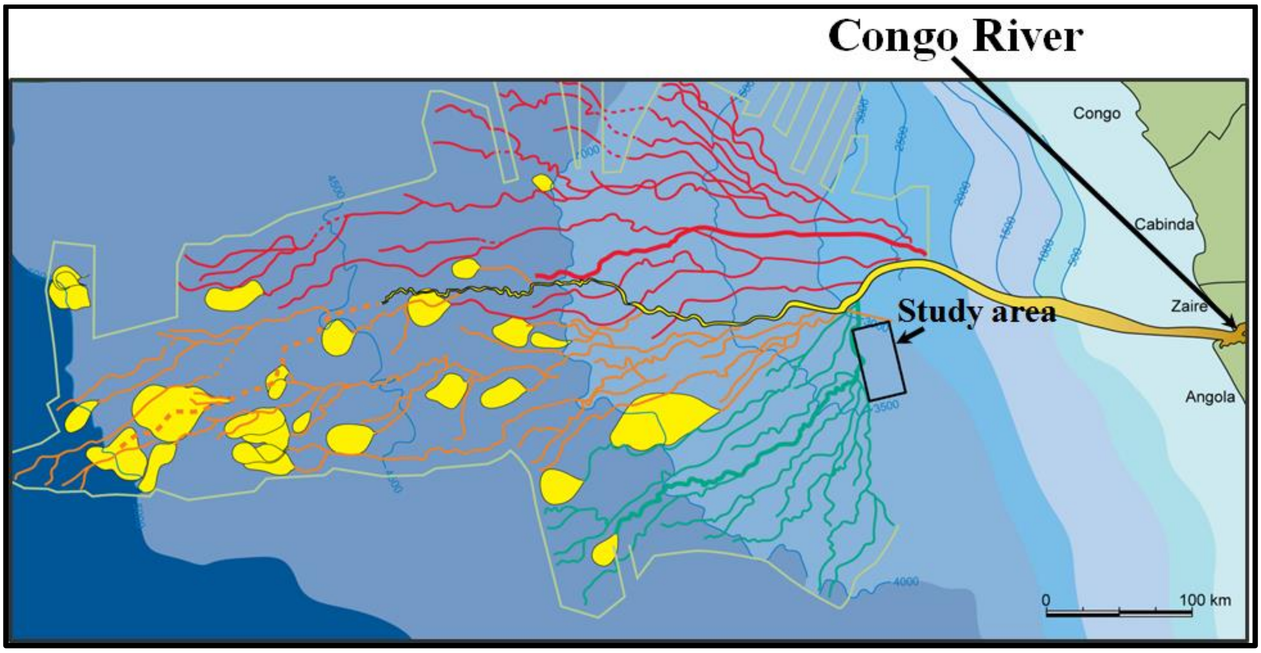


Figure 1-2: Overview map of study area black squared Lower Congo Basin offshore Angola (Modified from Droz et al 2003).

Chapter 2 -Geological settings

2.1-Regional geology of the Lower Congo Basin offshore Angola

The tectonic evolution of the Angolan margin resulted from the plate tectonic movements taking place in Gondwana in Early Cretaceous. Opening to the south and north of the Walvis Ridge began at approximately 129Ma and 118Ma respectively (Alagoa et al., 1991). Sea-floor spreading by oceanic plate-accretion, south of the Walvis Ridge, was accompanied by extension of the continental lithosphere north of Walvis Ridge along the Angolan and Brazilian margins (Figure 2-2). During Albian times, oceanic plate-accretion began north of the Walvis Ridge between Angola and Brazil.

The tectonic evolution of the Angolan margin is subdivided into four different phases: (I) pre-rift, (II) syn-rift, (III) transition and (IV) post-rift basin (Figure 2-3).

Phase I

The pre-rift (late Proterozoic to Jurassic) is characterized by the extreme peneplanation (Gondwana planation), which extended most part of the central and southern Africa and eastern South America. The types of sediments deposited during this phase are alluvial, fluvial and lacustrine sediments.

Phase II

The syn-rift was a period during which Africa and South America began to separate. The Angolan and Brazilian margins suffered continental extension from early Valanginian to latest Barremian times. Throughout this period the continental lithosphere and crust were stretched and thinned to form rift basins. The mainly sediments deposits in this phase was lacustrine deposition.

Phase III

This is the transition phase between the Aptian to Albian times 110-105 Ma, (Teisserenc et al., 1990) corresponds to the salt deposition as evaporitic sequence (Loeme Formation) along the Angola margin. The fractures Rifting ceased in the early Aptian (Karner et al., 1997) and the terrestrial rift basins were transgressed by marine water. Evaporitic sediments of the (late Aptian) Loeme Formation recorded the first marine transgressions from the south across the subsiding volcanic Walvis Ridge (Brognon et al., Verrier 1966) (Figure 2-1).

Phase IV

The post-rift phase (early Albian) started with a breakup unconformity just above salt. Also is characterized predominately by salt tectonics. The structural modifications of this phase resulted mainly from sediment loading, updip extension and mobilization of Loeme (Aptian) salt and to a lesser extent Albian platform rafting and basement. The deformation lead to the formation of various complex types of salt related structures such as domes, growth faults and antithetic faults (Alagoa et al., 1991).

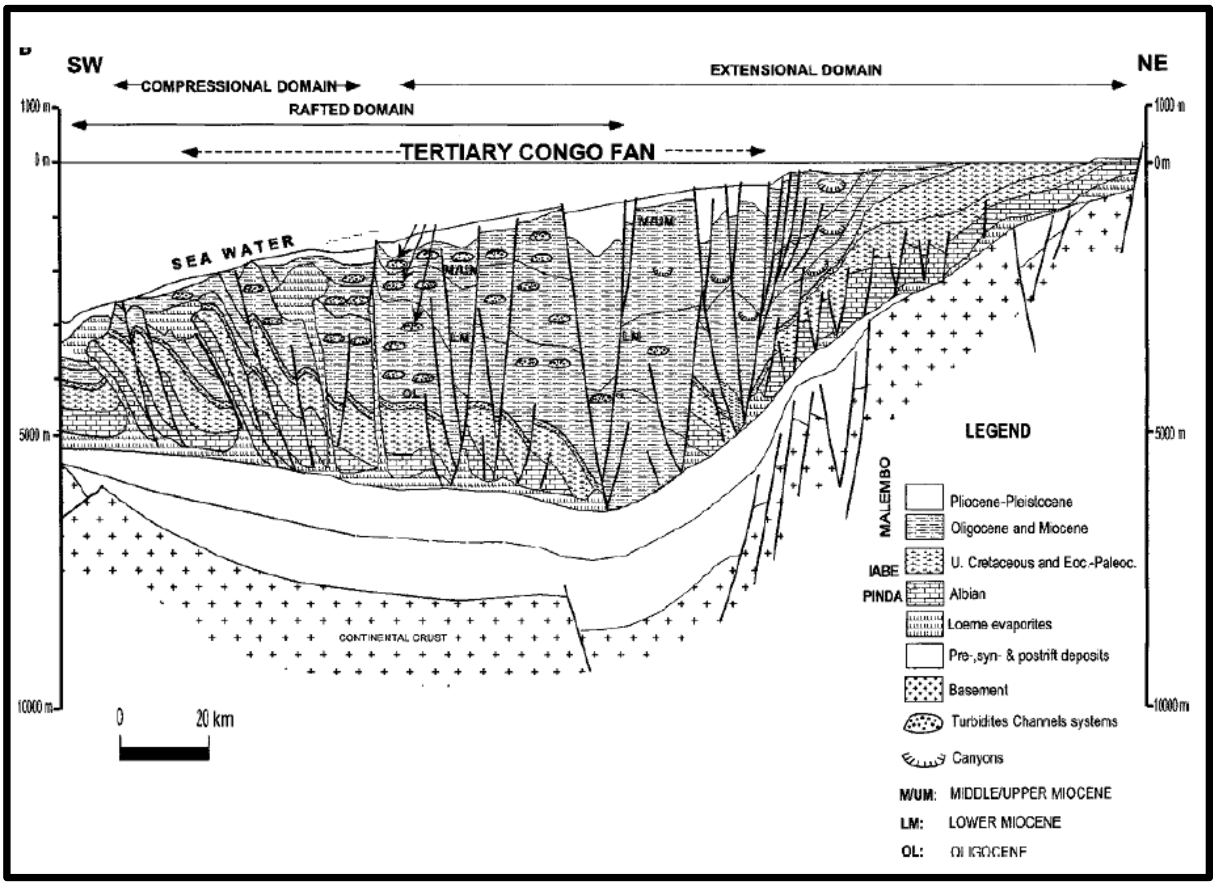


Figure 2-1: Schematic geologic section of the Angolan continental margin modified after (Amaral et al., 1998) and Evolution of deep-water tertiary sinuous channels offshore Angola (West Africa) and implications for reservoir architecture).

The Lower Congo Basin is one of the numerous sub-basins that developed during the opening of the South Atlantic, in the early Cretaceous (130 Ma), (Marton et al., 2000). Following the deposition of thick evaporites during mid-Aptian time (Kamer et al., 1927), the margin developed in four phases between the late Cretaceous and the Present (Seranne et al., 1992). The sub-basins share a common origin related to early Cretaceous break-up of Gondwana (Bradley & Fernandez et al., 1991) (Figure 2-2).

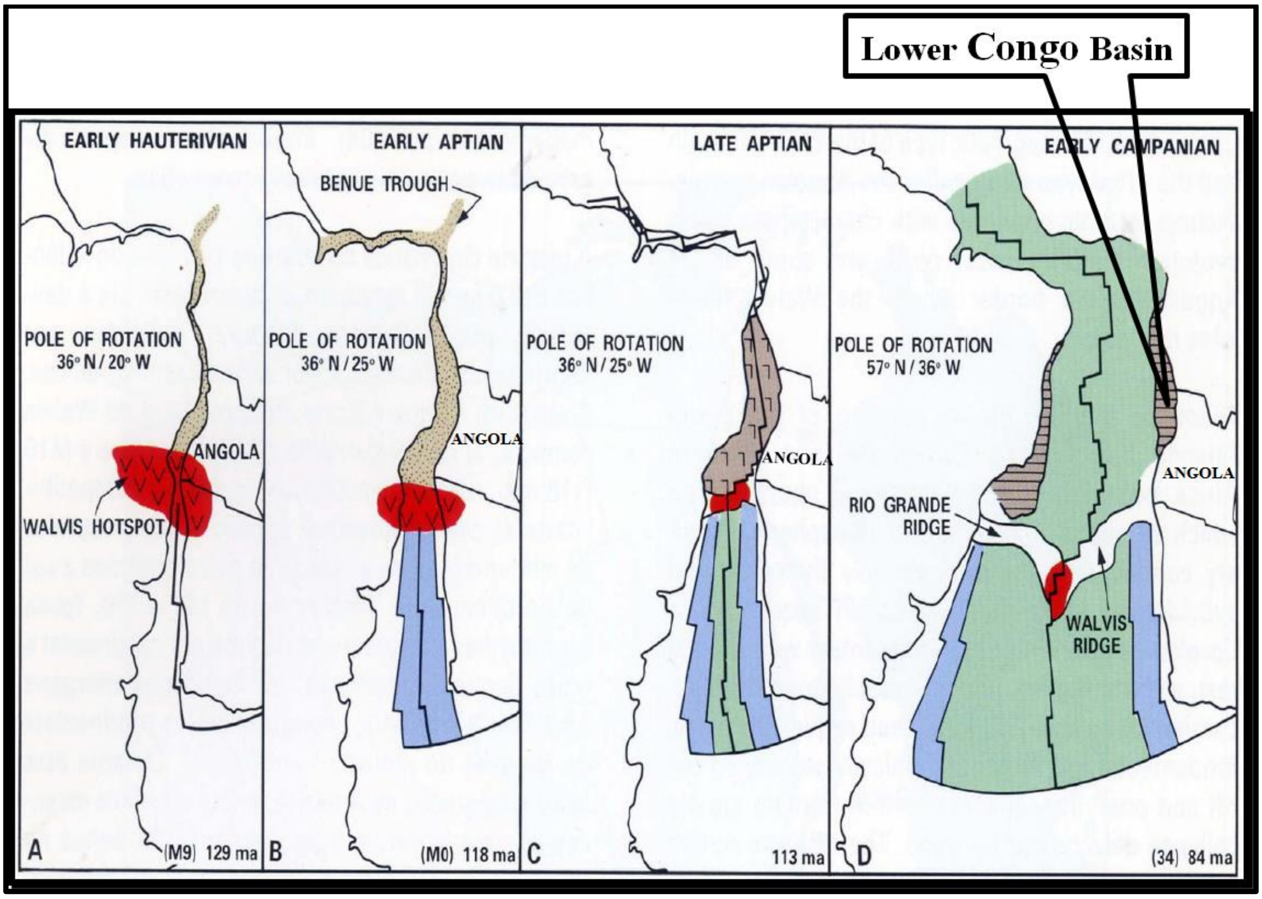


Figure 2-2: Cretaceous plate-tectonic reconstructions of the South Atlantic showing the relative motion of the Angolan and Brazilian rifted margin. Clastics are shown as fine dots, volcanics in the red and original salt deposits in hatched mauve. Current salt occurrence is shown as mauve with horizontal lines. Ocean floor is shown in blue and light green (Bradley & Fernandez et al., 1991).

2.2-Stratigraphy of the Lower Congo Basin

Aptian

Continental rifting, resulted in extensive syn-rift volcanism was marked by deposition of thick successions of evaporites Loeme Formation (Abilio, 1986; Duval et al., 1992). During the Aptian, repeated marine incursions came into the basins from the south (Figure 2-3).

Late Aptian to early Albian

Extensional faulting ended in the late Aptian to early Albian. The transition to the post-rift-drift stage is noted with development of a west-facing passive margin. The major processes controlling the basin topography were now post rift cooling with regional subsidence (Valle et al., 2001).

Albian to late Eocene

The Pinda Formation consists of a sequence of continental-shelf siliciclastiscs and carbonates. After deposition of the lower Pinda formation limestone and dolomite section the shelf collapsed westward. A possible onshore uplift caused major salt related faulting and salt displacement, sometime in the early late Cretaceous mid-Cenomanian (Brice et al., 1982). As a result, large carbonate blocks started to rift drift seawards bound up dip by a series of salt detached listric faults. Salt tectonic structures such as pillows and rim synclines were generated during the time (Duval et al., 1992).

Clastic terrigenous sediment largely from the migrating Congo River drainage system, started to cover the older shelf deposits in the late Eocene (Karner et al., 1999 & Mc Guinness et al., 1993). A major erosional event (Middle Oligocene unconformity in (Figure 2-3) and a dramatic change in depositional environment marked the transition from the Eocene to the Oligocene epoch 36 Ma (Haq and Vail 1987).

Two major unconformities are recognized within the Tertiary succession in the area, namely the Eocene-Oligocene unconformity, and the base Middle Miocene unconformity. Seranne et al., (1992) and Lavier et al., (2003) suggested that the Eocene-Oligocene unconformity was caused by erosion related to ocean currents at 500-1000m water depth and uplift of Africa in the easternmost parts of the margin.

Paleogene to Neogene

The **Paleogene Landana-Group** was with a slow sedimentation rate, condensed intervals with a significant basin wide unconformity developed at the Tertiary. There was generally a slow sedimentation rate for both Paleocene and Eocene with minor unconformities related to the sequence boundaries. Most of the sediments are argillaceous open marine shelf deposits (Valle et al., 2003).

The **Miocene**, (Figure 2-3) parts of the Malembo Group were deposited during rapid subsidence. This also led to erosion and winnowing of sandy shelf sediments, re-sedimented as turbidites in the deeper part of basin. Significant relative sea-level fall at end of Miocene caused local exposure of the shelf and subsequent erosion of coarse grained sediments and transport into the deeper basin. Raft grabens developed local depression on the sea floor, which became important fairways for gravity flows (Valle et al., 2003).

In the contraction part throughout the Miocene the Congo River spread submarine turbidite deposits across the basin, with the vector of sedimentation varying with time within an arc from southwest to northwest. Deposition of the deep-water turbidite facies occurs in channel dominated submarine fan system. Sand systems were generally deposited at sequence boundaries in cut and fill channels which commonly exhibit internal meandering geometries (Figure 2-3)

Quaternary

Lowstands resulted in erosion of exposed areas during tectonic, and deposition of the deep marine clastics and marine shales in the deep parts of the basin. Wear coast uplift, coupled with offshore subsidence, also caused tilting of the marginal and further salt rafting (Gjelberg et al., 2000). The Lower Congo Basin was fed by sediments from the east. The large input of sediment changed the shape of the deep Miocene ramp, creating a shallow shelf with a sharp shelf break as it is today (Lavier et al., 2000) **(**Figure 2-3).

Deposition of the **Malembo Formation** in the Lower Congo Basin was influenced by tectonics uplift. Salt rafting near shore and subsidence offshore, combined with salt tectonics, sea level changes and also changing sediment supply (Haq et al., 1987 & Haq et al., 1988). In addition, the salt induced changing sea floor topography which may have played an important role on the channel evolution. The depositions of Malembo Formation sandy turbidites are associated with Congo fan, offshore of the delta (Figure 2-3).

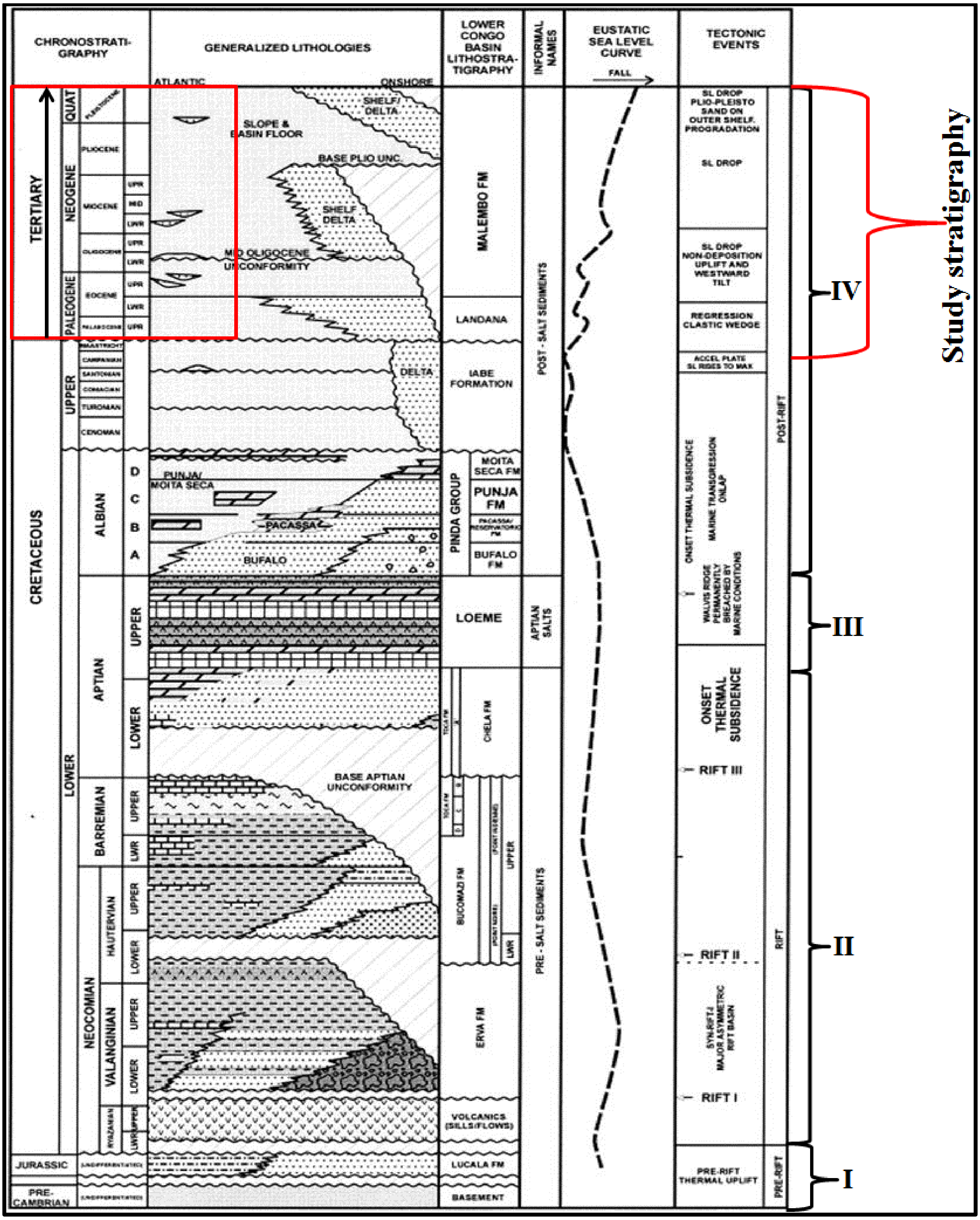


Figure 2-3: Stratigraphic subdivision in the Lower Congo Basin (Anderson et al, 2000). The red squared boxed shows the stratigraphic level on my study area.

2.3-Structural style of Lower Congo Basin

Figure 2-4 and Figure 2-5 illustrate the structural sequence setting of the West African and, South Atlantic margin. These structural settings are differentiated into Extensional, Translational and Compression zones. The structural domains of the Angolan margin in Lower Congo Basin are illustrated in the Figure 2-4 and Figure 2-6.

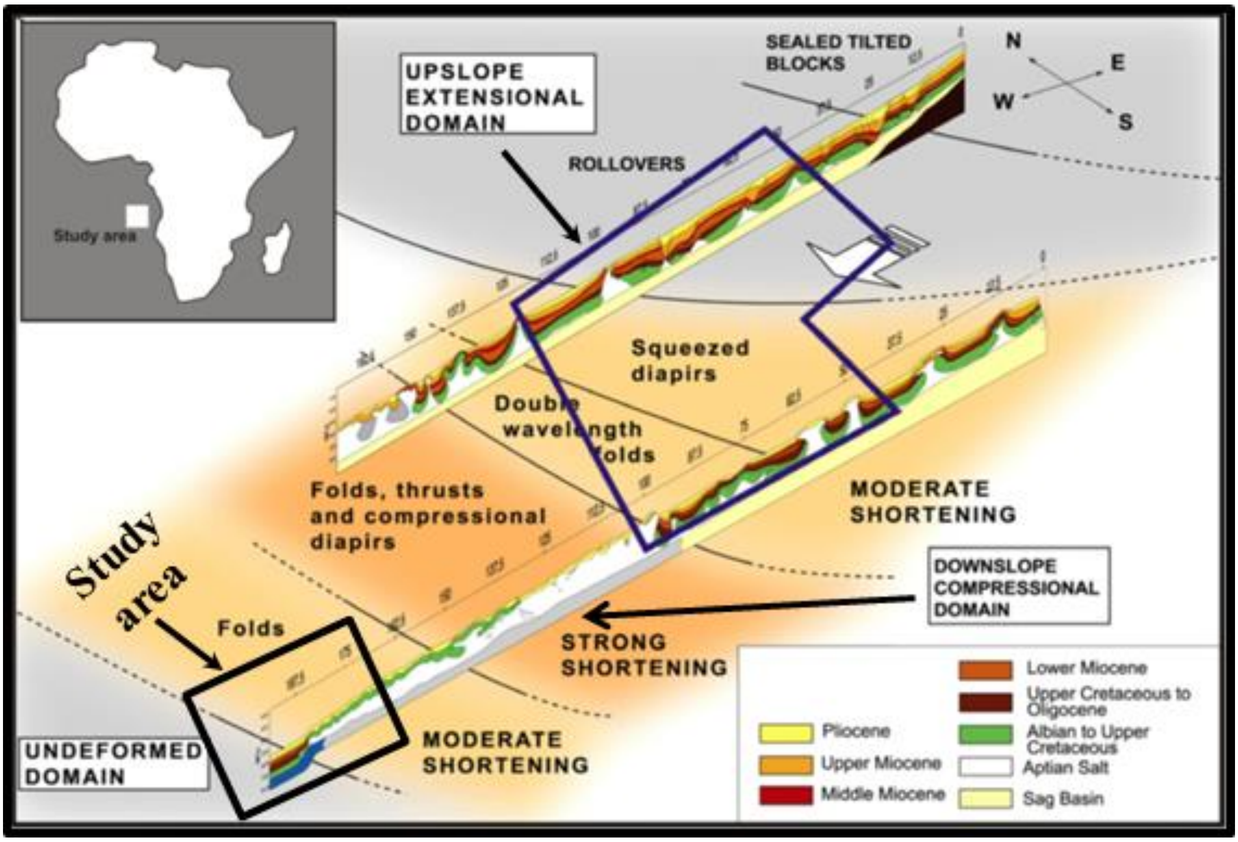


Figure 2-4: Tectonic provinces of the post-salt stratigraphy of the Lower Congo Basin slope-parallel section across extensional and compressional domains. Approximate location of the study area is marked in black color in compressional domain and the other purple color squared is showing extensional zone (Modified from Fort, 2004).

Figure 2-4 illustrates the extensional and compressional domains and associated structures. From a structural point of view, the proximal extensional domain displays ocean-ward sealed tilted blocks, rollovers and diapirs and the compressional domain is characterized by growth folds, squeezed diapirs and thrusts.

The extensional zone is the area where the slope angle increases with subsidence. The sediment loading and the salt flow, which resulted in the formation of gravitational extension structures as consequence of displacement of the sediments (Fort et al., 2004). The extensional domain has the following subdomains: sealed tilted blocks, synthetic growth fault and rollovers and extensional diapirs between rifts as illustrated in the (Figure 2-5) with purple color (Figure 2-4) squared.

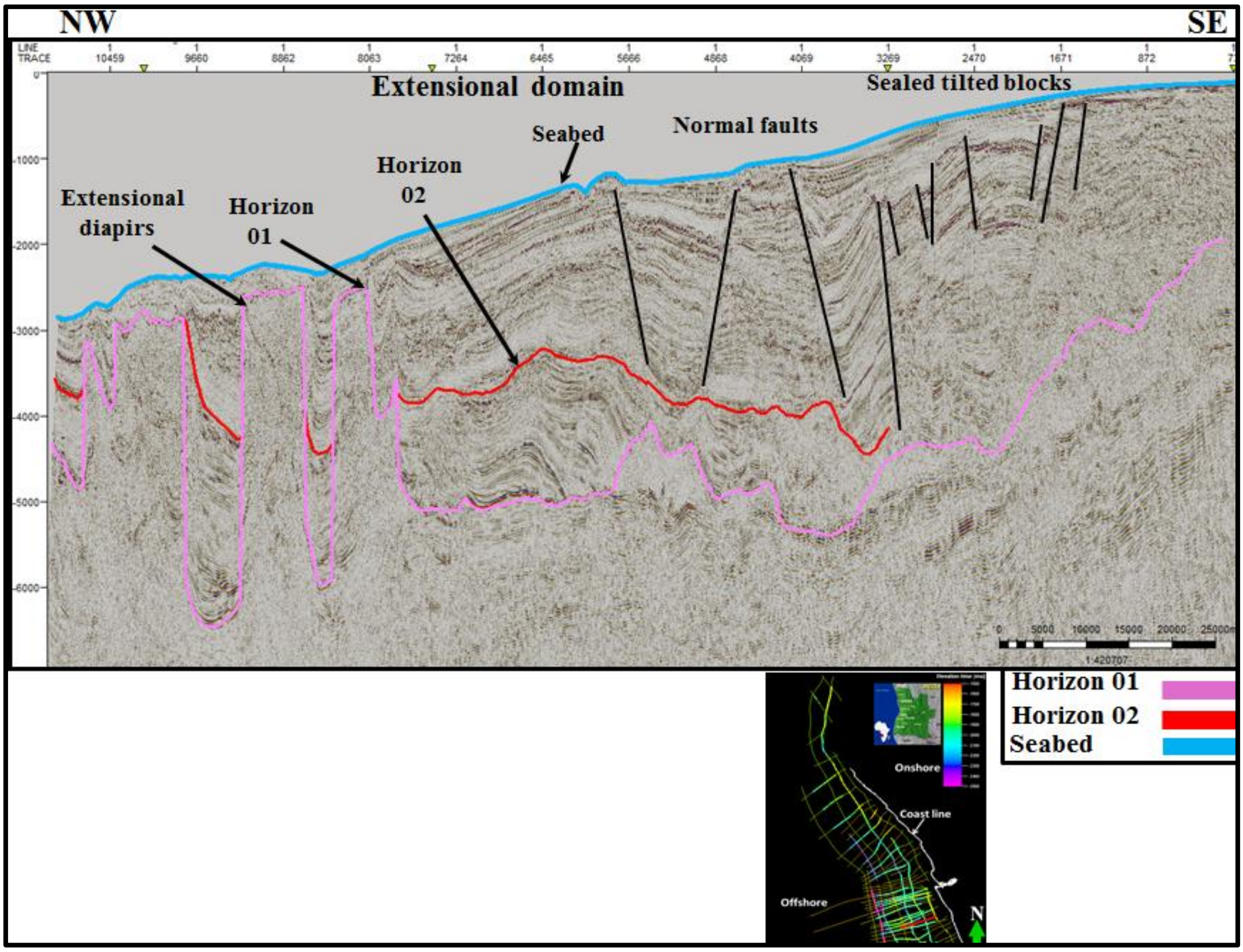


Figure 2-5: Seismic line shows horizon and fault in extensional domain dip line 2850 (Caetano E. 2012).

The translational zone is the zone between the extensional to compression zone. The common structures are diapirs and folds in the deeper basinal part (Figure 2-6).

The compression zone is the contraction domain with high quantity of the salt. Also it consists of growth folds, thrust folds and salt canopies (Dickson et al., 2003 & Fort et al., 2004) (Figure 2-6 and Figure 2-6).

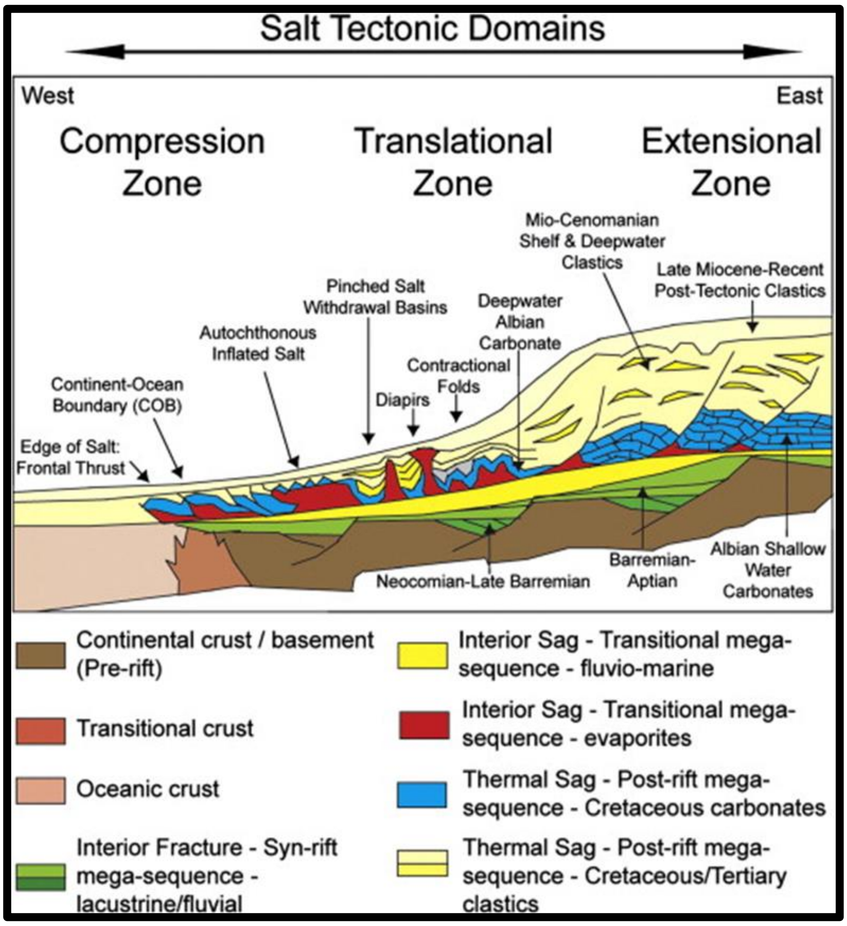


Figure 2-6: shows the mega sequence of events of different age in separate colors. The brown color is the continental crust basement (Pre-rift), and the light brown is the transitional crust. Following the seismic section the light/dark green are the interior fracture syn-rift mega-sequence and lacustrine fluvial sediment. So the yellow color is the interior sag transitional mega-sequence fluvio-marine, and the red is evaporites sequence. The light pink is the oceanic crust, while the blue color marks the thermal sag-post-rift mega sequence of Cretaceous carbonates. The light/dark yellow is the thermal sag-post-rift mega-sequence of Cretaceous/Tertiary clastics (Dickson et al., 2003).

2. 4 -Methodology and data set

The initial stage of this study comprised two key components:

- Literature study of the geology of the Lower Congo Basin, including basin evolution and depositional systems.
- Interpretation of 3D Seismic data set using Petrel software in order to map the most important channels and geological features, in the basins in the recent part of the stratigraphy.

The purpose of this project is to conduct a detailed geologic interpretation of turbidites channels, in other to understand the depositional systems in the basin. 3D seismic data were interpreted using Petrel software. Maps of interpreted horizons capture the geomorphology of the channels. The excellent quality of the seismic data allows detailed interpretation with attribute maps that would help in capturing these channels and study their evolution.

This study utilizes 3D seismic data set. The data consists of 2930 xlines and 2028 inlines. The Inline and xline the intervals are 25m meters. Inline length is 70255.40m and the xline length is 50629.50m. The 3D seismic sections were acquired in the West Africa near in blocks 31 and 32 of Cabinda-Angola province. The seismic interpretation was done on an area of 655.36km². The seismic data set survey is a 3D pre stack time migration (PSTM), and was recoded in two way travel time in milliseconds (TWT ms).

In the course of the work, I have mapped 3 horizons Horizon-A, Horizon-B, and Seabed (SB). Surface maps are used to generate isopach maps to observe the thickness from these horizons. Imaged RMS attribute surface maps, RMS variance surface maps and blended of amplitude and Variance were generated to visualize the channel. Flattening of surface and flattened variance cubes techniques were used to map lateral extension of the channels in the 3D seismic dataset.

Interpretations were made by utilizing the following visualization techniques and workflow (Figure 2-8):

1. Interpretation Window led to a better understanding of the seismic interpretations and consequently the data quality.
2. Three-Dimension (3D) windows when used for seismic visualization using cube. The windows visualize seismic data, horizons and time slices. Seismic data can be interpreted in any direction in 3D data. It is an essential tool for quality control of the interpretation. For example: inline, xline and random lines and time slice line may be displayed concurrently.
3. A two-Dimension (2D) window is the window that displays the base map. It is divided by inline and xline, the colour bar scale identifies the depth in mille second (ms).

We were two students interpreting the same data set. The data set was divided into two intervals. The Shallow interval goes from Seabed to Horizon A, which is my focus, and the Deep- part start in Horizon A. (Figure 2-7).

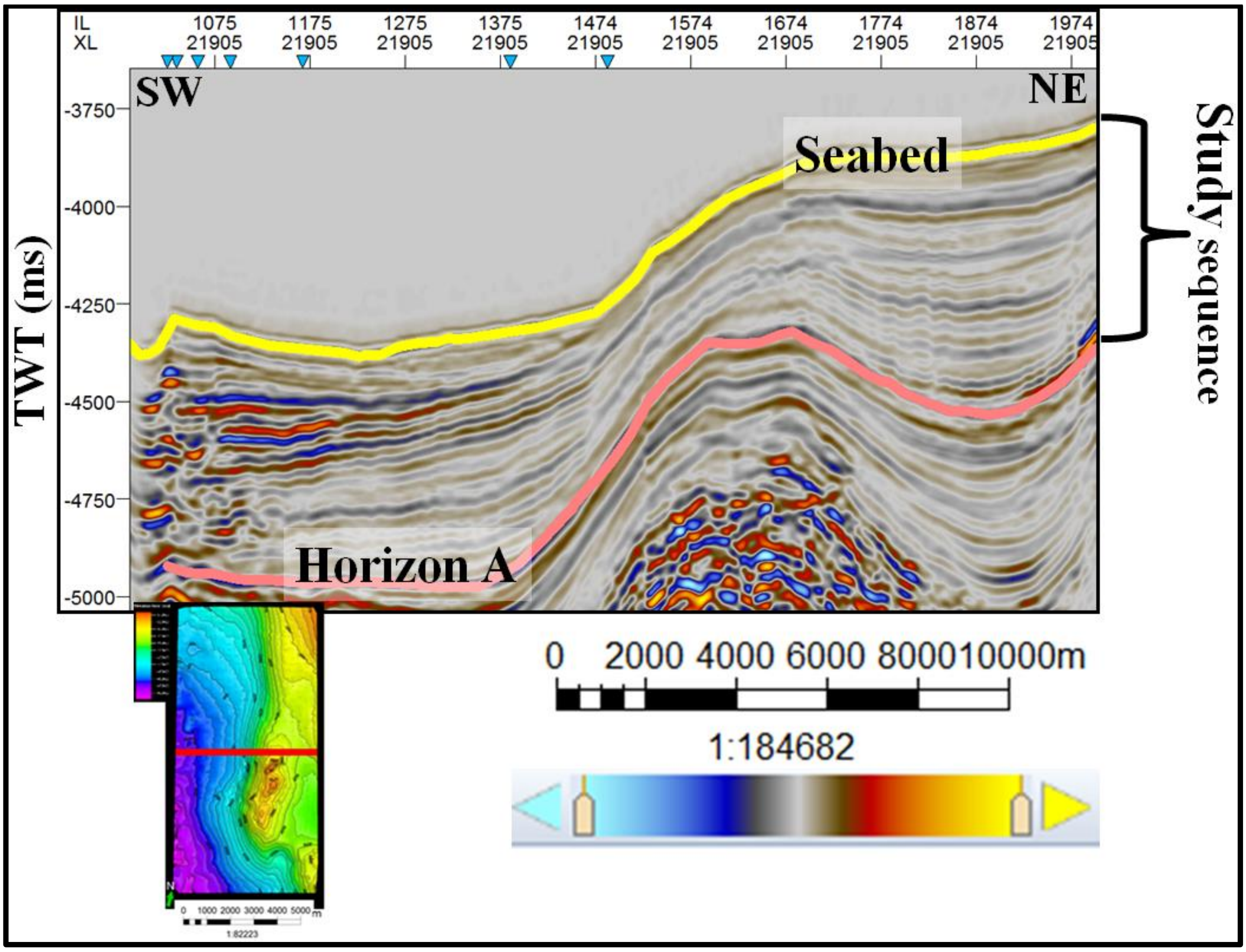


Figure 2-7: Seismic section illustrating the study sequence interval 5000 to 4000ms in this thesis with respectively horizons interpreted.

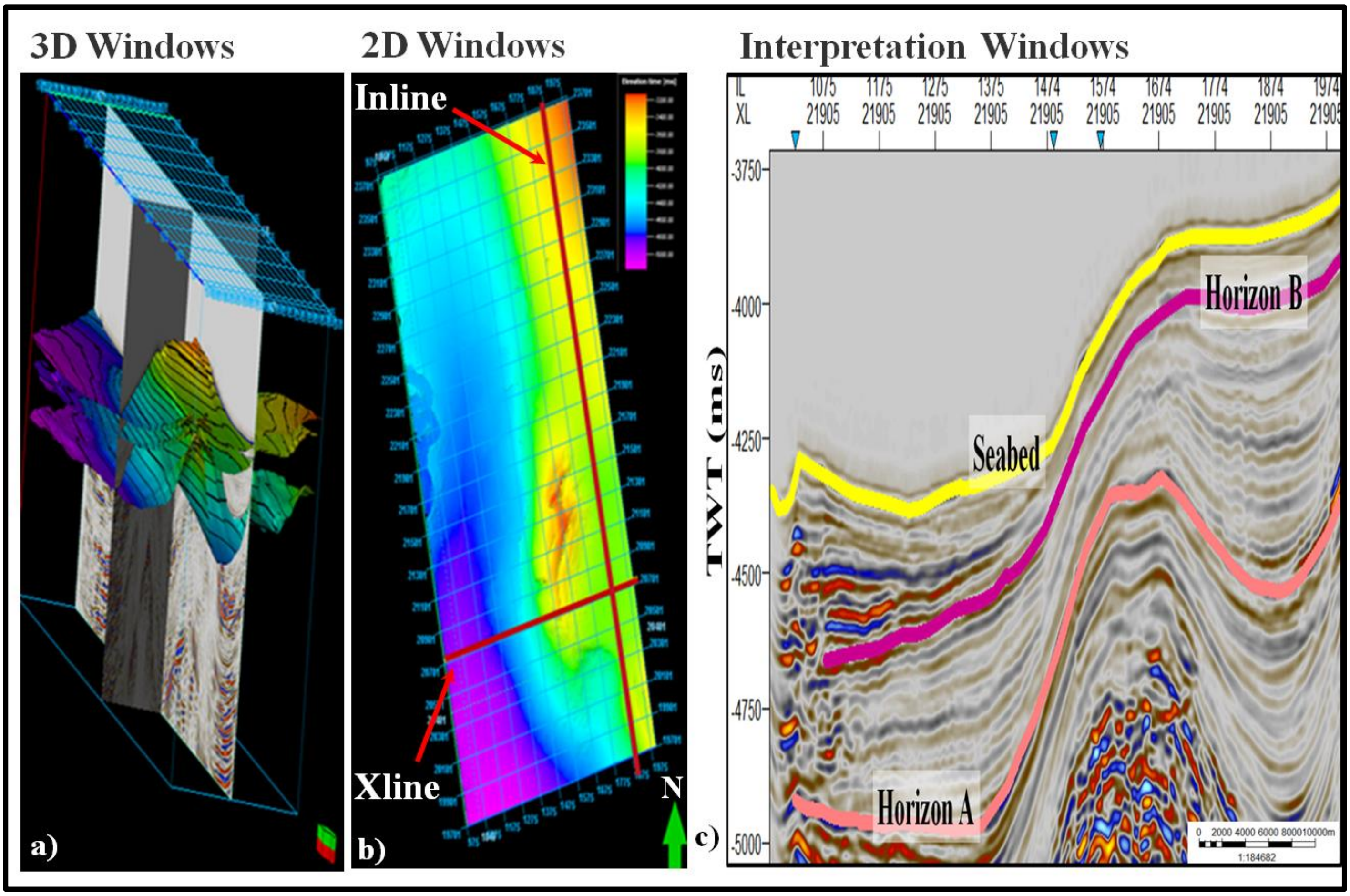


Figure 2-8 Shows the windows Petrel software: a) Illustrates 3D window where is displayed surface attribute maps, b) Illustrate 2D windows where the surface map is displayed, c) Illustrates the interpretation window where the horizons are interpreted.

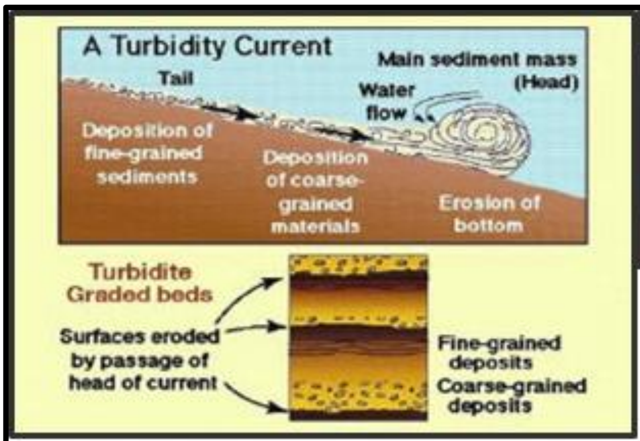
Chapter 3 - Deep-water depositional environments processes and products marine deposits

3.1-Deepwater processes

3.1.1- Turbidity flows

Turbidites are sediments formed as a result of turbidity currents and by density flows. In this type of flow, fine-grained sediments in suspension increases the density of the flow relative to the surrounding water. In turbidity currents, the higher the velocity of the flow the larger the particle size and the greater the volume of the sediment that can be transported. This kind of current usually occurs in lakes and oceans, sometimes trigged by earthquakes or slumps. But more commonly results from sediment delivered to shelf-edge via deltaic and or shallow marine process. The morphology of turbidity current can be described using the terms Head, Body, and Tail. The Wake can be likened to a sweeping movement which rolls, mixes and causes the sediments to flows down the slope onto deep marine floor (Figure 3-2 and Figure 3-1).Turbidity currents flows are controlled by two major factors: slope angle and sediment load.

Tectonism influences the nature of the basins drainage (i.e. its geometry and gradients) as well as the geometry of the receiving basin (Richards, 1994).



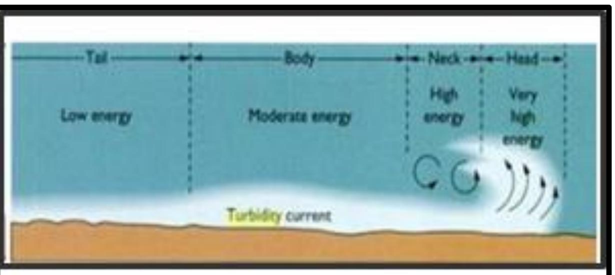


Figure 3-2: Turbidite current Cycles- Down-slope (Bouma 1962).

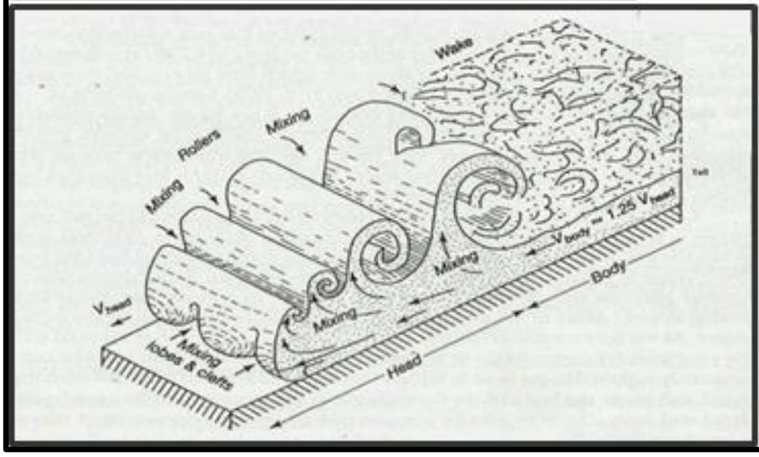
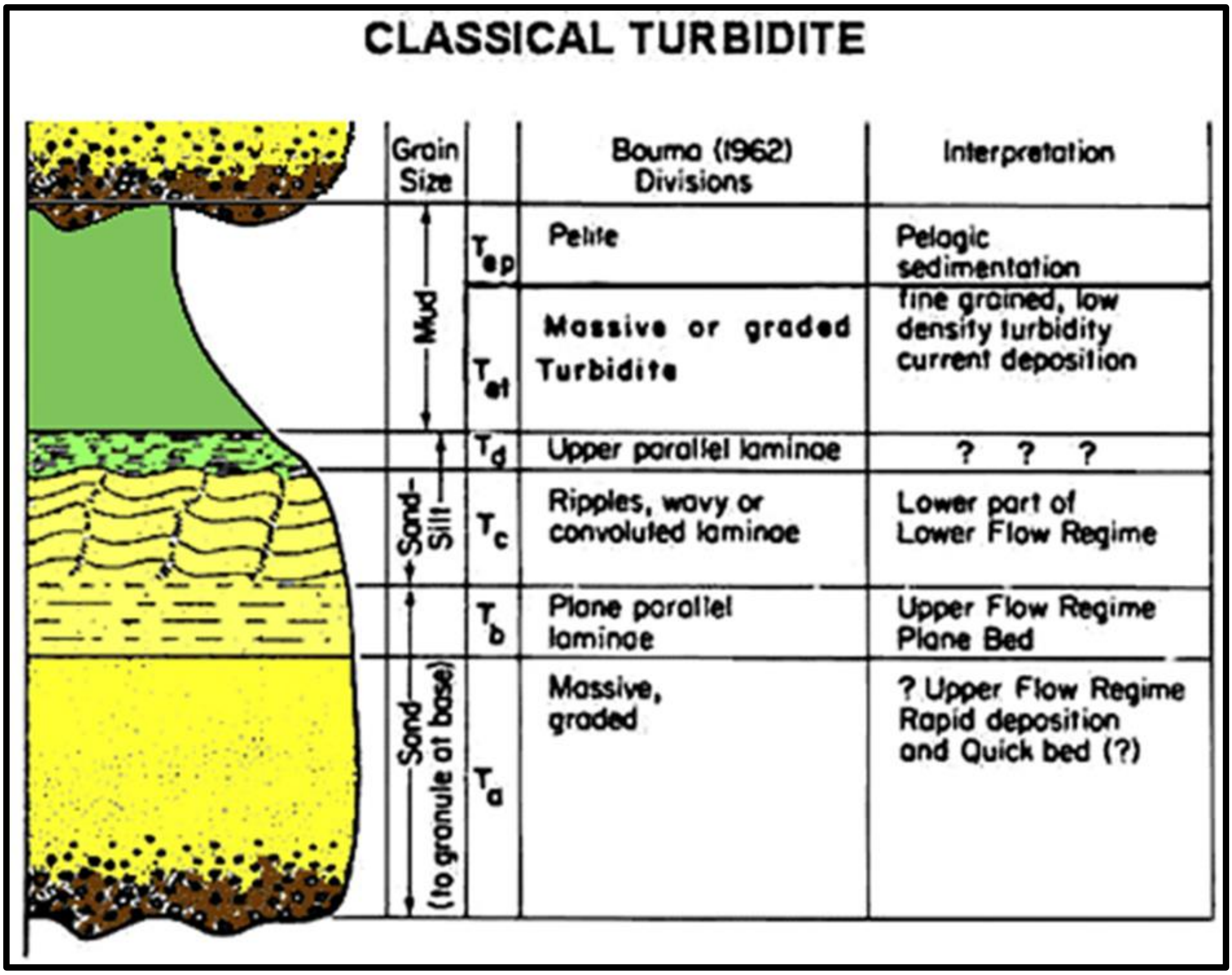


Figure 3-1: Shows the transportation of the sediment and structure of the head and body of a turbidity current in deep-water (Allen et al., 1993).

Turbidities can be classified in two types that are: Turbidities with high-density flow and turbidities with low density flow. Turbidities deposited from high-density flows (from high sediments concentrations) typically form thick-bedded successions containing medium to coarse-grained sands while turbidities resulting from low sediments concentrations are made up largely of clay, silt and fine to medium-grained sand-size particles that are supported in suspension entirely by turbulence mentioned by (Boggs, 2006).

3.1.2- Classical Bouma sequence

A single finning upward sequence which included a lower basinal unconformity, overlain by coarse grain sand this is followed massive sand deposit. This is progressively overlain by a plane parallel sand unit (indicting lower energy of deposit). Above the plane parallel sands it has ripple wavy or convolute laminated sands. Upon this are hemi-pelagic and pelagic sediments deposits (mud) (Figure 3-3).



Grain Size		Bouma (1962) Divisions	Interpretation
Mud	T_{ep}	Pelite	Pelagic sedimentation
	T_{et}	Massive or graded Turbidite	fine grained, low density turbidity current deposition
	T_d	Upper parallel laminae	? ? ?
Sand-Silt	T_c	Ripples, wavy or convoluted laminae	Lower part of Lower Flow Regime
Sand (to granule at base)	T_b	Plane parallel laminae	Upper Flow Regime Plane Bed
	T_a	Massive, graded	? Upper Flow Regime Rapid deposition and Quick bed (?)

Figure 3-3: Bouma sequence idealized sequence of sedimentary textures and structures in a classical turbidity (Bouma 1962).

3.1.3- Debris flows

Debris flow deposits: Form many of the same features of that turbidite sands express. These range from low-sinuosity channel fills, narrow elongate lobes, and sheets and are characterized seismically by contorted, chaotic, low-amplitude reflection patterns (Posamentier & Kola 2003). Where the flows are unconfined, divergent striation patterns probably reflect the flow direction and behavior. Debris flow can extend at least as far basinward as turbidites, and individual debris-flow units can reach 80m in thickness and commonly are marked by steep edges (Posamentier & Kola 2003).

3.1.4- Mass transport deposits

Sediment is transported basin wards from the shelf margin. Sediment gravity flows occur when the sediment is transported under the influence of gravity. Sediments are transported by a variety of mechanisms including suspension, saltation, traction, upward granular flow, direct interaction between grains, and the support of grains by a cohesive fluid (Figure 3-4 and Figure 3-5).

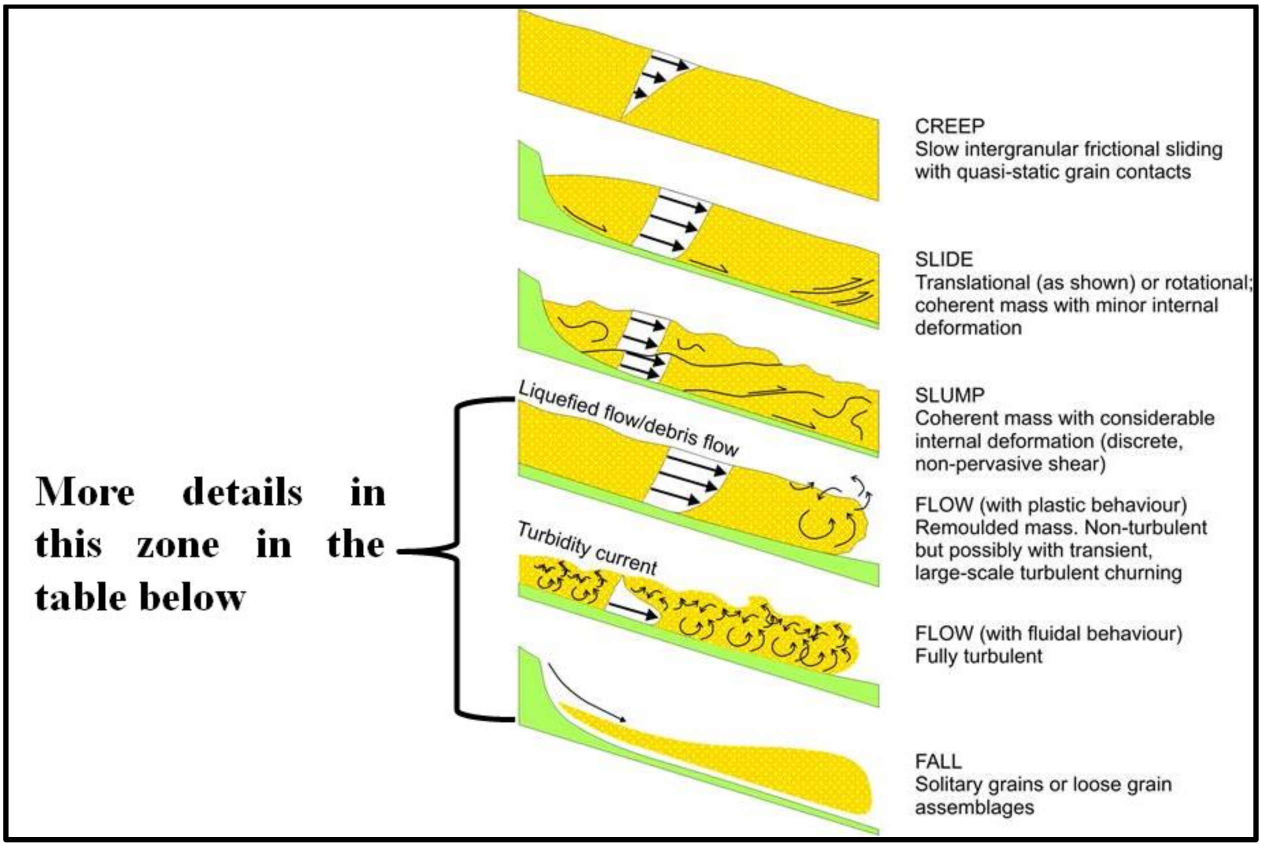
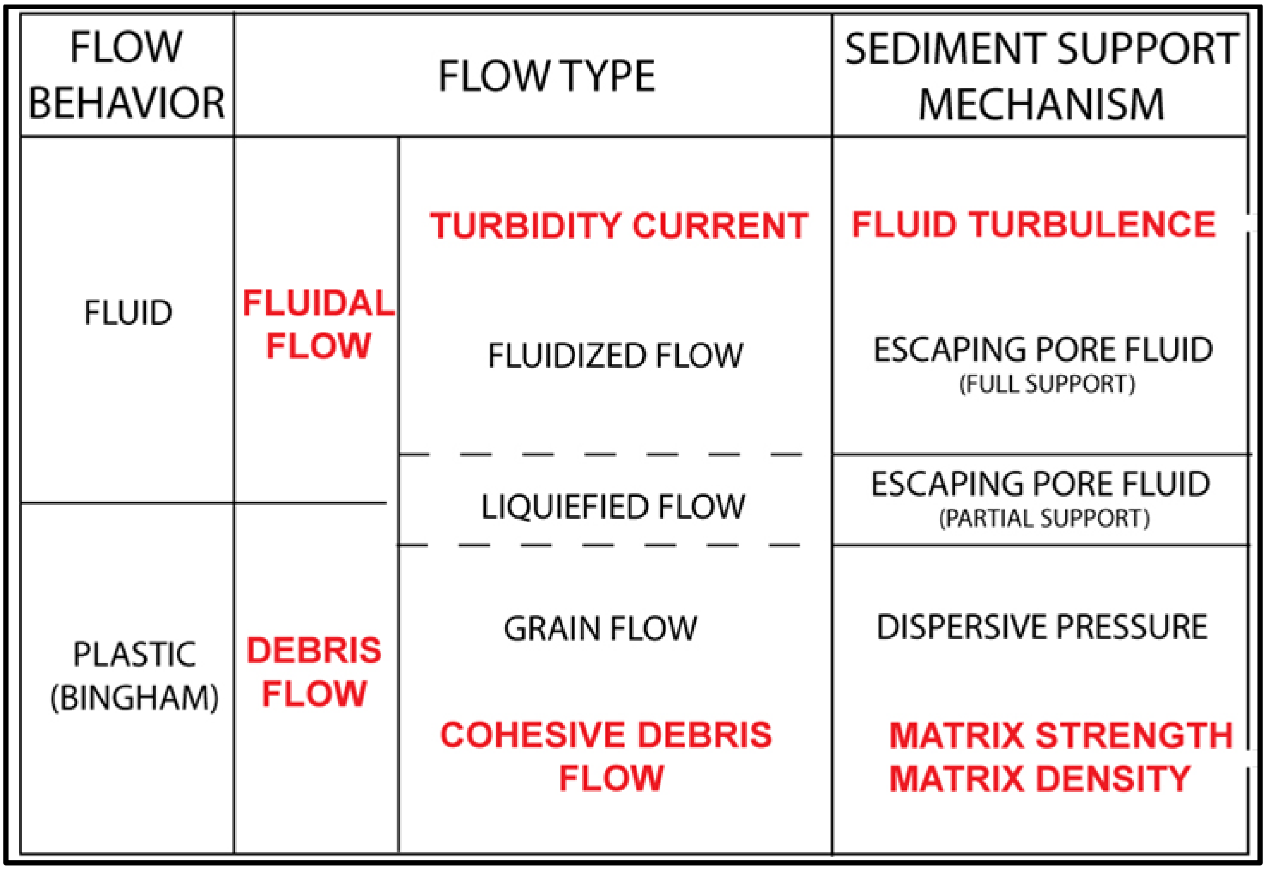


Figure 3-4: Classification scheme of mass movements based on movement rheologies (from Nemec, 1990).

Particle transport by sediment gravity flows:



FLOW BEHAVIOR	FLOW TYPE		SEDIMENT SUPPORT MECHANISM
FLUID	FLUIDAL FLOW	TURBIDITY CURRENT	FLUID TURBULENCE
		FLUIDIZED FLOW	ESCAPING PORE FLUID (FULL SUPPORT)
		LIQUIEFIED FLOW	ESCAPING PORE FLUID (PARTIAL SUPPORT)
PLASTIC (BINGHAM)	DEBRIS FLOW	GRAIN FLOW	DISPERSIVE PRESSURE
		COHESIVE DEBRIS FLOW	MATRIX STRENGTH MATRIX DENSITY

Figure 3-5: Table illustrating transport sediment (Lowe, 1979).

4- Deep-water depositional environments.

4.1-Submarine fan

Submarine fans are accumulations of sediment deposited at the termini of land-to-deep-sea sediment-routing systems (Menard, 1955) (Figure 3-6). They commonly occur at the terminus of big river systems like (Congo River) or outboard of the continental shelf. The sediments are deposited from turbidity currents, displaying partial or complete Bouma sequences (Figure 3-3) with common features such as lamination and grading. However, the thin beds are not necessarily confined to distal depositional sites, but can be part of inter-channel area and occur in more proximal regions. (Figure 3-8) illustrates the submarine fan facies in plain view doing together with predicted Bouma.

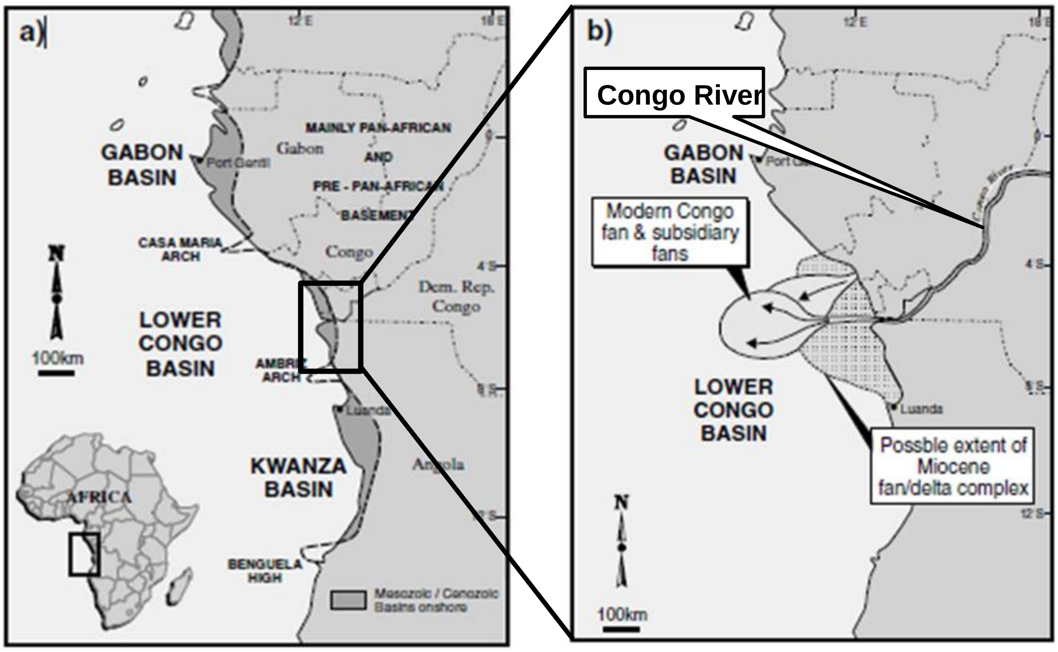


Figure 3-6: a) Location component basins comprising the West African passive margin; and b) Congo fan in the Lower Congo Basin (Anderson et al., 2000).

The sediment-transport zone between terrestrial source area and deep-sea depositional sink can include submarine canyon-channel systems, which generally pass from erosional V-shaped canyons indenting the continental shelf and uppermost slope, to U-shaped channels with overbank deposits across the lower slope and rise (Figure 3-7).

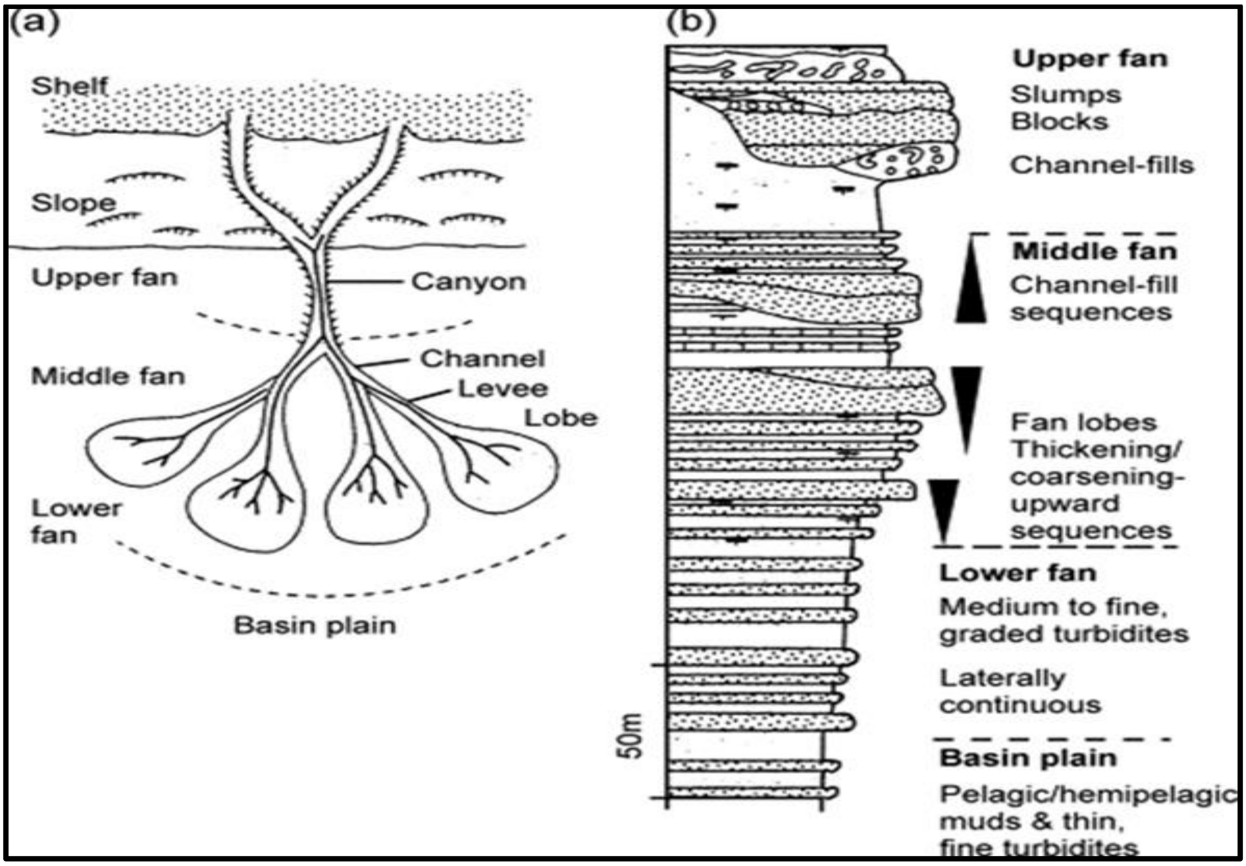


Figure 3-7: Submarine fan facies model (Tucker, 2001).

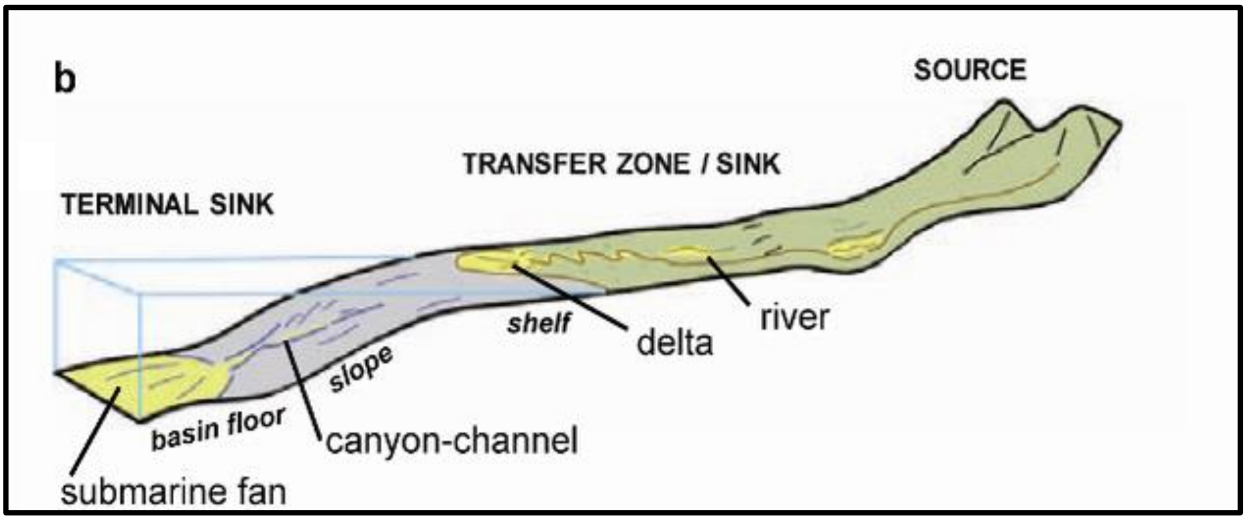


Figure 3-8: Generalized sediment-routing system (Modified from Graham et al., 2011).

4.2- Model for submarine fan development

Submarine fans typically comprise massive accumulations of turbidites and other deep-water deposits. Sequence stratigraphy places submarine fans and related turbidite systems in the temporal and spatial context of sedimentary-basin development (Mitchum 1985, Posamentier et al., 1988, 1991). Sequence stratigraphy is a method of describing and interpreting strata on the basis of changes in the internal and morphologic character of stratigraphic packages within a framework of chronostratigraphically significant surfaces (Vail et al., 1977, Catuneanu et al., 2010). One of the fundamental concepts is the importance of the balance between sediment supply and space for sediment accumulation, called accommodation (Jervey 1988). When sediment fill is enough to overwhelm near cost accommodation on the shelf deposition may be focused on submarine fan in deep sea. Accommodation formation and destruction is tied to sea-level fluctuations, driven by glacial eustasy. Hypothetically, when sea level falls, accommodation on the shelf is relocated basinward to the deep sea. Fluvial systems are able to cross the sub-aerially-exposed shelf and deliver their sedimentary loads to the heads of submarine canyon-channel systems, which funnel the sediment to deep-sea fans (Figure 3-9 a, b).

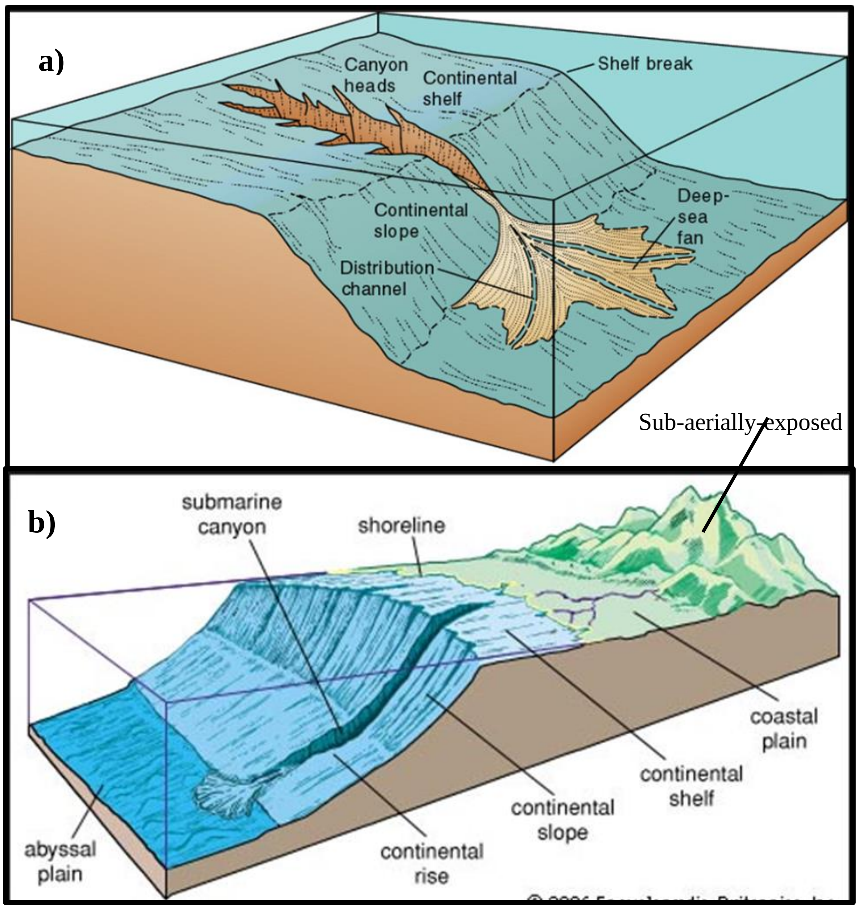


Figure 3-9: Continental margin features (Brooks/Cole a division of Thomson Learning, 2002 and 2006 Encyclopedia Britannica Inc.).

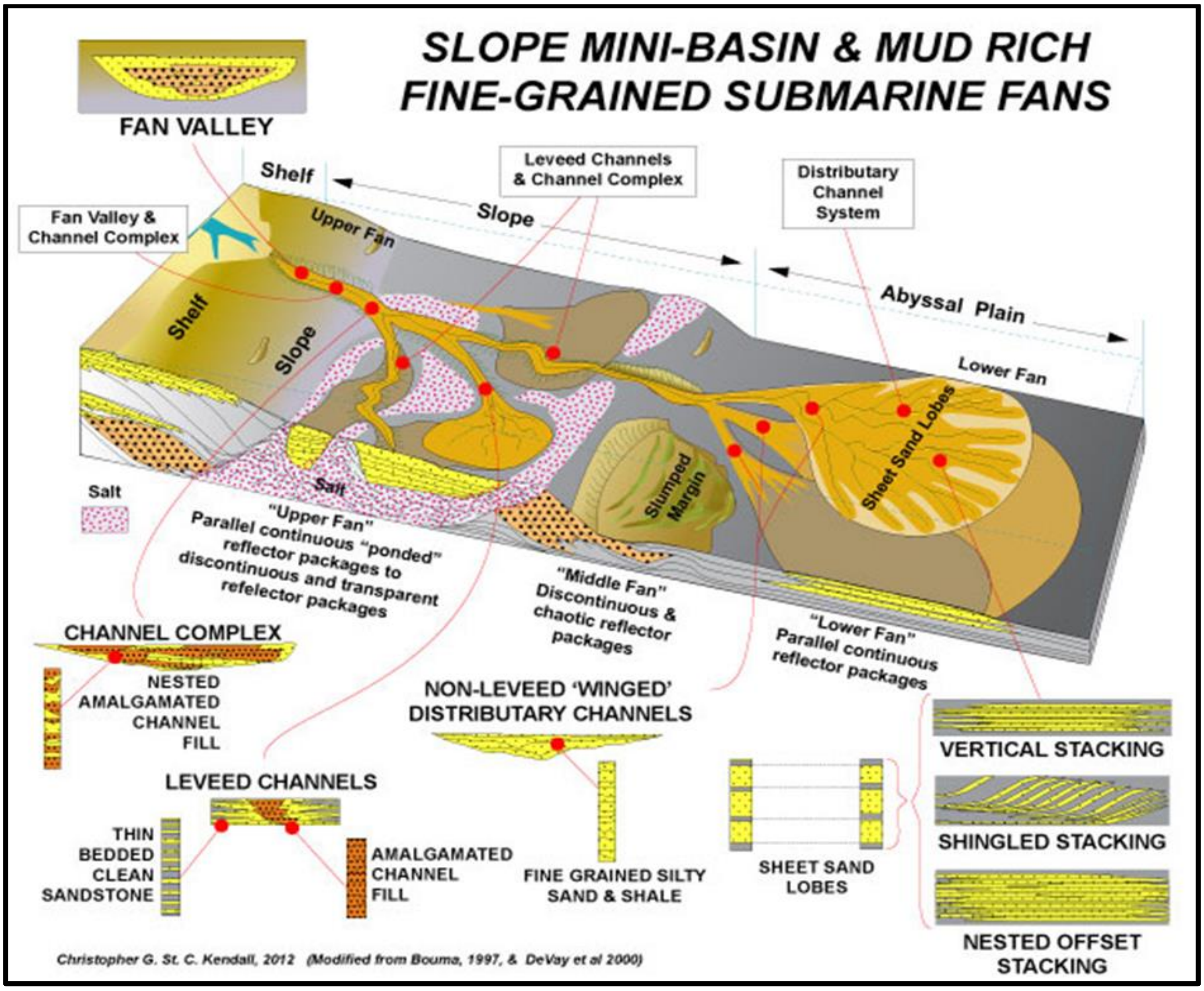
4.3-Deep- water submarine fan

Fan system typically comprises sediments that exhibit a wide range in grain-size and reflect spatial and temporal variations in transport mechanism and pathway. The geomorphology and facies associations associated with fine-grained, mud-rich turbidity fan systems in unconfined basins can be divided into three regions (Stelting et al., 2000) (Figure 3-10).

Upper inner proximal fan region- Is noted by erosive canyon that down dip towards the middle fan becomes an erosional constructional channel complex Fan valley.

Middle fan- Aggradational and characterized by a channel-levee complex that starts at or near the base of slope. This complex is typically sinuous and decreases in size upward and in a down channel direction (Peakall et al., 2000).

Outer lower or distal fan- Surfaced by small, ephemeral channels (distributaries) that grade down dip to sheet-sand complexes that mark distal portion of the fan lobe.



Christopher G. St. C. Kendall, 2012 (Modified from Bouma, 1997, & DeVay et al 2000)

Figure 3-10: Slope mini-basin & mud rich fine-grained submarine fans, (Peakall et al., 2000).

5- Submarine Channels

5.1-Depositional environment turbidity channel

The depositional environment is set out by (Mutti et al., 1991) as the basic mappable components of both modern and ancient turbidity systems and stages that can be recognized in outcrop and subsurface studies.

Levee sand: Is sediment deposited in channel margins and overbank areas. These sands are typically poorer quality than the channel fill. Levees may be breached during periods of high flow depositing sediments outside of the channel (Faria E. 2011).

Overbank: Typically refers to sediment deposited in inter-channel areas and comprises pelagic, and hemi-pelagic and very fine grained sediments that escape the channels confinements. The margin relief associated with deep-water channels on the one hand, and super elevation of turbidity flows and flow-stripping around channel bends on the other, may further complicate the helicoidal circulation (Peakall, et al., 2000 & Imran, J., 1999) (Figure 3-12).

5.2-Canyon and canyon development

A **submarine canyon** is a steep-sided valley cut into the sea floor of the continental slope, sometimes extending well onto the continental shelf. Some submarine canyons are found as extensions to large rivers; however most of them have no such association (Brice et al, 1982 and Stark, 1991). Canyons cutting the continental slopes have been found at depths greater than 2 km below sea level. Many submarine canyons continue as submarine channels across continental rise areas and may extend for hundreds of kilometers. Ancient examples have been found in rocks dating back to the Neoproterozoic (Uenzelmann-Neben et al., 1998).

The canyon fed turbidity systems of the Congo fan were deposited in both pro-delta slope and basin floor settings (Anderson, 1998) and can be traced as far back as the Oligocene (Brice et al, 1982 and Stark, 1991) and the Miocene (Bolli, et al., 1978 & Uchupi, 1992). The rejuvenation of sediments supply to the Lower Congo Basin, commencing in the Oligocene was potentially the result of global sea level fall in response to the onset of the Antarctic glaciation (Bark et al, 1991).

Figure 3-11 illustrates some of the seismic characteristics from Lower Congo Basin offshore Angola. Due to changes in relative sea level widespread unconformities can be seen. The Seabed also shows the current processes of sedimentation and source of sediments.

The seabed reflector is characterized with high acoustic impedance and positive amplitude. The Seabed shows erosion associated with the currents of the Congo fan deposition system.

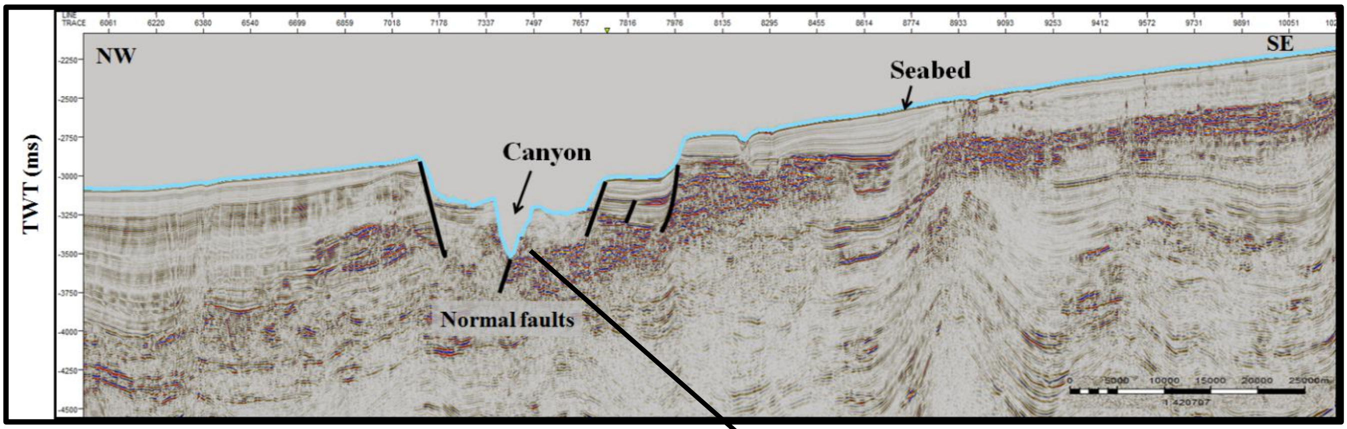


Figure 3-11: Seismic section dip line showing canyon from Lower Congo Basin (Caetano. E. 2012).

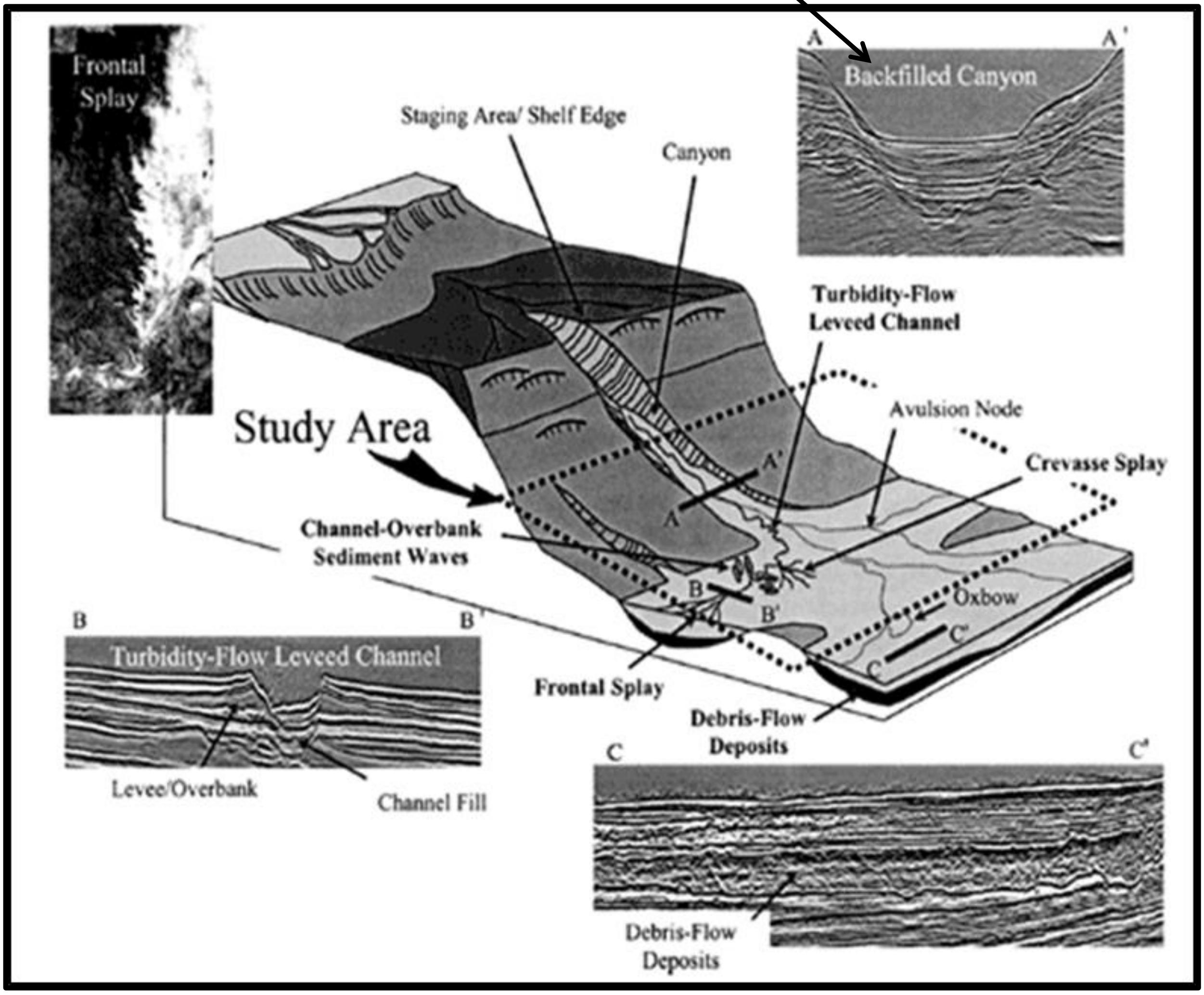


Figure 3-12: Illustrate elements principle in deep water (Posementier et al., 2003).

5.3- Channel Hierarchy

Gardner & Borer (2000) proposed a model to explain observed depositional geometries and stacking patterns of deep-water deposits based on hierarchical concepts (Figure 3-13). This Deepwater Hierarchy and comprises: **Submarine Fan Conduit Complex**, **Submarine Fan Conduit**, **Channel System Complex** and **Single-Story Channel**. The deep-water stratigraphic hierarchy is based on the principles of sequence stratigraphy, which is the recognition of genetically-related strata packages and their bounding surfaces (Mitchum, 1977; Mitchum et al., 1991) In the constricted salt province of the Gulf of Mexico and the West Africa continental slopes sheet sand and channel-levee systems are vertically inter-layered. This is caused by changes in the gradient of micro-basins or the locally scoured and uplifted basin surface and fluctuating rates of sediment supply as the basin fills and sediment spills into the next basin downslope. The four elements that fill the confined basins are: leveed channel sands; amalgamated channel sands; amalgamated and layered sheet sands; and slumps, debris flows, and marine shales (Steffens, 1993). In (Figure 3-13) the black color is the organic rich siltstone, and white color is inter-bedded sandstone and siltstone with beds thinning from channel margin. Also the yellow color is heterolithic channel fill with rip-up clasts and red structure less sandstone with horizontal laminated cap and last one the red line is the erosional surface.

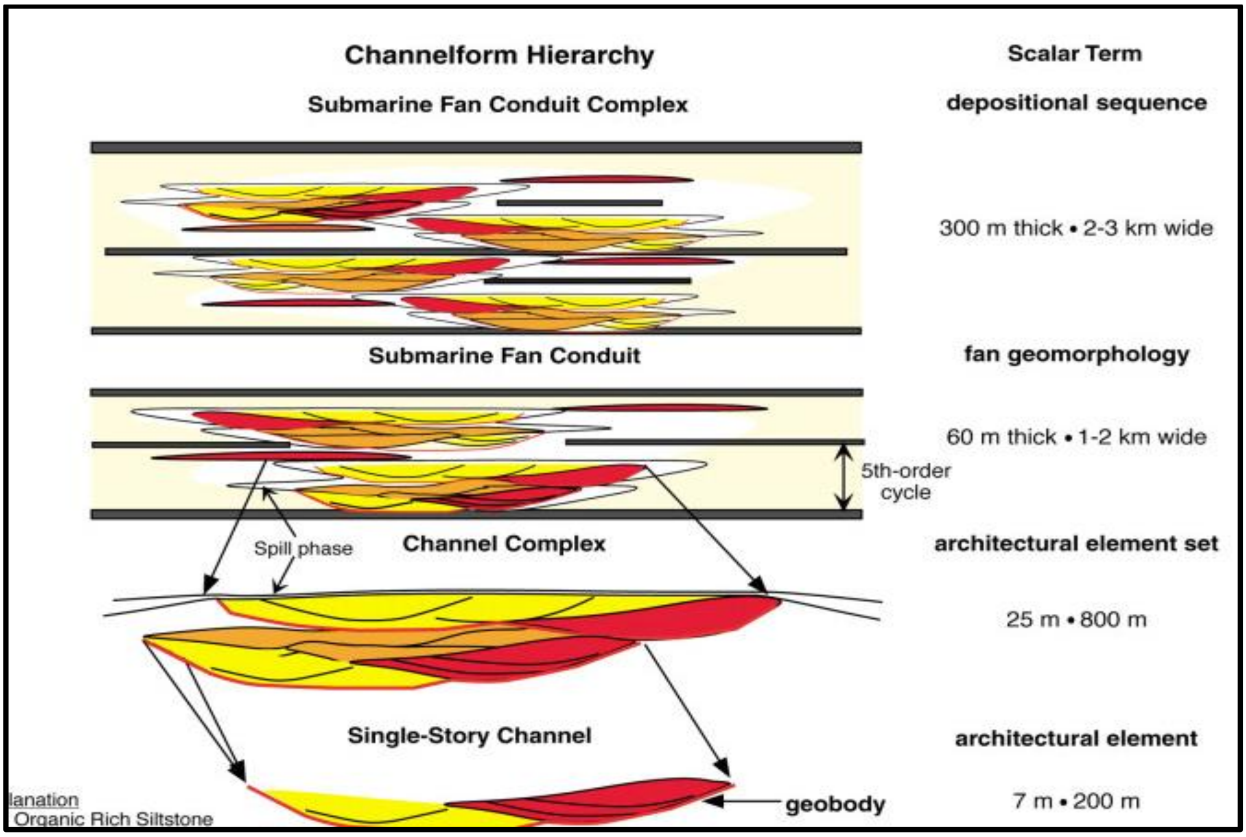


Figure 3-13: Channel form hierarchy (Gardner & Borer 2000).

5.4- Channel stacking

Figure 3-14 illustrates the different types, shapes and channel stacking patterns that may be observed on seismic and commonly observed in deep marine systems. The observed depositional geometry a function of the interaction of erosional and depositional processes, sediment caliber and useable accommodation. In most cases the channels essentially aggrades vertically. The topography and shape characteristics of a basin will however affect the stacking pattern and organization of individual architectural elements.

Channels confined by erosion often occur in the mid fan to distal areas of the base of the shelf margin slope. In the distal portions of the fan channels are not as deeply incised as they are up dip and more widely spaced and grade down dip into sheet-sand complex that mark the distal portions of the fan lobe (Posamentier & Kolla, 2003).

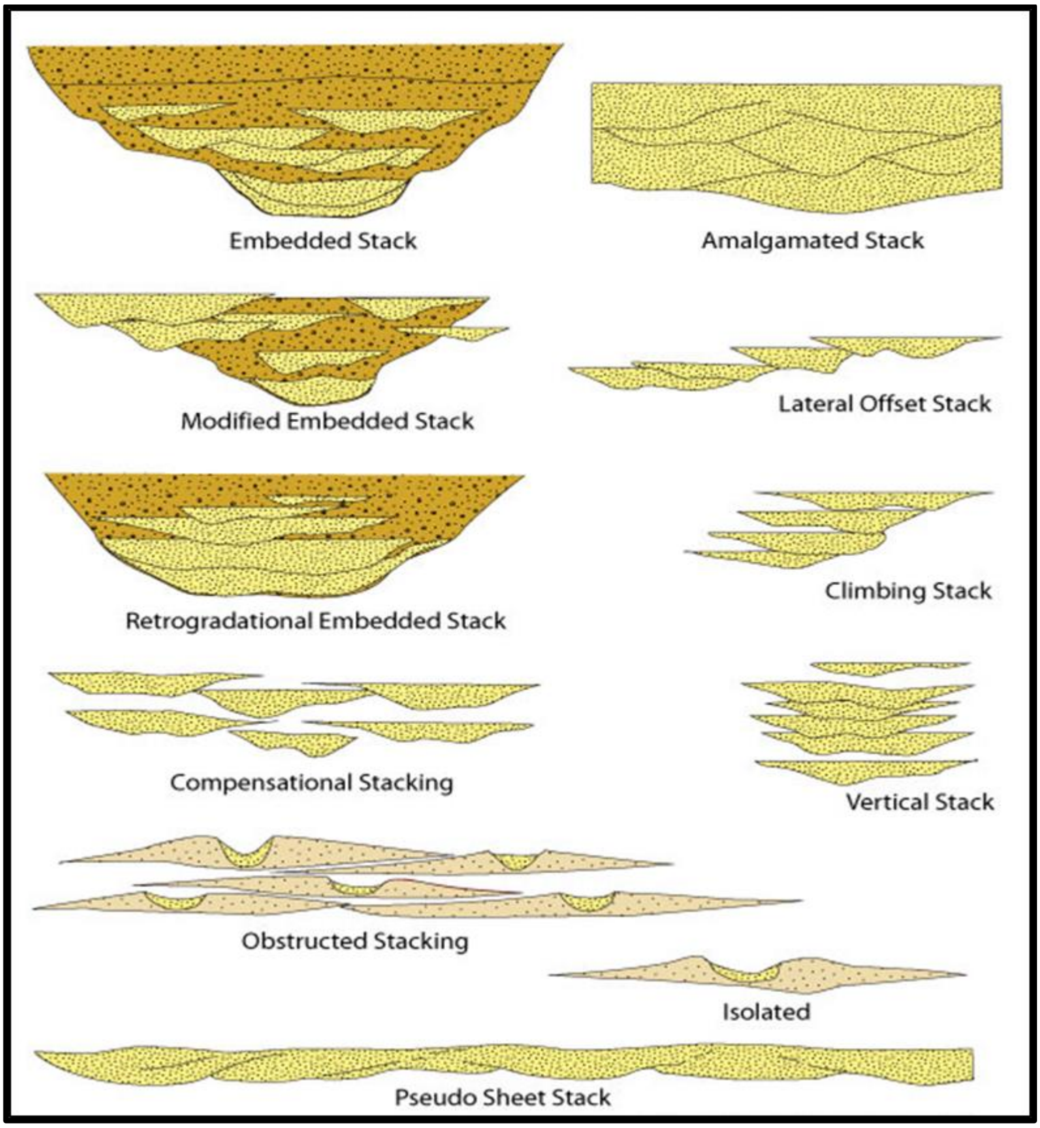


Figure 3-14: Type of channels stacked (Kendall C. et al., 2006).

6-The effect of salt in the basin

The Angolan margin is widely recognized as having outstanding examples of salt tectonics. The amount and quality of available data in particular from the oil industry is high (Brognon et al., 1966).

At passive margins, the salt basin width is commonly in the range of 200–400 km. Salt is most often pinched out landward and seaward. The salt thickness is not constant and can reach several thousand meters within the basin. A shallow water environment of thick salt deposition implies a horizontal top salt surface, close to the global sea level (Fort et al., 2011).

The Angolan margin evolution is related to the process of rifting and that opening the Atlantic Ocean that led to the deposition of the salt layer due to subsidence and regional tectonics. After the deposition of the ductile salt post-salt sedimentation and westward margin tilt caused the onset of extensive salt tectonics. The process leading to the salt deposition was periods of confined marine sea conditions and evaporation.

The salt is very important in hydrocarbon exploration in oil the industry. Due to the physical properties like density and viscosity, the behavior of salt is different relative to other sedimentary rocks. As salt has a lower density and higher viscosity it tends to deform forming geological structures such as: faults, diapirs, rollovers etc that are useful in hydrocarbon exploration.

The exploration of oil in Angola requires getting a better understanding the relation between salt movement and sediment deposition all this factors are related to salt tectonic. (Figure 3-15) illustrates possible hydrocarbon accumulations related to salt tectonic.

For a good accumulation of hydrocarbon to occur, several key steps are required. 1. Good source rock to generate hydrocarbons, 2.Good reservoir rock with good porosity and permeability, 3. Trap for accumulation of hydrocarbon, and 4. Good Seal (Figure 3-16).

Figure 3-15and Figure 3-16 illustrate a combination of structures. In this figure the **Pre-salt** is another play for hydrocarbon. The salt can act as a top seal preventing the hydrocarbon to leak up. The **Sub-salt** formed channels or pinching out against salt diapirs. In the **Post-salt** the turbidites channels and sheets are folded because salt movement or confined by salt structures.

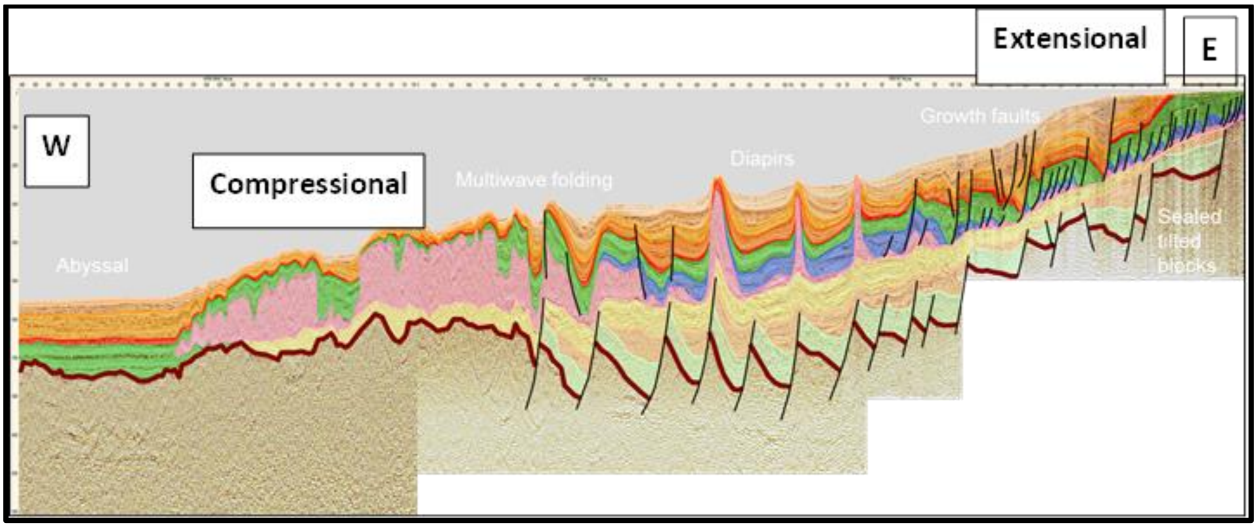


Figure 3-15: Seismic section from Kwanza basin illustrating two domains and theirs structures Extensional and Compressional (Bartolomeu I & Caetano E. 2010).

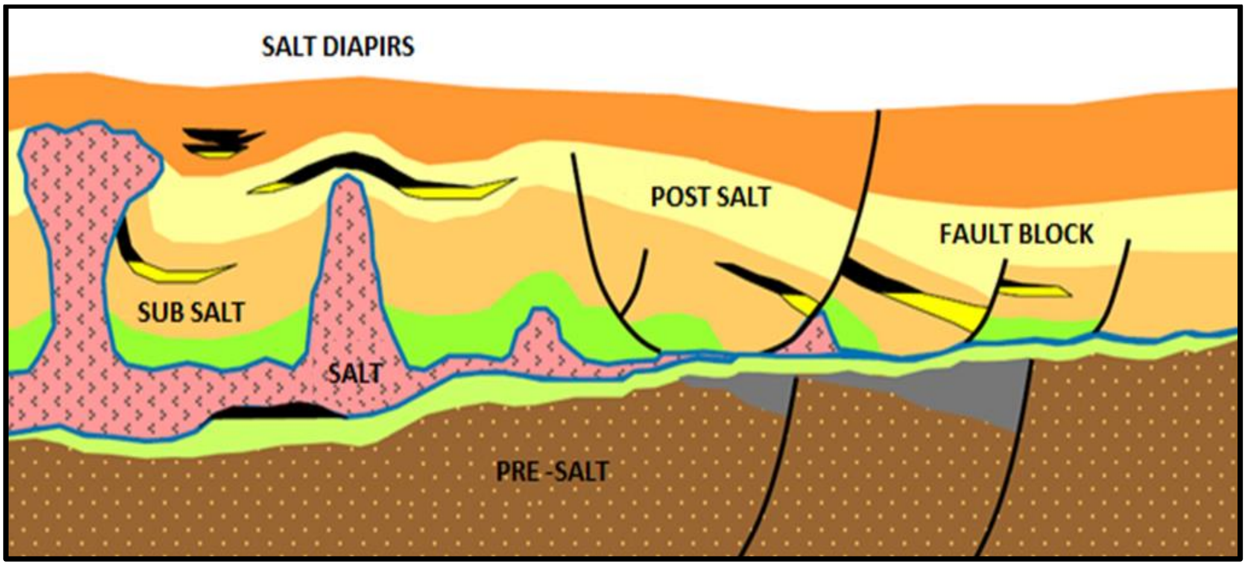


Figure 3-16: Showing salt deformation to form traps for hydrocarbon accumulation (Fejerskov M. et al., 2009).

Chapter 4 Seismic interpretation workflow and techquines

4.1- Workflow of interpretation

The present study area is covered on 3D seismic over an area of 655.36 Km^2. The area is in western of the Lower Congo Basin in Northwest part in offshore Angola (Figure 4-1 a). Angola-Cabinda is the province of this country located in the North where the Lower Congo Basin is situated. The space between crosslines and inlines are 25m and the total lines number is 25625m were used for seismic interpretation (Figure 4-1 b).

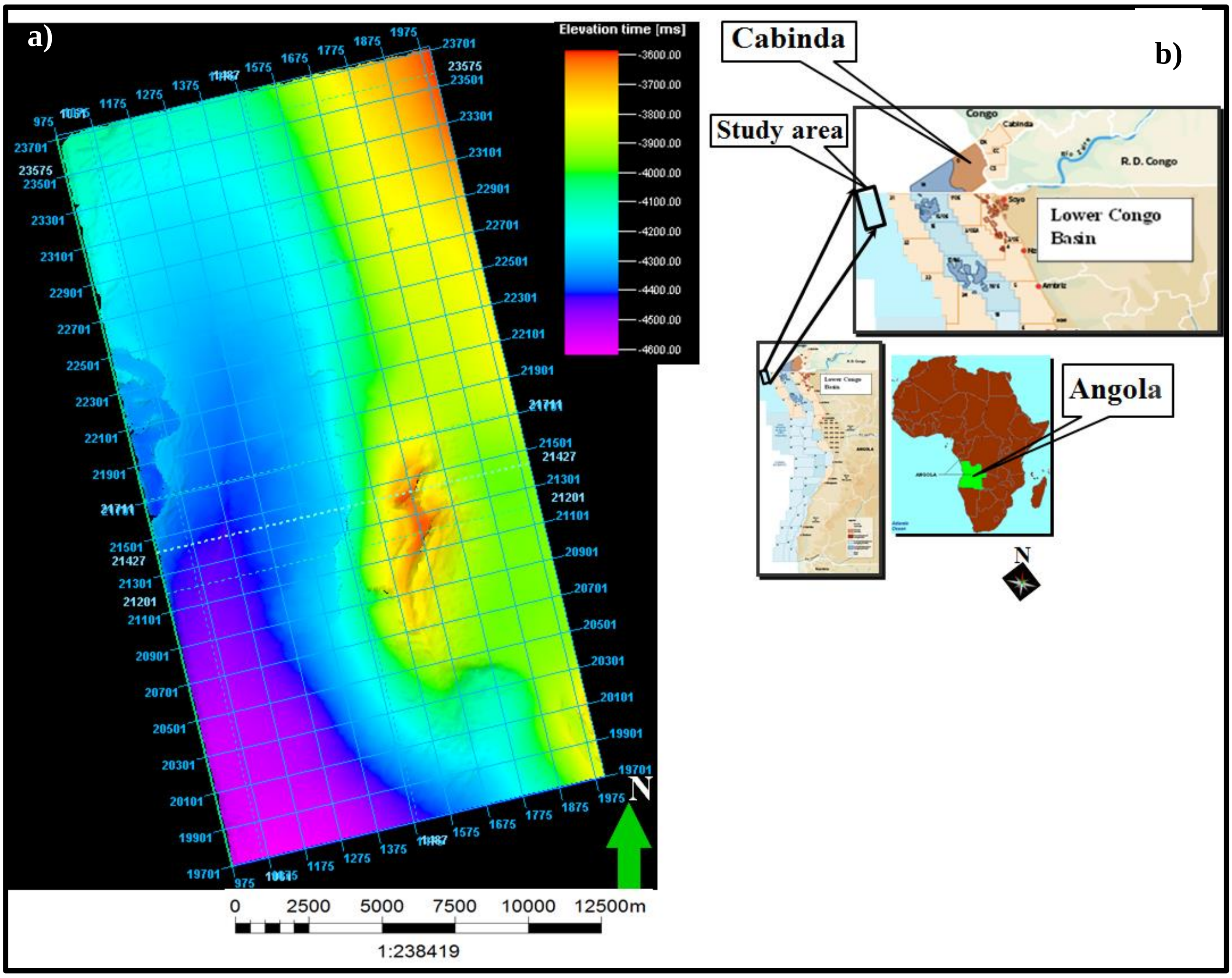


Figure 4-1: (a) Illustrates base map showing study area in the Northwest of Lower Congo Basin (Angola-Cabinda province), with seismic inlines and xlines (Xline ranges 975 – 1975, Inline range 19701- 2370), (b) Illustrates Lower Congo Basin and study area marked by a black rectangle and Africa continent showing where Angola is located.

4.1.2- Reverse polarity standard

In accordance to the Society of exploration Geophysics (SEG) standard there are two type of polarity, normal (America) and reverse polarity (Europe or Australia) polarity (Sheriff 1995). The normal polarity consists is positive amplitude for increasing acoustic impedance. Normally it is displayed as peak wiggle trace and red in color display. The reverse polarity corresponds in negative amplitude with increased acoustic impedance. Normally it is displayed as trough wiggle trace and stronger color display. In this project the standard used is reverse polarity (European) as it shown in the (Figure 4-2).

In (Figure 4-2 a) the reverse polarity is a strong trough that is from the seabed interphase between sediments and seawater. It is an increase in acoustic impedance. This was also commonly observed at the top of salts bodies at the boundary with the overlying sediments. The stronger trough reflections, of the salt layers are distinctly strong due to their high acoustic impedance contrasts with overlying sediments. Also observed are district “pull up” events within the salt. This could be attributed to high velocity in the salt in relative to the sediments.

The seismic profile below in (Figure 4-2 b) illustrates variation in amplitudes in colors. The main reason for changes in the amplitude is because of different physical properties in the sediments such as density and rigidity. In Figure 4-2 a, the seabed is the first reflector with negative amplitude this is due to the contrast in acoustic impedance between the seawater and the sediments. The stronger amplitude in seabed represents the negative amplitude and the low amplitude represents the positive amplitude. It shows increasing acoustic impedance with negative amplitude. During the interpretation I have interpreted the seafloor horizons on the blue color.

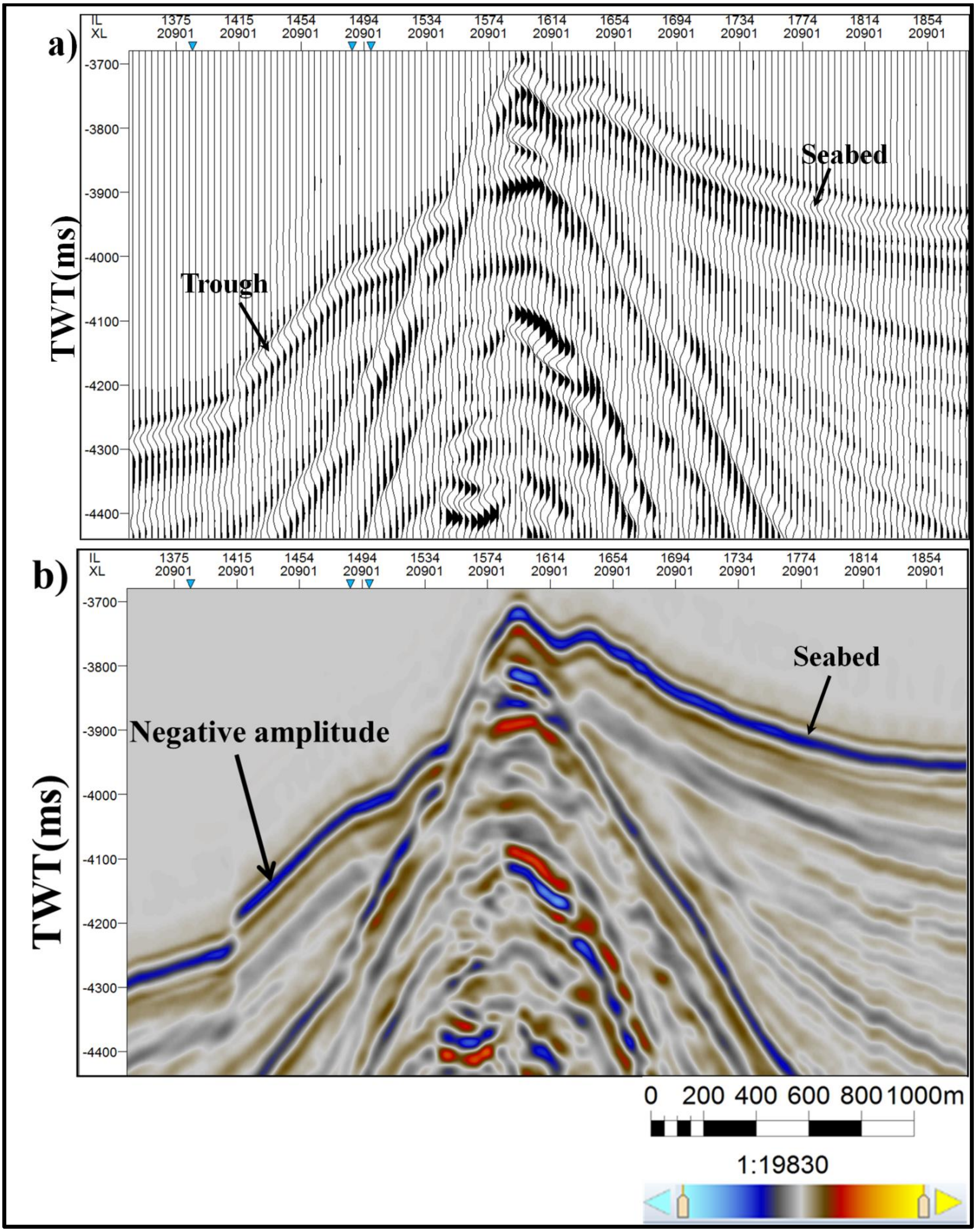


Figure 4-2: Xline 20901 illustrates reverse polarity displayed in the project: a) shows the wiggle trace, b) shows the seismic colored amplitude.

4.1.3- Seismic Data

The excellent quality of the data was possible to make this interpretation most clearly. In addition the good interchange between the 3D/2D window and interpretation window, led to a better understanding of the seismic. The interpretation started by picking horizons with high amplitude. I interpreted three horizons namely the Sea bed (SB), Horizon B (HB) and Horizon A (HA). The interpretation was concentrated in shallower part of seismic section. The two seismic sections in Figure 4-3 and Figure 4-4 capture the sections in their pristine state before interpretation were done on them and also showing the limit of the studied vertical sequence level in the area as captures in the seismic lines of xline 21905 and inline 1025.

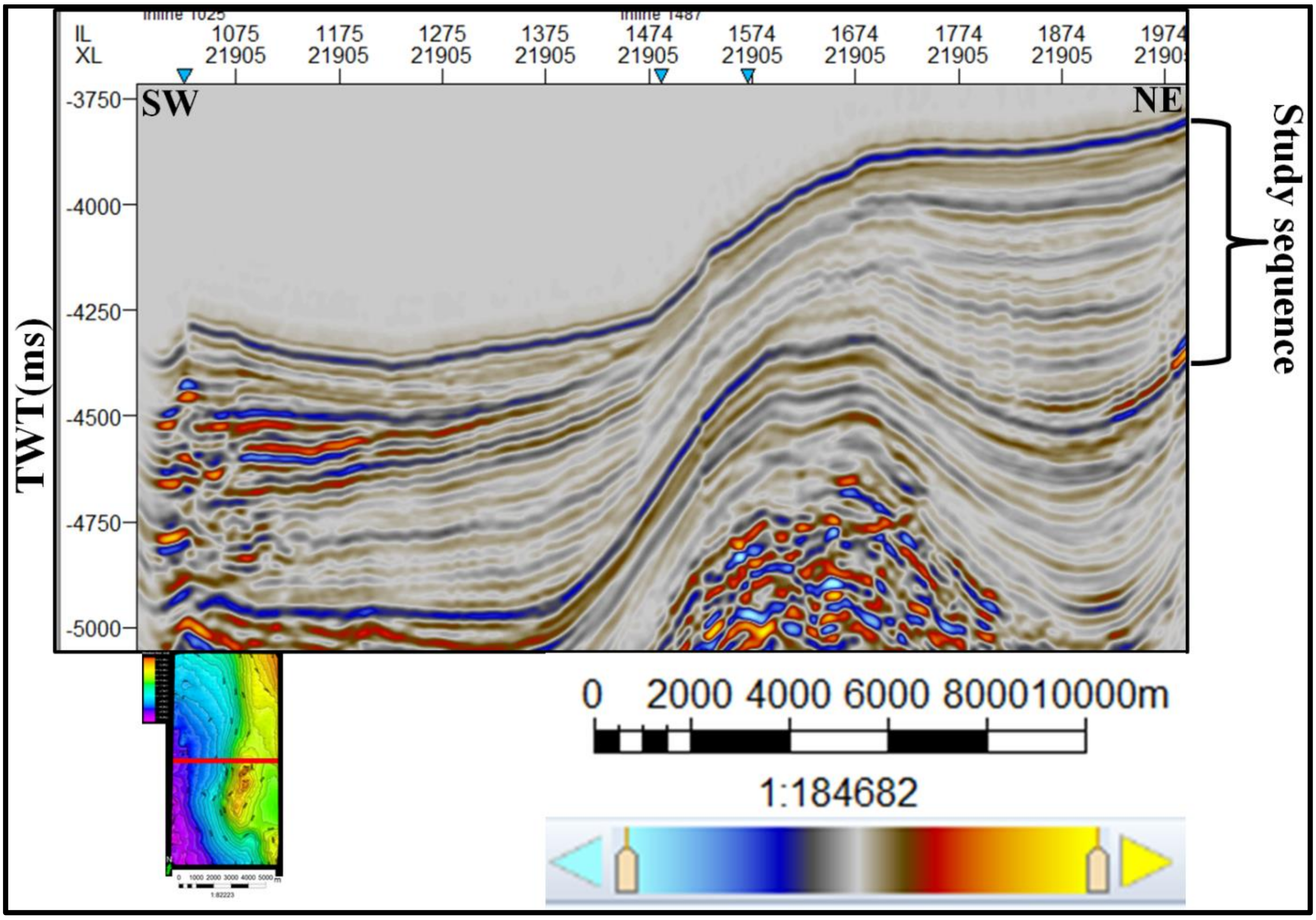


Figure 4-3: Non-Interpreted seismic xline 21905 to illustrate the studied sequence area. The bracket shows the limit of stratigraphic interpretation in the seismic section.

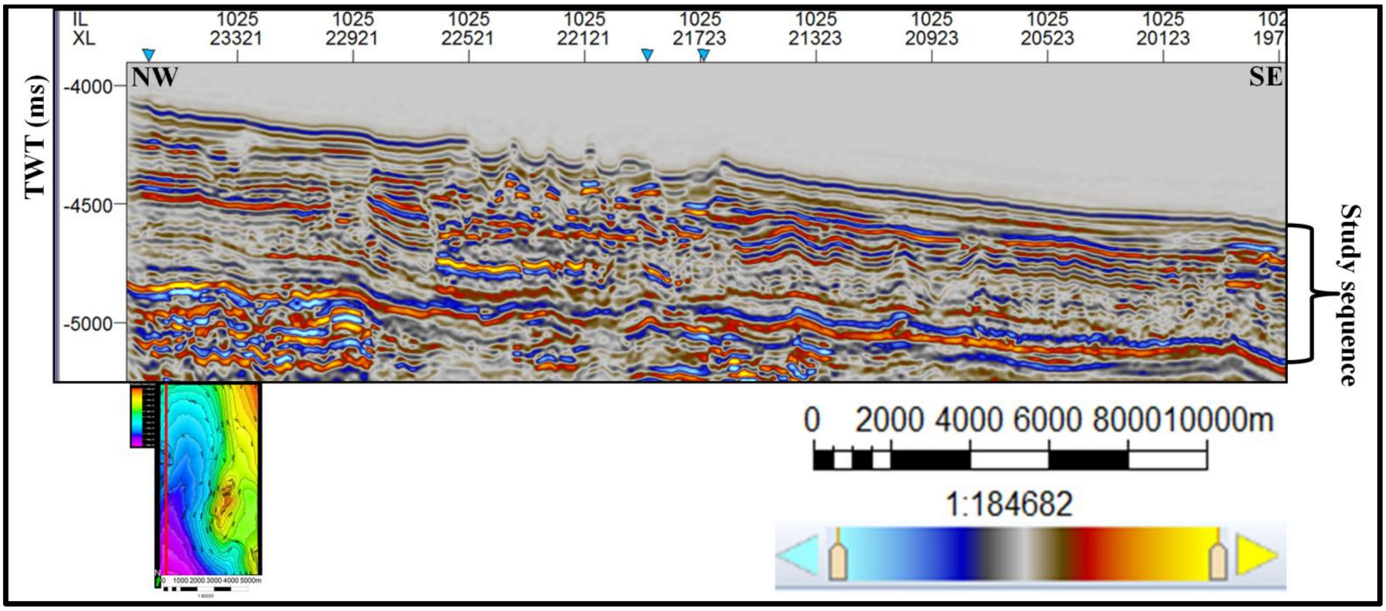


Figure 4-4: Non-interpreted seismic line inline 1025. The brace shows the limit of stratigraphic interpretation in the seismic section.

5- Seismic based techniques applied to main interpretation.

5.1 - Seismic Surface maps extraction

The surface maps were extracted from seismic interpreted horizons, Seabed (SB), HB and HA. These surfaces are illustrated by contour lines which correspond to time (TWT). The surface maps were generated to see the geomorphology. It is useful to understand the connection between salt movement and sedimentary layers.

The interpreted horizons were also visualized. These make the horizon interpretation to be better quality checked by the maps interpretation. The color scale is deep as purple color and orange color as shallowest depths.

The HA, HB and Seabed maps are continuously seismic mapped horizons in the whole seismic area. The HA has ridge like structure (anticline) extend from South to North, on the East side. The western part of the map is relatively flat. The ridges like structure are caused by salt movement. Also on the HB the west side of map is dominated by gentle ridge (anticline) that extends from South to North. The South side has slope gentle in the South to West direction. The effect of the salt is decreasing on this map. In the SB map is dominantly slope in the North-South directions, and gentle ridge (anticline) in the eastern side and was easily identified sinuous channel on Middle Western edge of the map. It shows also four way closure along the uplift area. Theses closures were observed in maps hydrocarbons may be trapped in such structural closures (Figure 4-5).

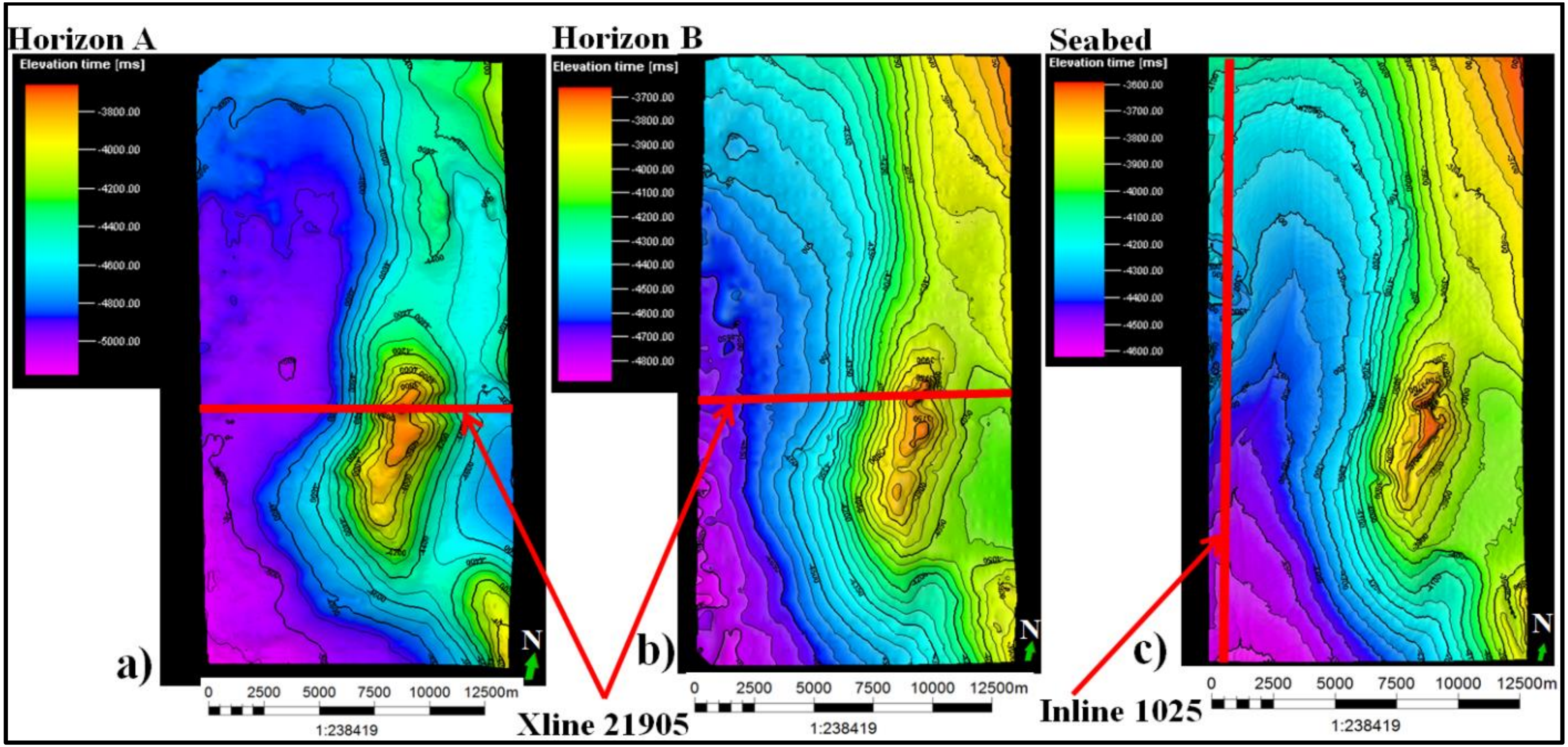


Figure 4-5: Surface maps with respective xline 21905 and inline 1025 red color: a) Shows Horizon A (HA), b) Horizon B (HB) and c) Seabed (SB).

5.2- Isopach maps

According to (Bishop, 1960) isopach map can show the shape of a basin, the position of shoreline areas of uplift and under some circumstances the amount of vertical uplift and erosion can be recognized by mapping the variations in thicknesses of given stratigraphic interval. It may also determine the main tectonic and structural characteristics during sedimentation.

An isopach map has contour lines that connect points of equal formation thickness of stratigraphy unit. The isopach map is fundamental key in understanding the stratigraphic thickness of the sediments, and it also represents thickness variations within tabular unit on the layers (Bishop, 1960).

I made two isopach maps between the interpreted horizons, which invariably corresponds to the interpreted unit thickness of units I and II. The color scale has purple color for the thin layers and orange color for thick layers. It shows that the thickness increases from the base to the top according the color scale (Figure 4-6 a).

The seismic xlines 21905, 21649 and inline 1025 (Figure 4-7 b and Figure 4-8 c) show the thickness variations and their position is shown isopach maps.

The isopach map shows nature of the thickness profile of the sediments. The first isopach map correspondent to unit I, HA-HB between, where the Surface A is the base and Surface map B is on top. In these map areas with purple color show smaller thicknesses due to the diapiric salt movement thins overlying sediments in the crest areas of the salt intrusives. The sediment isopach are related to salt movement as they affect their accommodation spaces created within the salt locations. The second isopach map is for unit II, between Seabed and HB. The isopach map shows yellow and green colors in this area of the channel incisions on the seabed. These shows the thicknesses are smaller around the channel areas, but still thicker compared to thin sediment covers in the units above salt domes (Figure 4-6 a).

There is a significant change in the observed isopach between xlines 21905, 21649 and inline 1025. This reflects the impact of the growing salt on deposition thickness around the seismic sections.

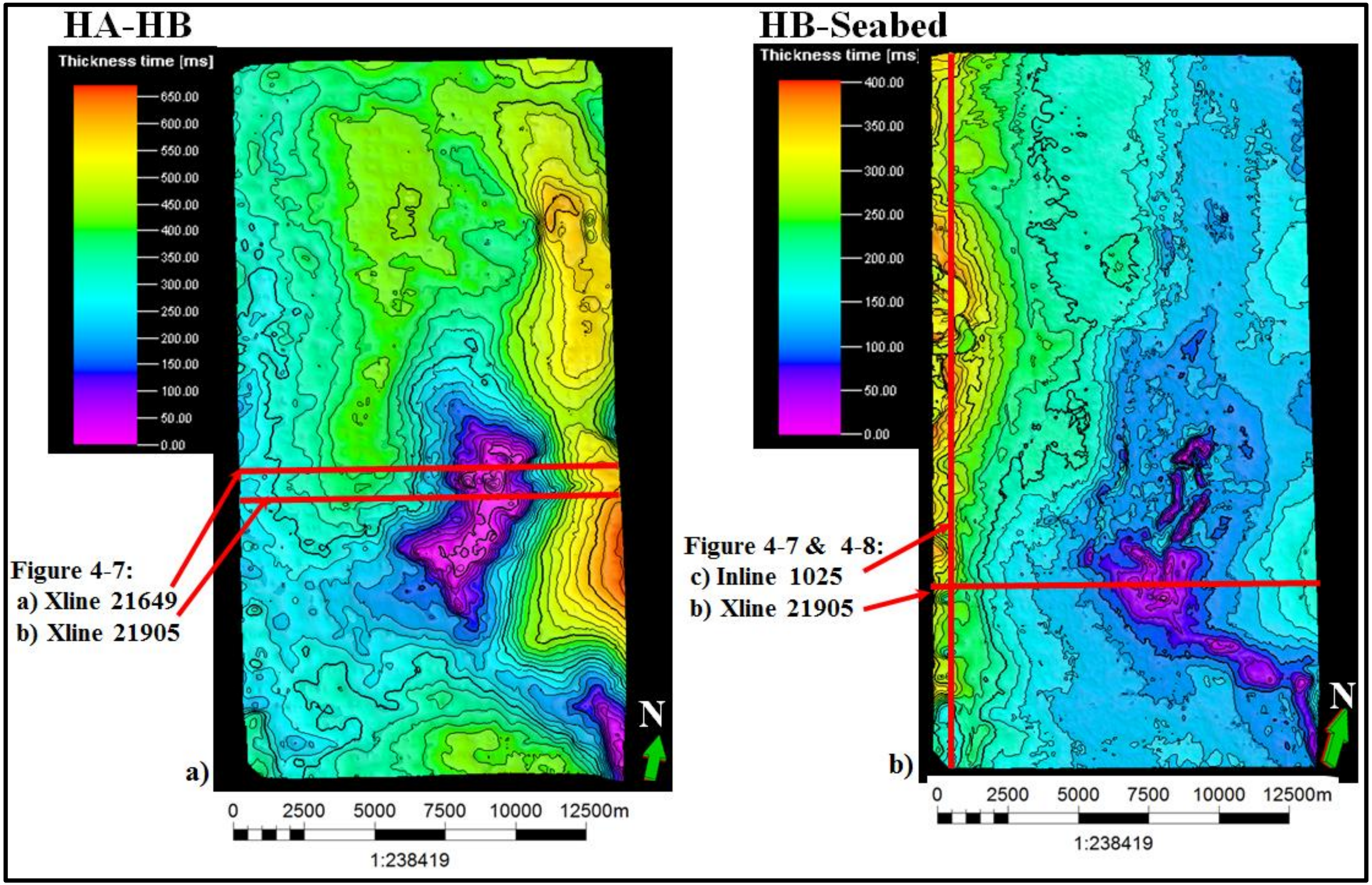


Figure 4-6: a) shows isopach maps with horizons interpreted: a) represents isopach between HA-HB and red color xlines 21905 and 21649, b) represents Isopach between SB-HB, red color inline 1025 and xline 21905.

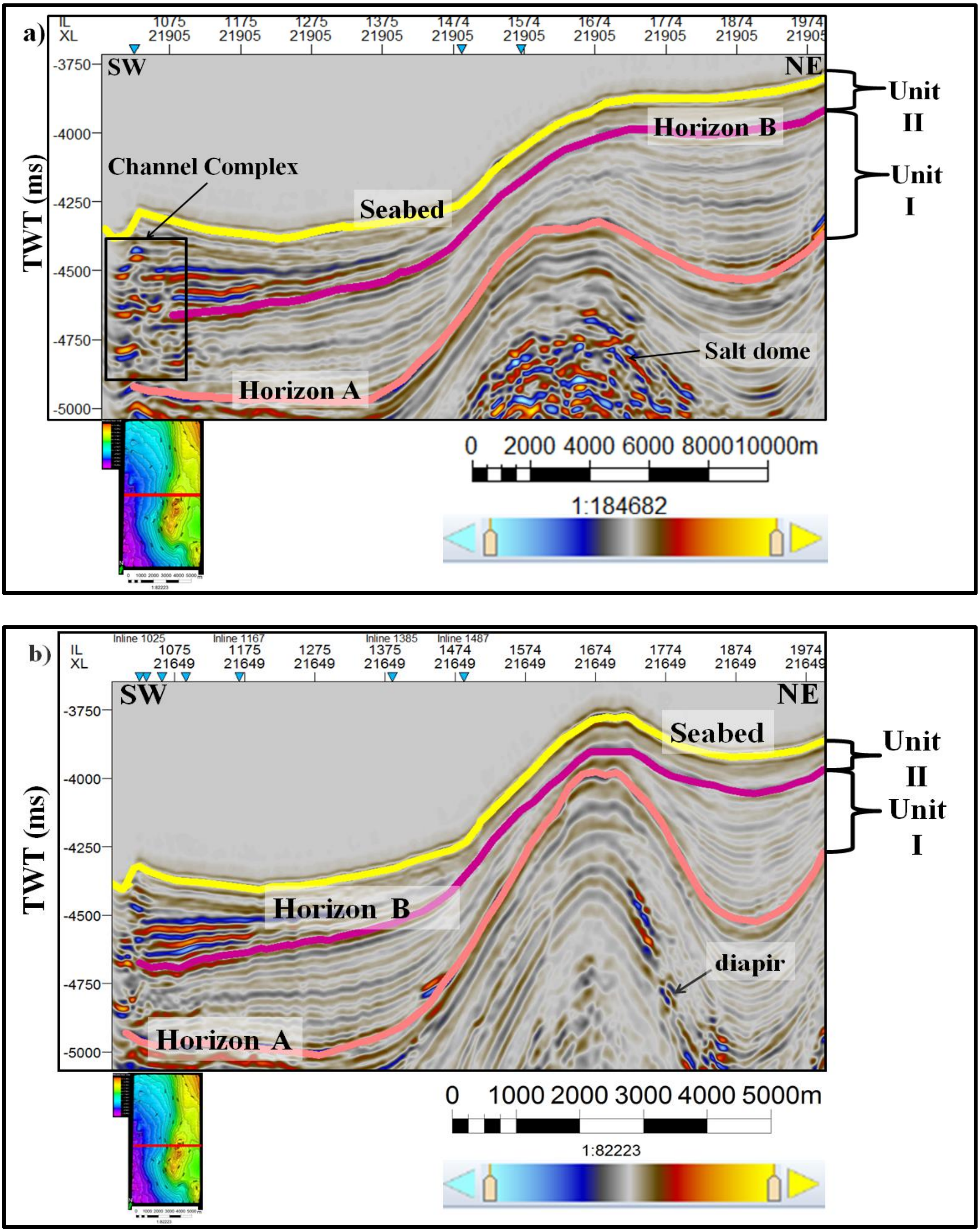


Figure 4-7: Illustrates seismic lines, (a) (b) xlines 21905 and 21649 Shows the thickness variations using seismic lines to show the horizons to compare with Isopach maps.

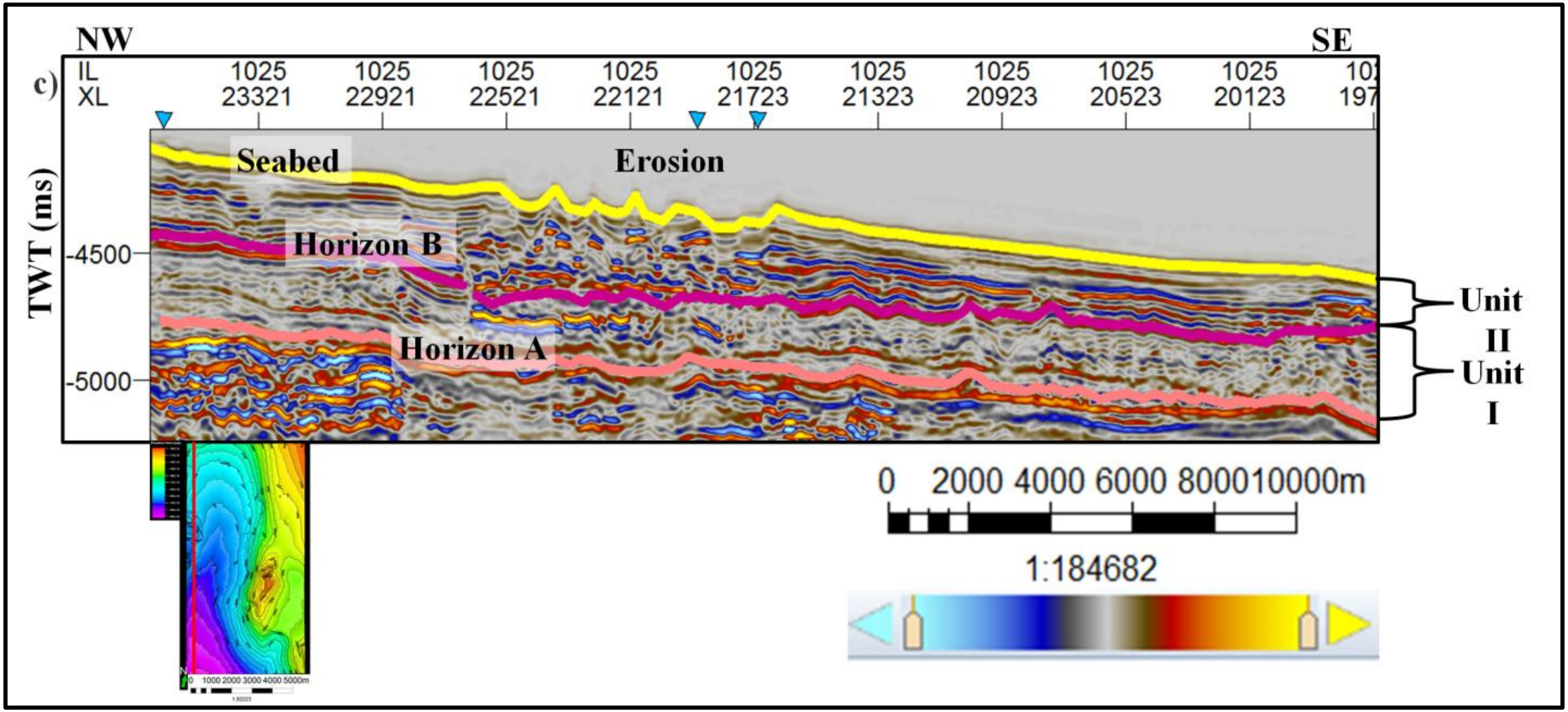


Figure 4-8: c) Inline 1025: Shows the thickness variations using seismic lines to show the horizons to compare with Isopach maps.

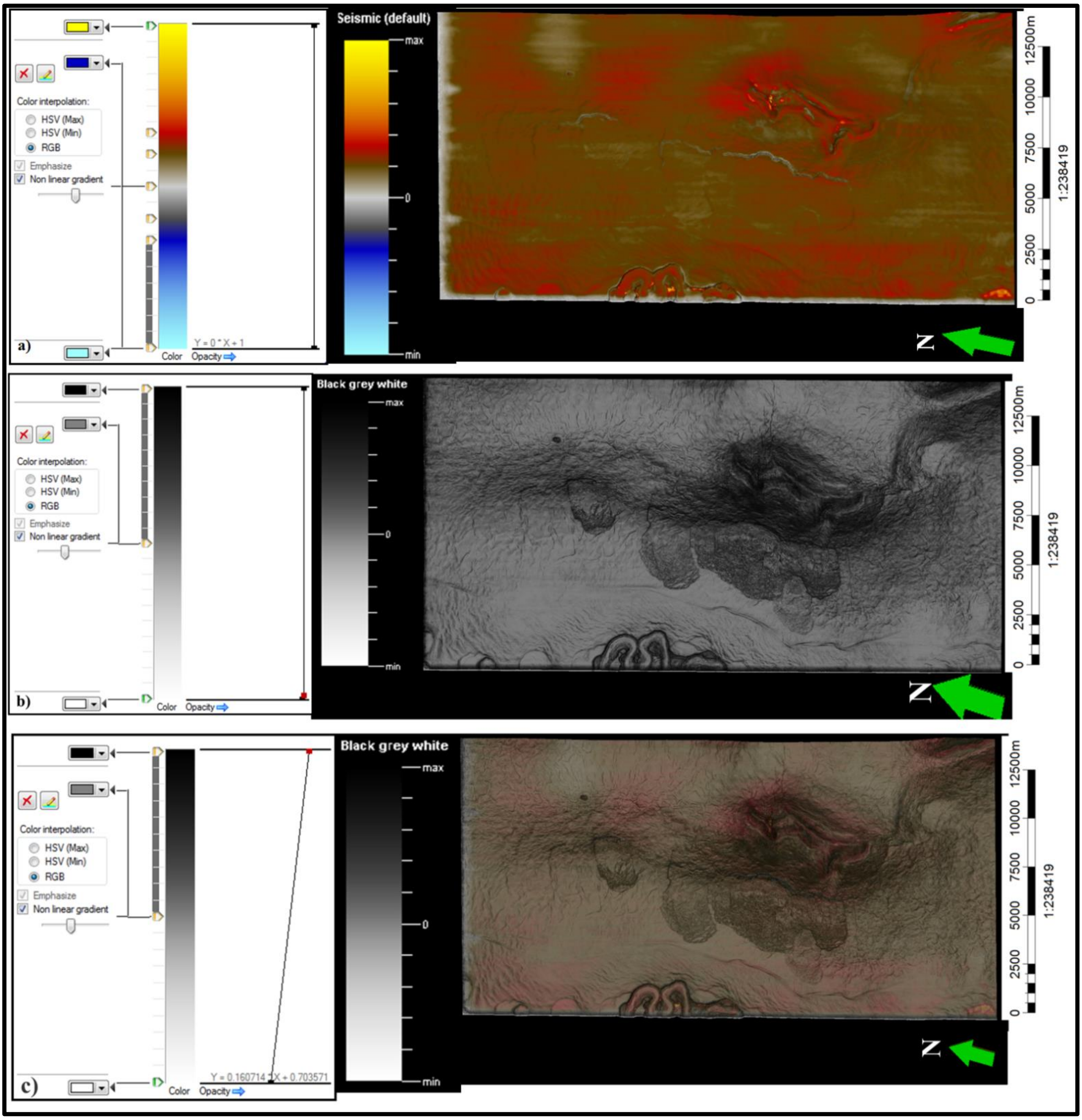
5.3- RMS amplitude surface maps extraction

The RMS amplitude attribute, map can characterize geological anomalies that are isolated from background features by amplitude response. Also RMS amplitude map helps to identify geological features, hydrocarbon accumulations and lithological changes (Taner, 2001**).**

Interpretations of seismic based attributes are divided into two general categories: geometrical and physical. The objective of geometrical attributes is to enhance the visibility of geometrical characteristics of seismic data; they include dip, azimuth, and continuity. Physical attributes have to do with the physical parameters of the subsurface and so relate to lithology (Tanner et al., 1994).

During the interpretation I extracted three RMS maps in several intervals. The purpose was to choose the best interval to observe the many features in time and space. The map was extracted from the seabed and other interpreted horizons to see the impact of the attributes in identifying and having clearer identification of features and their morphologies. In this study, RMS attribute maps were mainly extracted to analyze the channels architecture geomorphology and the sinuosity of channels. The attribute maps were done using three predefined attribute algorithms; First was RMS of seismic amplitude (Figure 4-9 a), secondly was RMS of variance (Figure 4-9 b) and lastly the Blended amplitude and variance (Figure 4-9c) which is a combination of the RMS of seismic amplitude and variance.

The figure below shows the robustness of these attributes as applied in the sea bed surface profile. The channel sinuosity and salt intrusions were best identified using the blended amplitude and variance section as well as the RMS of variance. These maps showed the meandering channels, pockmarks, slump debris, salt intrusive outcrops, with polygonal fault lines cleanest. These attributes were therefore used to analyze the internal features of the channels and other features in study area.



a)

Color interpolation:
○ HSV (Max)
○ HSV (Min)
● RGB
☑ Emphasize
☑ Non linear gradient

Y = 0 * X + 1

b)

Color interpolation:
○ HSV (Max)
○ HSV (Min)
● RGB
☑ Emphasize
☑ Non linear gradient

c)

Color interpolation:
○ HSV (Max)
○ HSV (Min)
● RGB
☑ Emphasize
☑ Non linear gradient

Y = 0.160714 * X + 0.703571

Figure 4-9: Shows the attribute seismic correspondent to Seabed (SB). A) Is the RMS amplitude map, b) is the RMS variance map, c) is the blended amplitude and variance map.

5.4- Time slice flattened and polygonal fault display

According to Schlumberger glossary (2013), seismic time slice is the horizontal display or map view of 3D seismic data, having a certain arrival time. A time slice is a quick, convenient way to evaluate changes in amplitude of seismic data. Time slices are convenient displays for visual inspection of seismic attributes, especially amplitude.

In this project I extracted time slices in order to visualize the deep-water and submarine channels, to facilitate a better understanding of the channels evolution, to analyze the channels migration and direction.

Before analyzing time slice I flattened the seismic volume on seabed horizon. The time slice flattened was extracted below Horizon A (HA) and until Seabed (SB) in my interval (Figure 2-7). The purpose of flattened volumes was to avoid time slices cutting the main geological features in studying area. This allowed me to see the geologic evolution of features and morphologies in the interval.

Time sliced displays of the flattened volumes were interpreted. Which are corresponds to Horizon A, Horizon B and Seabed (SB). The bright (orange) color represents high variance. The light (black and white) color represents low variance. All the maps display evidence of salt diapirs and polygonal faults due to salt influence. The development of channels with orientation N-S, is captured in different time slices. In the first slice map (Figure 4-10a) the channel is very weak but in second slice map (Figure 4-10b) the channel is visible and the polygonal faults cover all the map, and the third slice map (Figure 4-10c) is from Seabed (SB) where the channel is more visible. The others geomorphologic like slumps located on the western side of the salt domes. Polygonal faults are much stronger in this spatial view compared with the wavy slump features.

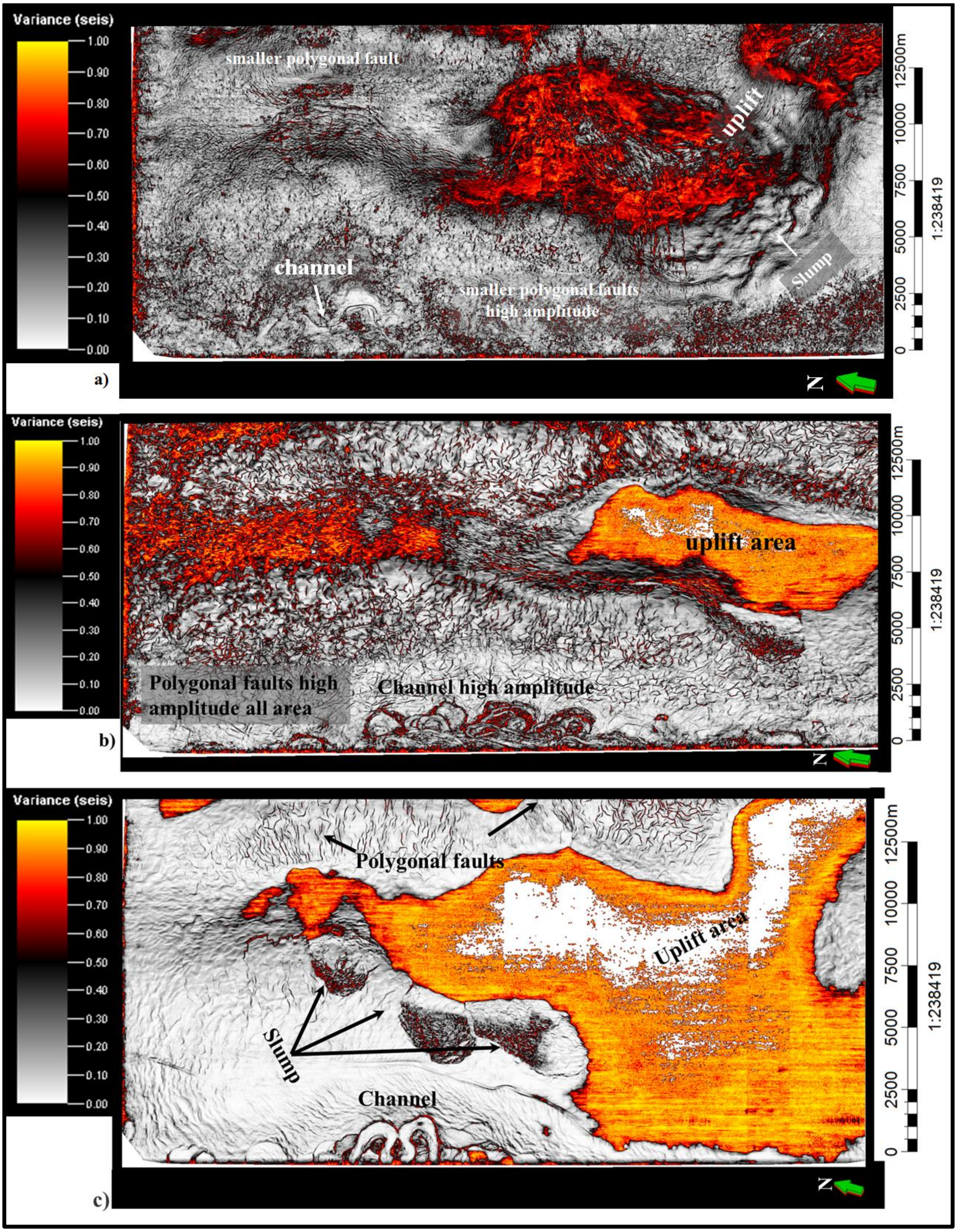


Figure 4-10 Shows time slice flattened maps extracted in different horizons with high amplitude and the channel coming from N-W in all time map. a) Time slice flattened Horizon A (HA), b) Time slice flattened Horizon B (HB) and a) time slice flattened Seabed (SB).

Chapter 5 -Seismic evaluation of stratigraphic identified units characterization of main features

In this chapter, detailed look will be given to how each seismic techniques and applications. Also were used in interpreting the identified features in the seabed and within each horizon units. The channel incision and salt related features as it affect the sediments within the stratigraphic units of the study area.

5.1- Seabed features

Figure 5-1 shows the sea bottom imprints and topographic expressions of surface features with the RMS seismic amplitude maps and variance attribute display. Distinctively observed, are positive features showing the salt diapiric positions which indicates that the salt cropped out to the sea bottom level. Also, are distinct expressions of slump features of cascaded sediment with slump on the sea bottom due to the halokiness. Also present is the meandering channel feature, which shows that the channel development of lowstand sediment incision is active to current seabed as sediment supply is active in recent geologic time (Quaternary). From the surface the channel system shows a landscape flow direct due to N-W direction, which also conforms to the regional flow direct of the Congo River as sediment flux to deposition of submarine fan lobes with in the section.

Slump debris extending downhill a short distance away from the head scarp had been reconstituted into debris flows as the initial movement. In Figure 5-1 shows the slump feature formed due to uplifted triggered movement of salt diapirism occurred. These features of moving avalanche have long been recognized by geologist as part of mass flow movements. They are said to be probably by the presence of soil on steep mountain slopes and are commonly the result of unusually heavy precipitation (Varnes. 1978).

The Figure 5-2 shows the meandering channels, with a detailed observation from RMS amplitude sections and the seismic overlays. It shows a main channel axis, with a sinuous pattern which suggests that the sediment transport in the channel is much affected by the nature of sediment and bedload compactions. This axis would evidently be a good reservoir position since fluid flow and winnowing actions is naturally in place. Also, it is observed that the sinuous system tend to form an ox bow feature with point bars located within each wavelength section of the channel, this could also evidently be a good reservoir position within the channel, as most point bars are deposited of the heavier sediment fractions of the channels. Furthermore, ridge structures that confines or borders the channel axis were identified, these are believed to be channel levee which separates the interpreted flood plain sections from the channel axis, and these could suggest areas of fine deposition or overbank deposits. The combination of the RMS maps and the seismic sections give a more clearer explanation, that the chaotic reflection signatures within the channel axis is mainly due to the reflections of different sub channel facies like point bars, channel axis, levee ridges, flood plains etc.

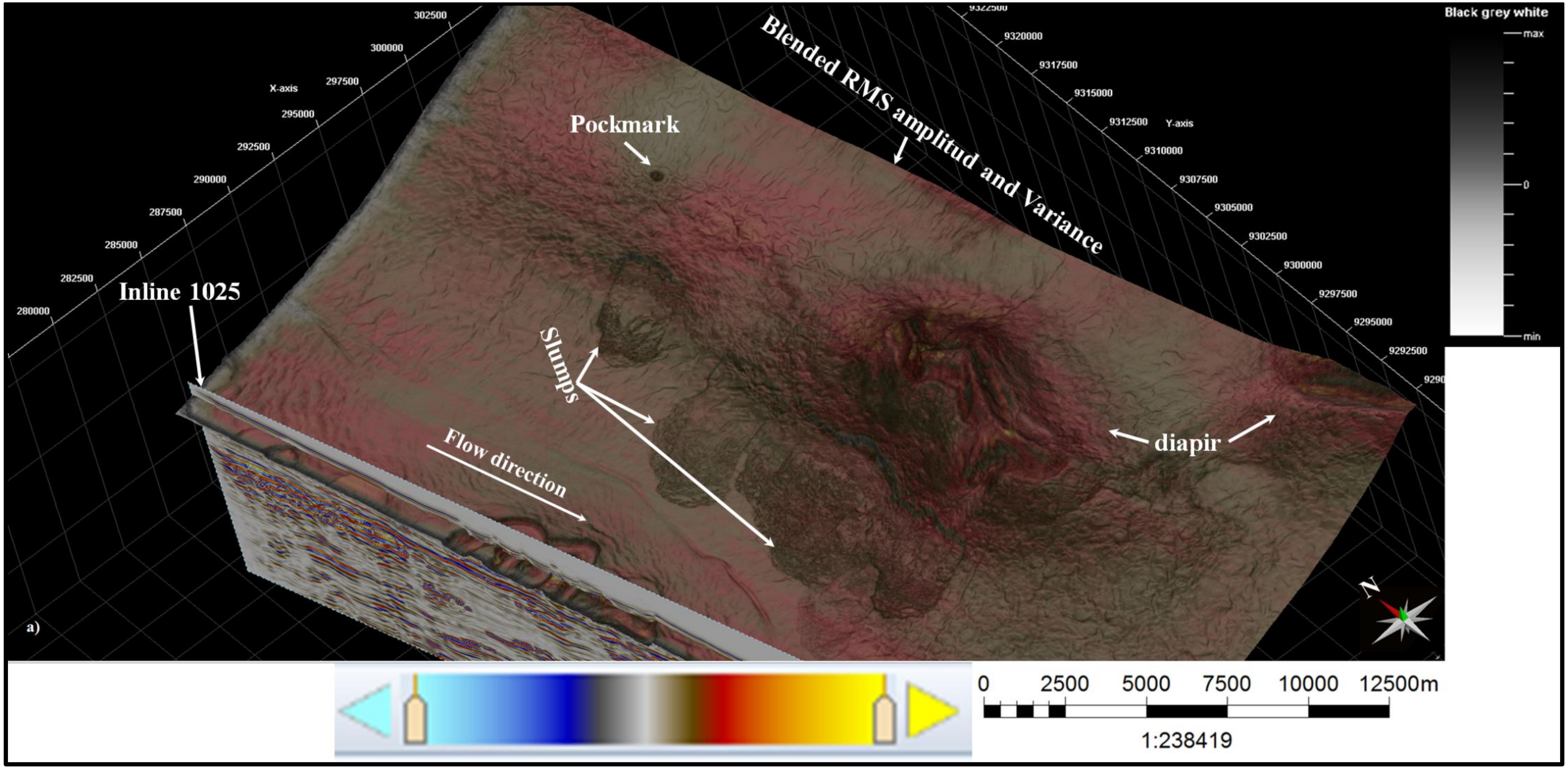


Figure 5-1: a) shows the 3D view of a blended amplitude and variance map. Location of seismic line 1025 is shown in the western part of the obliquely viewed figure.

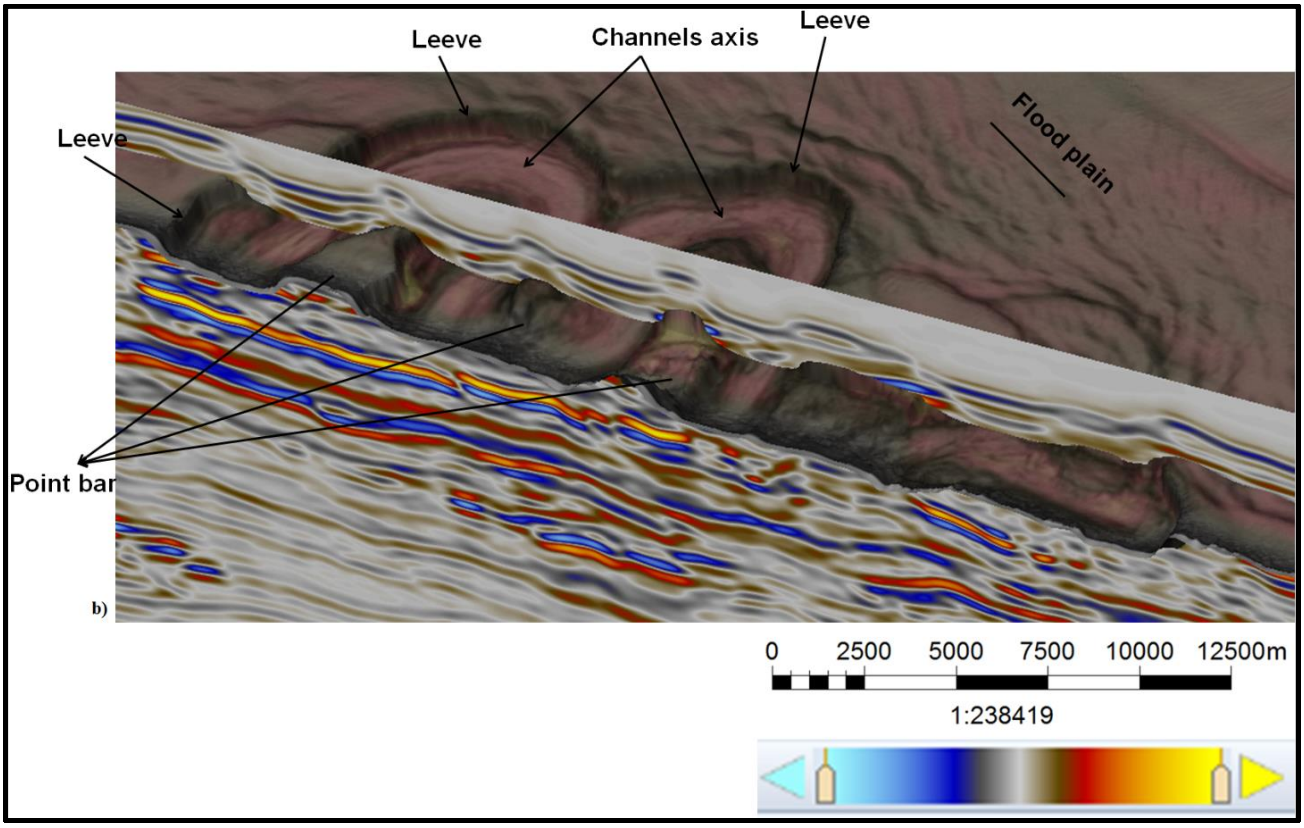


Figure 5-2: b) illustrates attribute map highlight combined by seismic facies, from the figure 5-1a.

It is also noteworthy to mention the Pockmark features, which shows an oval fluid escape features as interpreted within subsurface, that escape fluids beneath an identified structure.

Evidence of offshore fluid seeps at the seabed was first reported on sidesccan records from Scotian shelf (King & MacLean, 1970). Fluid seeps generally appear in unconsolidated fine-grained sediments as cone-shaped or elliptical depressions named pockmarks.

Therefore most often these fluid expulsion are recognized by their effects on the physiography of the seafloor an acoustic properties of near-surface sediments because both chemosynthetic communities and authigenic carbonates, that are commonly associated with them, may cause higher acoustic impedance and roughness than in surrounding seafloor (Kaluza & Doyle, 1996).

It is noteworthy to mention that the pock mark lies beneath a section of the seismic, within area of laterally strong amplitudes of flat events noticed in (Figure 5-3a). This flat event was seen in a crested structure, cutting across stratigraphic and been parallel with the Seabed (SB).

The RMS amplitude was interpolated with seismic line (Crossline 22803) in 100ms interval, to show the pockmark in 3D view (Figure 5-3a). The (Figure 5-4b) shows the pockmark in spatial view with respectively measurement. In the study area within Lower Congo Basin an isolated elliptical pockmark is identified measuring 400m by 700m, and from a few meters to a maximum of 50ms in depth. The fluid scape pockmark can be occurring through course-grained sandy.

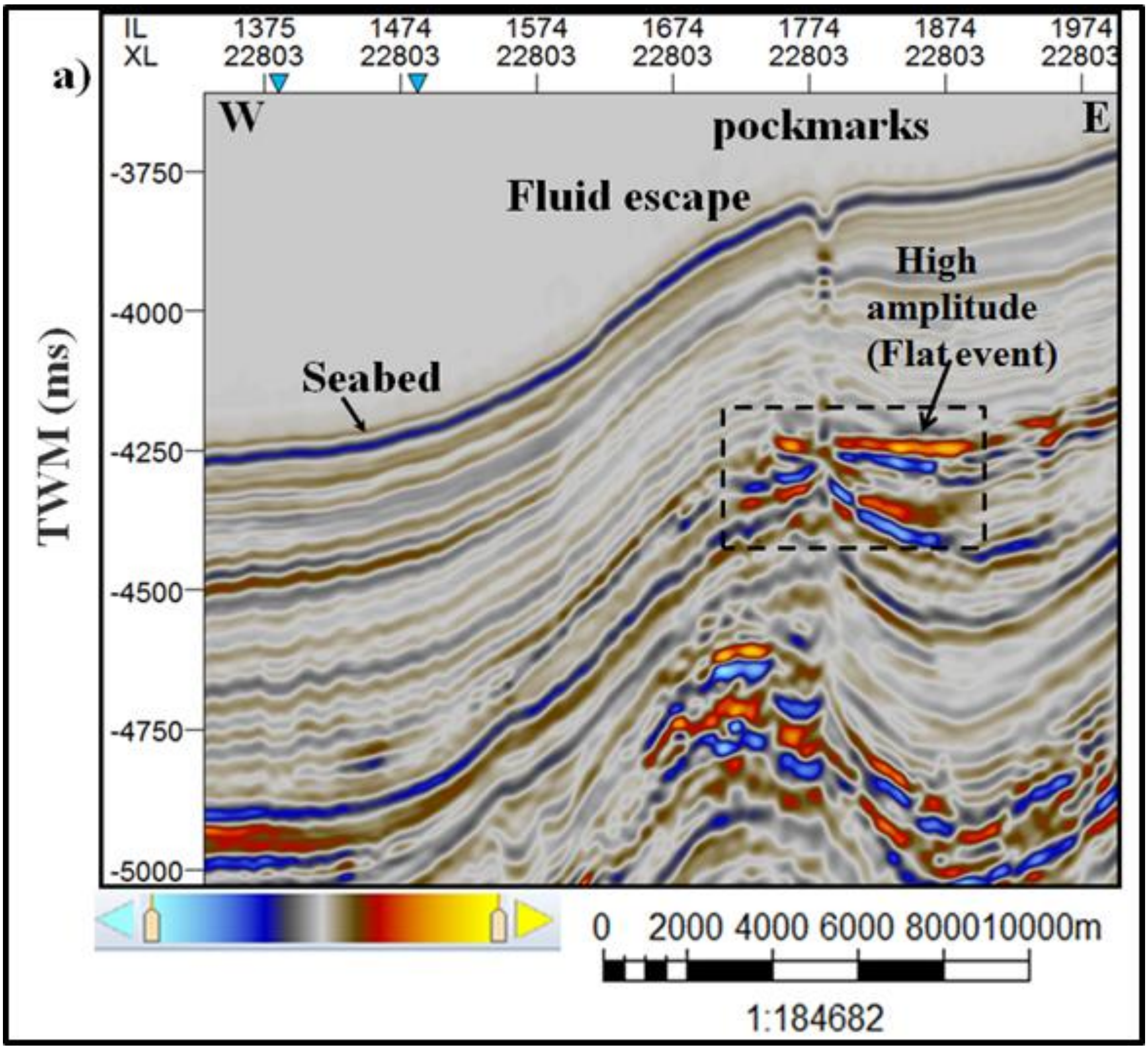


Figure 5-3: a) Illustrates pockmark with stronger lateral flat events with high amplitude.

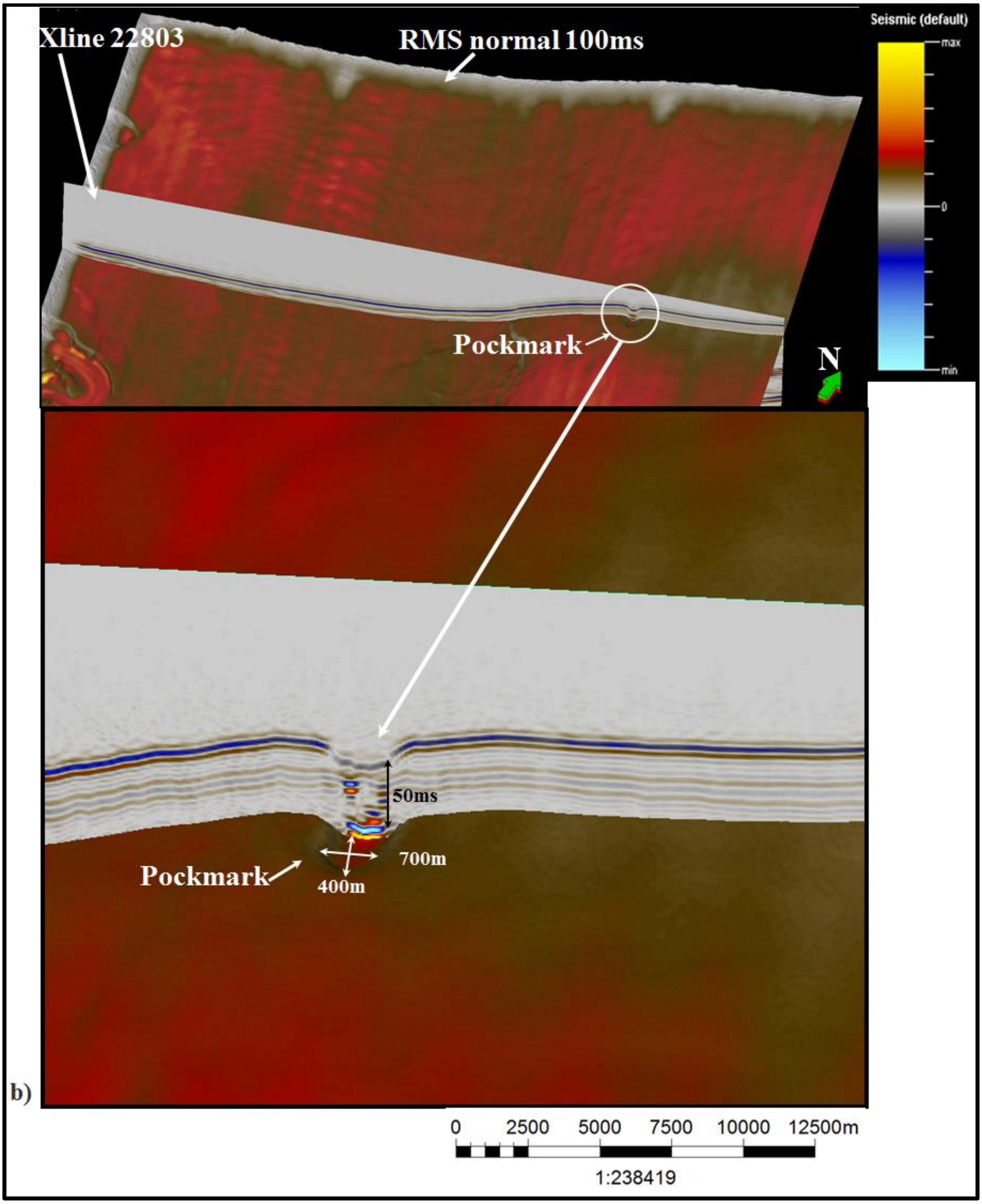


Figure 5-4: Showing fluid scape in 3D view with RMS an interval 100ms and seismic line xline 22803.

5.2- Polygonal faults

It is observed around the oval salt relief of tiny lineament features that are distinctly distributed around the salt of adjacent sediments. These are said to represent the polygonal fault features, that were formed as sediments were probably re-worked leading to faulting due to halokinesis (Figure 5-5).

Polygonal faults are characteristically formed in the overburden sediment at the upper sections of the seismic. These faults occur because the development of polygonal faults discontinues temporarily as a result of change in regional sedimentation leading to inactive polygonal faults. The faults are confined to stratigraphic horizons with observed distinct spacing in among faults (Cartwright 1994 & Lonergan et al., 1998). The formation of these features is linked to differences in lithologies and volumetric contraction of the fine grained sediments leading to pore fluid expulsion (Cartwright 1994 & Lonergan et al., 1998). It seems, that the high interconnection between the faulted layers leading the fluids reach shallow depth to forming pockmark on the sea floor.

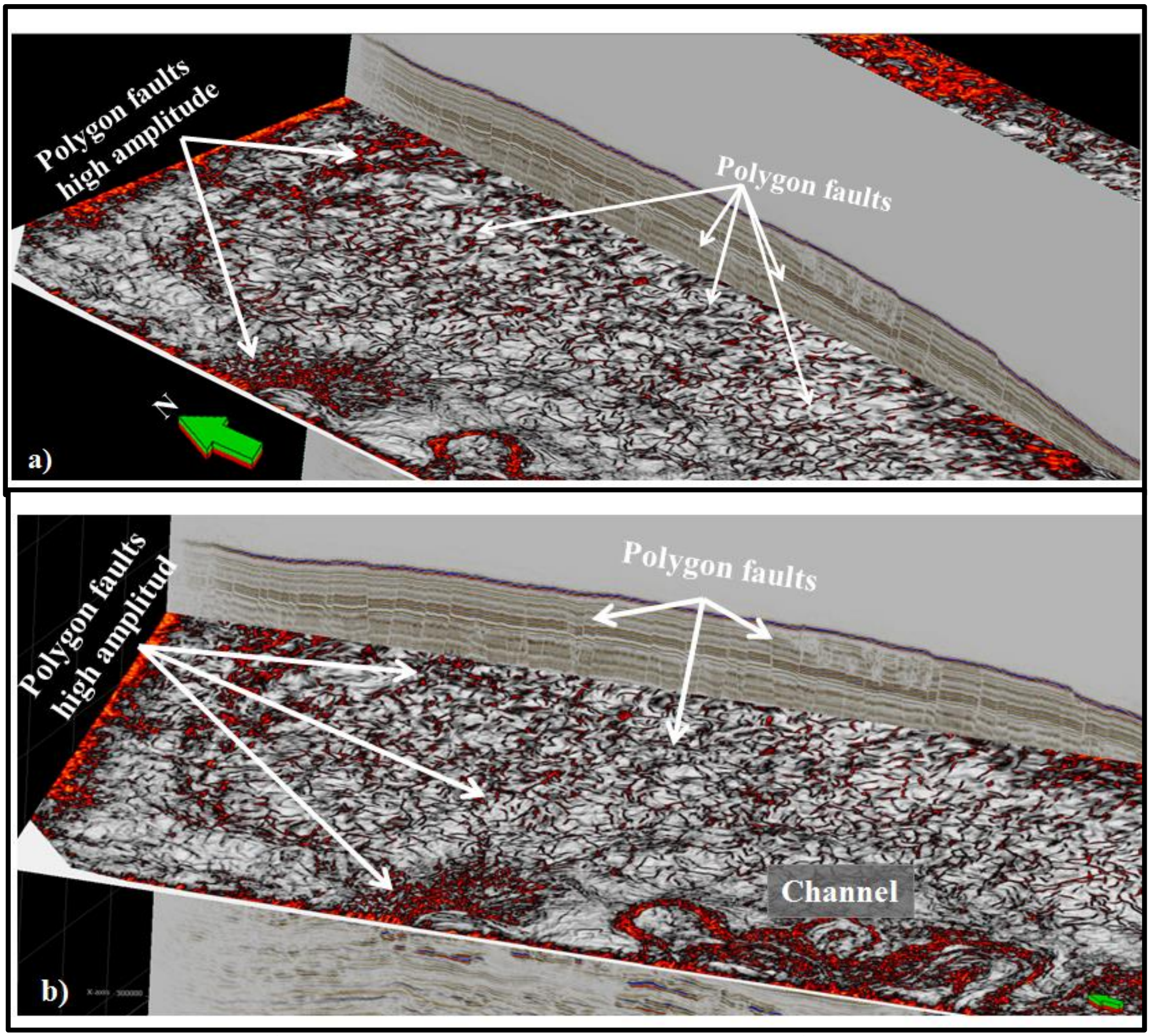


Figure 5-5: Time slice flattened a) and b) illustrates highlights polygonal faults and channel in 3D view with flattened Inline 1499 intersected.

5.3- Seismic stratigraphy

The seismic stratigraphy analyses of this thesis identified two stratigraphic units which is shows two seismic section xline 21905 and inline 1025. Unit I and unit II are of assumed recent to Pleistocene age. They are separated by the horizons I have interpreted (Figure 5-6 and Figure 5-7). In these seismic units are also internal boundaries between the horizons. Based on the horizons interpreted and internal descriptions of features of identified seismic facies, spatial reflection patterns, channels morphology and thickness variations within each of the units.

Unit I (UI)

The excellent quality of the seismic data allowed horizons interpreting and the extraction for many depositional features in the section.

This unit is bounded by Horizon A (HA) and Horizon B (HB). The HA horizon were easy to pick due to high continuity of reflectors. The horizons were selected in concordance to the seismic layered package. This horizon consists of high amplitude, continuous and regular seismic reflection. Below the horizons were salt domes which affected the shape of the layers and horizon. The top salt reflection shows high amplitude because the acoustic impedance between salt and others material is very high. This salt dome forms anticlinal and synclinal structures between. The horizon interpretation takes into the impact of the salt movement as they affect the interpretation, which is more noticed in horizon HA (Figure 5-6).

Internal unit description

The Horizon B (HB) is above horizon (HA) and below the Seabed (SB). This horizon marks the base boundary of unit II. It is characterized by continuous and regular seismic reflection with a strong reflector and high amplitude. It continues to the western part of the seismic section in the area as marked with the squared boxed within Figure 5-6. Here channel features are identified as main internal features.

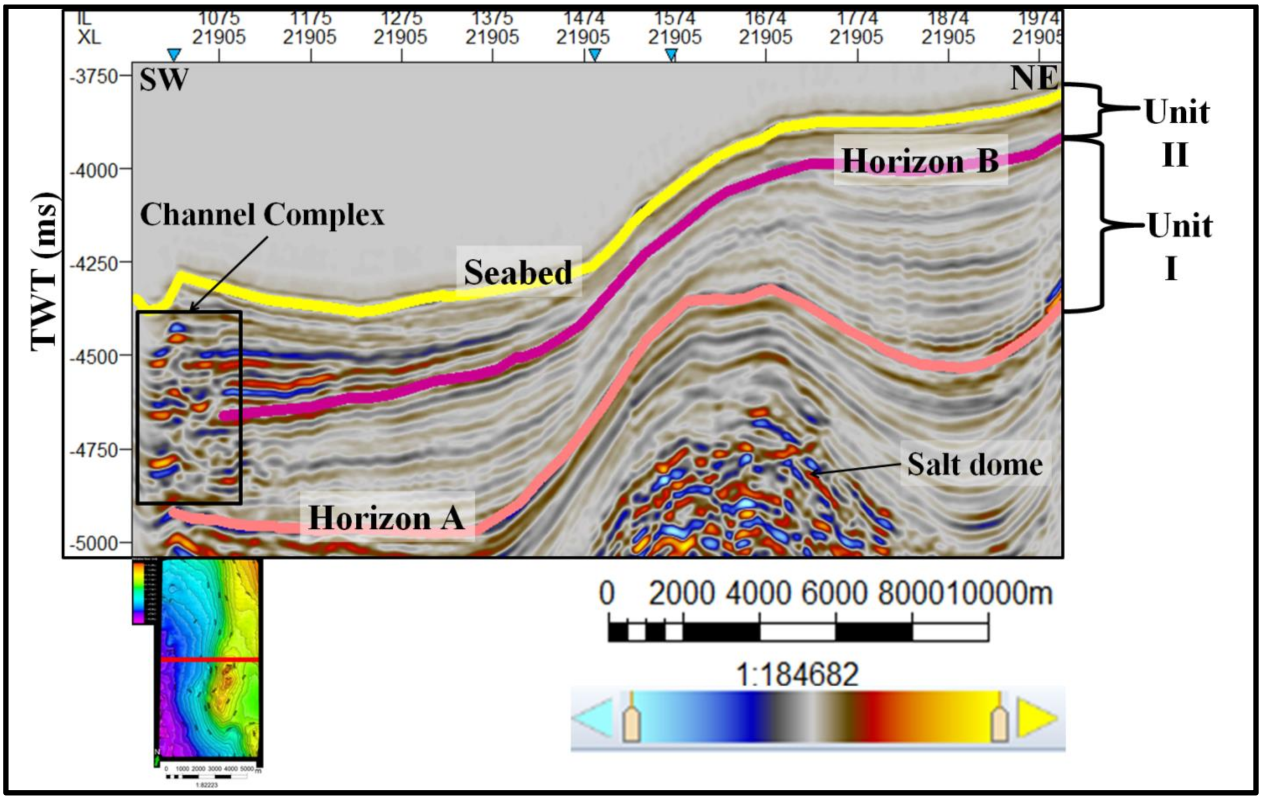


Figure 5-6: Xline 21905 illustrates horizons interpreted HA, HB, Seabed (SB), channel complex and Units I and II between the horizons.

Unit II

The Seabed (SB) is on the top and horizon (HB) is the base of unit II which consists of continuous and regular seismic reflections. Seabed (SB) was the first horizon to be picked and was interpreted using auto-track because the geometry is regular. The Seabed interpretation was interpreted on the minimum amplitude. Seabed dips toward W direction. The sediments are flowing from the shelf downwards the basin due to the gravity force (Figure 5-6 xline 21905). On inline 1025 Figure 5-7, a channel of Quaternary age was identified on the upper section of unit II, which is the most recently developed channels on the present sea floor. The channel complexes are responding to the drop in sea level with corresponding base level incision of Congo River to sea level topography during lowstand. The western part of the survey region, of inline 1025 captures the ondulated channel with xlines 22521-21723 and inline 1025 distinct sinuosity meandering patterns. Characteristically the channels are typified by chaotic reflection signatures, which is probably due to different channel subfacies sediments. The channel has different amplitudes responses on the seismic. This incision on the sea floor means that the channel system has developed the same time with recent incisions of the Congo River.

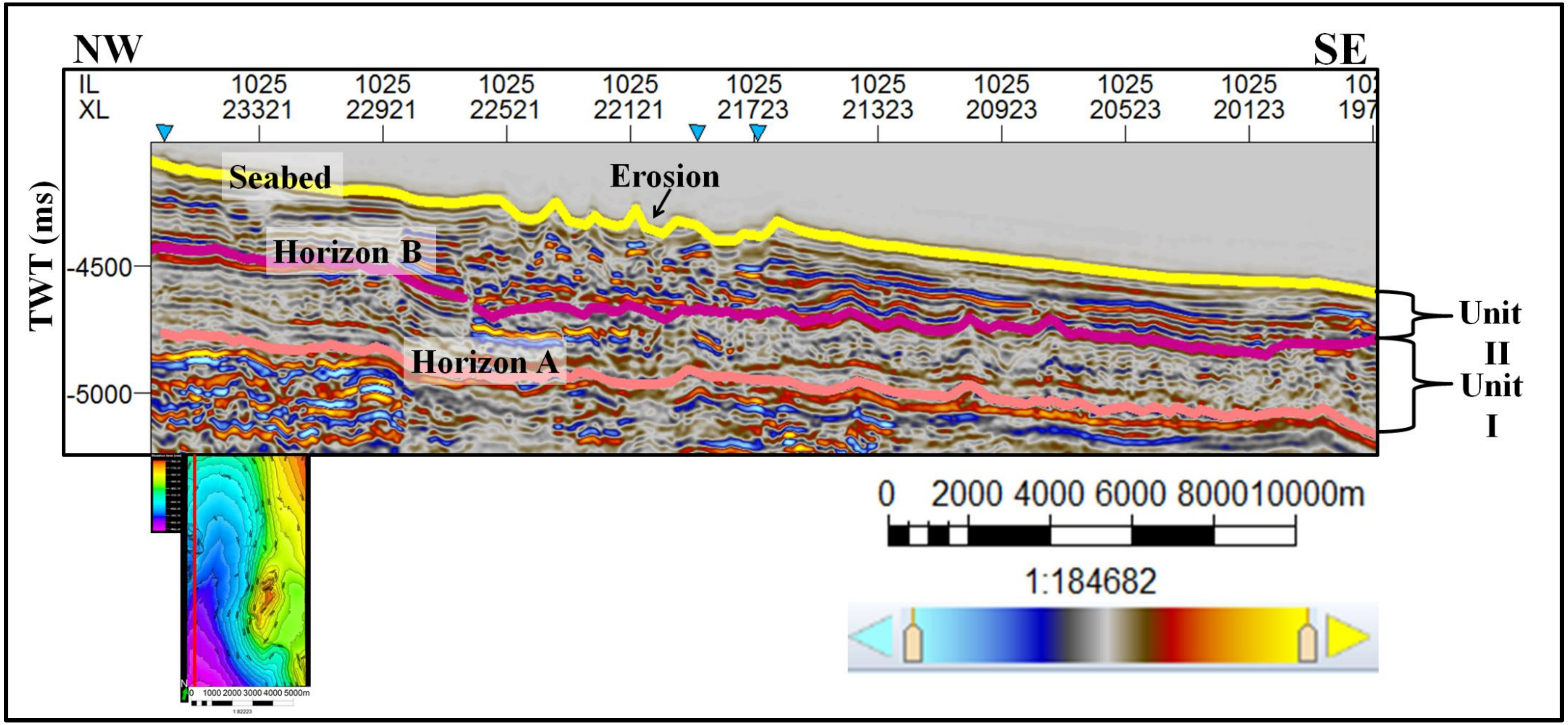


Figure 5-7: Inline 1025 illustrates horizons interpreted HA, HB, Seabed (SB), Erosion and Units I and II between the horizons interpreted.

5.4 Internal description of Horizon unit I & II

Isopach map of the units was made according the horizons in each unit to distinguish the thickness from each different unit. The unit I between horizon HA and HB identified in Crosslines 21649 and 21905 in the western section of the seismic survey (Figure 4-7 a, b) shows that the thickness trends tends to be much dependent on the position of the salt intrusives, as areas overlying the salt bodies tends to be much thinner compared to wedge sediments adjacent the salt. The unit II also had a much generally thin distribution been close to the sea bed, when compared the unit I .The salt influence is noted also in affecting the thickness profile of unit II. It was observed that the salt position had much effect on the thickness profile generally in the study area, (Figure 4-8 c) seismic lines taken away from location of the salt bodies, showed areas where the thickness became more uniform between the two studied units. Also in unit II close to the Seabed mainly within the western section of the seismic, observed is the channel complex features which adds variability in the isopach map mainly in the western direction of the seismic lines. This feature mainly form the internal architectural reflections between the horizons, with characteristic chaotic type reflections within the channel areas, this will be further discussed in the preceding paragraphs.

5.5- Seismic and channel reflections

The parallel amplitude reflections of the sediments which were much continuous in parts of the units, was observed to have characteristically wavy to chaotic reflection signatures which is noted to indicate erosional channel feature with imprints in seabed within unit II. This imprints to the sea bed suggests that the channel development has taken place at recent geologic time to present day due to the lowstand progradation of the Congo River.

The (Figure 5-8 b) was extracted in the seismic section to illustrate the wavy and chaotic channel reflections within the seismic section. It consists of low amplitude and continuous reflector on the top. The channelized seismic reflection consists of discontinuous low to high amplitude reflection, these interbedded low to high amplitude reflection results to the chaotic reflections (Figure 5-8b). The surface imprints of this channel of the sea floor (Figure 5-8), shows a characteristically meandering channel. Also, observed is that the sinuous channel system which tends to form an ox bow feature with point bars located within each wavelength section of the channel axis. Furthermore, ridge structures that confines or borders the channel axis were identified, these are said to be channel levee which separates the interpreted flood plain sections from the channel axis, and these could suggest areas of fine deposition or overbank deposits. The combination of the RMS map and the seismic sections gives a more clearer explanation, that the chaotic reflection signatures in (Figure 5-8b) could be further attributed within the channel axis to be mainly due to the reflections of different sub channel facies that ranges from point bar, channel axis, levee ridges, flood plain etc. It could also be said that these reflections with depth of the seismic might suggest an amalgamated channel development with vertical accretion of channel systems over geologic time due to lowstand progradation. The channel can be amalgamated, with different channel facies leading to varying amplitude responses with the channel complex. The high amplitude in the channel rather talks about relative strength of the amplitudes because of the type of sediment it could be sand it is characterized by high amplitude in the reservoirs. As thus high amplitude in the channel rather talk about relative strength of the amplitude may be typically shale and sand in the reservoir also the reflectors are discontinuous in the all area (Figure 5-8c).

The channel reflection sinuosity as indicated below (Figure 5-8a) shows a sinuosity channel of several meandering channel axis. This indicates a highly efficient or elliptical channel axis with incision depths and width of about 500 X 700ms (TWT) based calculation indicates of highly incised channels that transcends in thickness beyond unit I and II, this suggest that the channel are not delimited by the interpreted horizon of the seismic (Figure 5-8b).

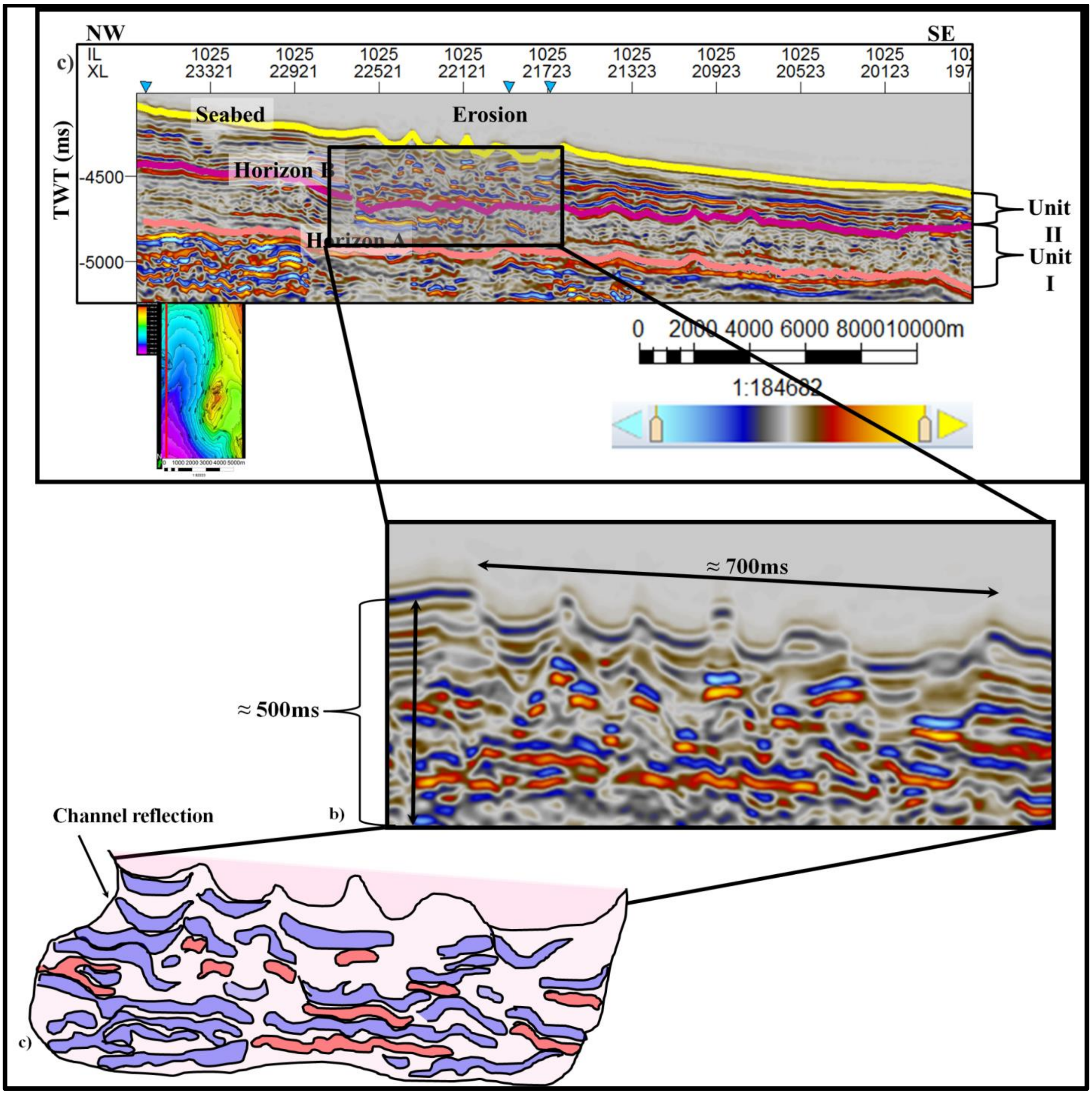


Figure 5-8: a) Illustrates Seismic section inline 1025 showing erosion b) Seismic extraction from main seismic line 1025. c) Channel reflection with high amplitude.

5.6- Geologic interpretation of the channels

The channels are characterized into geologic units based on qualitative and quantitative interpretations. The qualitative interpretations deals with seismic reflection geometry of the channels, orientation, structure while the use of channel sinuosity index offers a quantitative interpretation to the channels.

A comparism of the rendered surface section of the channel imprints and the time sliced sections shows qualitatively, (Figure 4-10) time slice for channel and RMS Amplitude maps) the channel systems noticed is a meandering channel with characteristic overbank channel sediment flood plain. Flood plain is characterized by overbank sediments and fine-grained of shale interval this is characterized with strong amplitude impedance on the seismic section (Figure 5-8). Also observed are point bar features that are mainly of sand body within the closure axis/neck of the meandering channels where they are mainly accreted, with composition of less clay material identified with less amplitude contrast when compared to the strong amplitude signatures of the flood plain deposit. The main channel axis which is bordered by the overbank ridge is seen to have wider lateral extension and has migrated within geologic time, the axis is meandering with snake like shape. This channel axis tends to have to have lowered amplitude contrasts as compared to the flood plain deposits.

Quantatively, according to sinuosity measurements, many authors have distinguished sinuosity mainly into two types i.e. Low and High sinuosity channels. Low sinuosity occur where the coarse grain sizes, such as gravels and sands, form the dominant load of the system in this cases, the lack of significant cohesive bank material leads to extremely mobile channel course (Leopold et al., 1957).

High sinuosity develops in drainage areas dominated by low gradients slopes, and where the river is commonly dominated by a high suspended load to bedload ratio (Leopold & Wolman, 1957). They are typically organized into channel and overbank segments.

Sinuosity index calculation

The sinuosity value was defined by (Leopold & Wolman 1957) as the ratio of the thalweg channel length to the length. Also (Brice, 1974) proposed a slightly modified sinuosity index as the ratio between the channel length and the length of the meander belt axis, which has the advantage of allowing for both straight and sinuous meander belts. In both publications an arbitrary value of 1.5 is used to distinguish between low and high sinuosity channels.

The sinuosity index of the channel was calculated for each path measured between two points A and B. Where point A is the beginning and B is the ending of the observed channel. The channel length is the distance measured along the channel while the channel path is the distance between A and B which is observed in (Figure 5-10a). The purpose of this measurement is to know which type of the channel features we have, if it is a low sinuous channel (Low) or meandering channel (High sinuosity). According the calculation in the Figure 5-10a) ratio of the channel length of the straight line distance and measured path along channel.

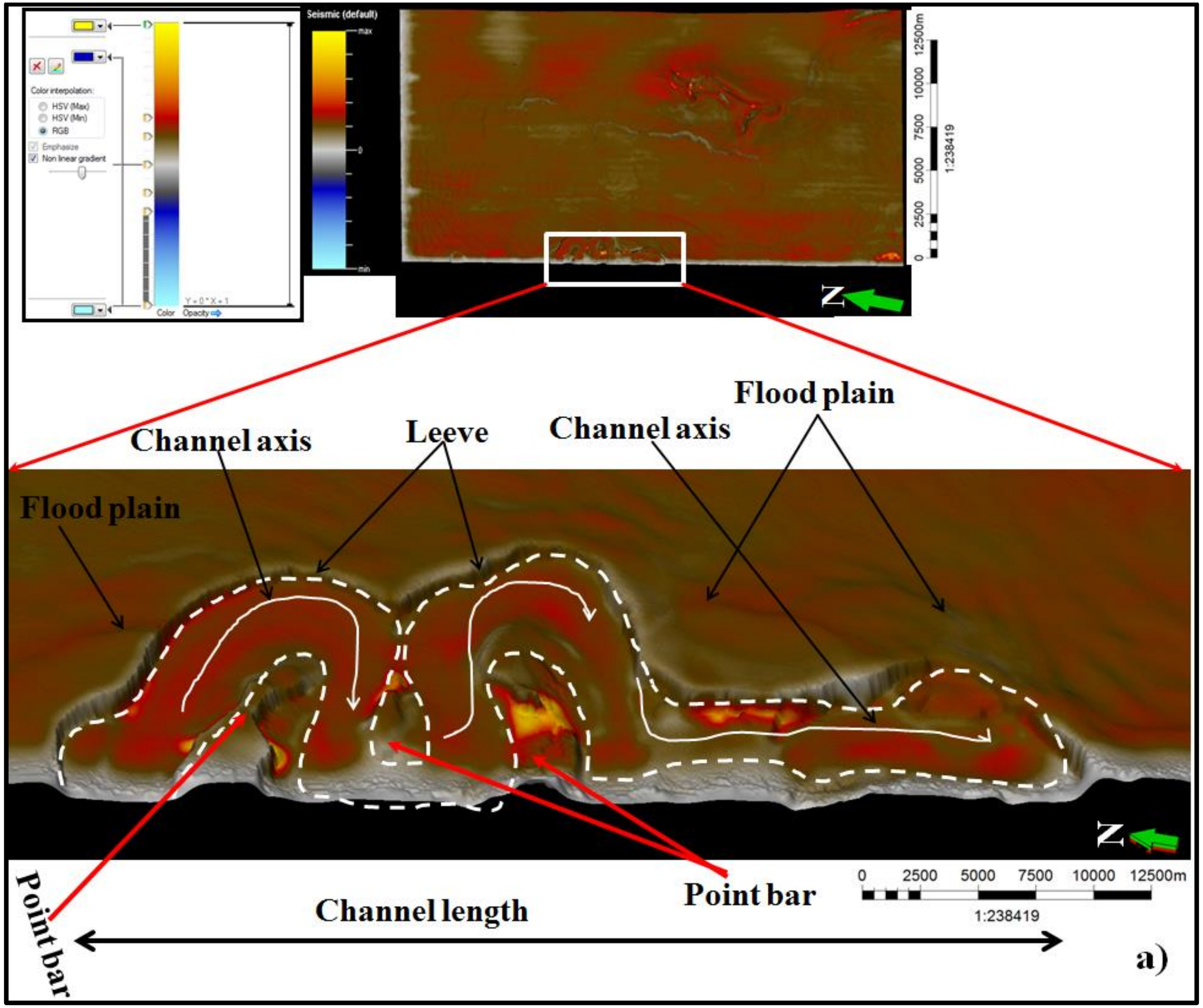

Color interpolation:
○ HSV (Max)
○ HSV (Min)
● RGB
☑ Emphasize
☑ Non linear gradient

Figure 5-9: a) illustrates the high sinuosity meandering channel extracted in RMS seismic amplitude.

Figure 5-10b is the example extracted from the (Figure 5-9a) to illustrate the measurement of the channel sinuosity using the formula below:

Calculation

$$\mathrm{SI} = \frac{path\ channel}{Channel\ lentgth} \quad \rightarrow \quad \mathrm{SI} = \frac{18.7}{11.5} = 1.6$$

1.6 Meandering channel high sinuosity

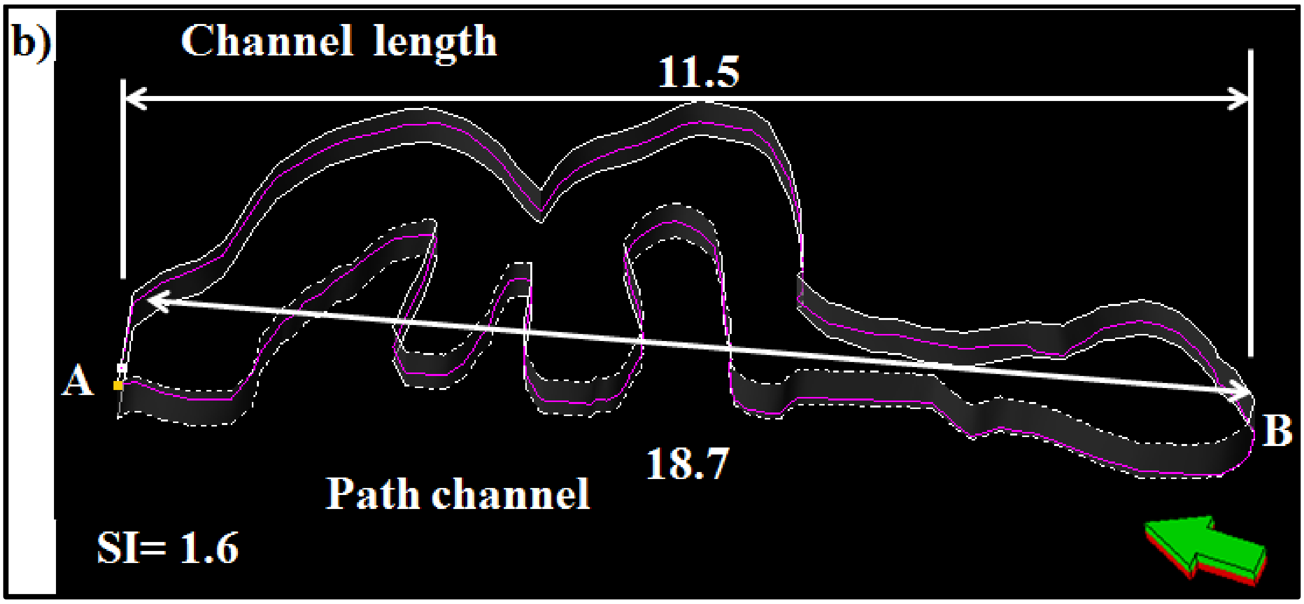


Figure 5-10: b) shows the sketch of the high sinuosity channel to emphasize the calculation sinuosity index.

Again from quantitatively estimated channel sinuosity by that formula (Figure 5-10 a) the channel sinuosity index is about 1.6 of the interpreted seismic channel which suggests that I have a meandering channel of high sinuosity greater than 1.5. This suggests that the channel tends to have less of bedload composition to high suspension composition. The river meanders as it travels; the moment the material becomes much heavier the channel try to shed off its load to form loops or accretion point bars.

The channel forming processes results to other features as oxbow deposit due to its curvature as river energy wanes off with flow path way been sinuous. Also present are food plain deposit within area like this in the Figure 5-11where these plains forms a ridge of within the channel axis, this has previously mentioned are picked out on the seismic with their higher amplitude reflections. It is known that the oxbow lake features are commonly found to develop within the later stages of channel where flow strength has ebbed and sediment discharge higher. The reference (Figure 5-11) shows a typical meandering channel with subfacies environment as described by (Brice, 1974)

In the seismic sections, the channels tend to have accreted point bar, leeve ridges, flood plain but crevasse splay deposit was not observed in the sections.

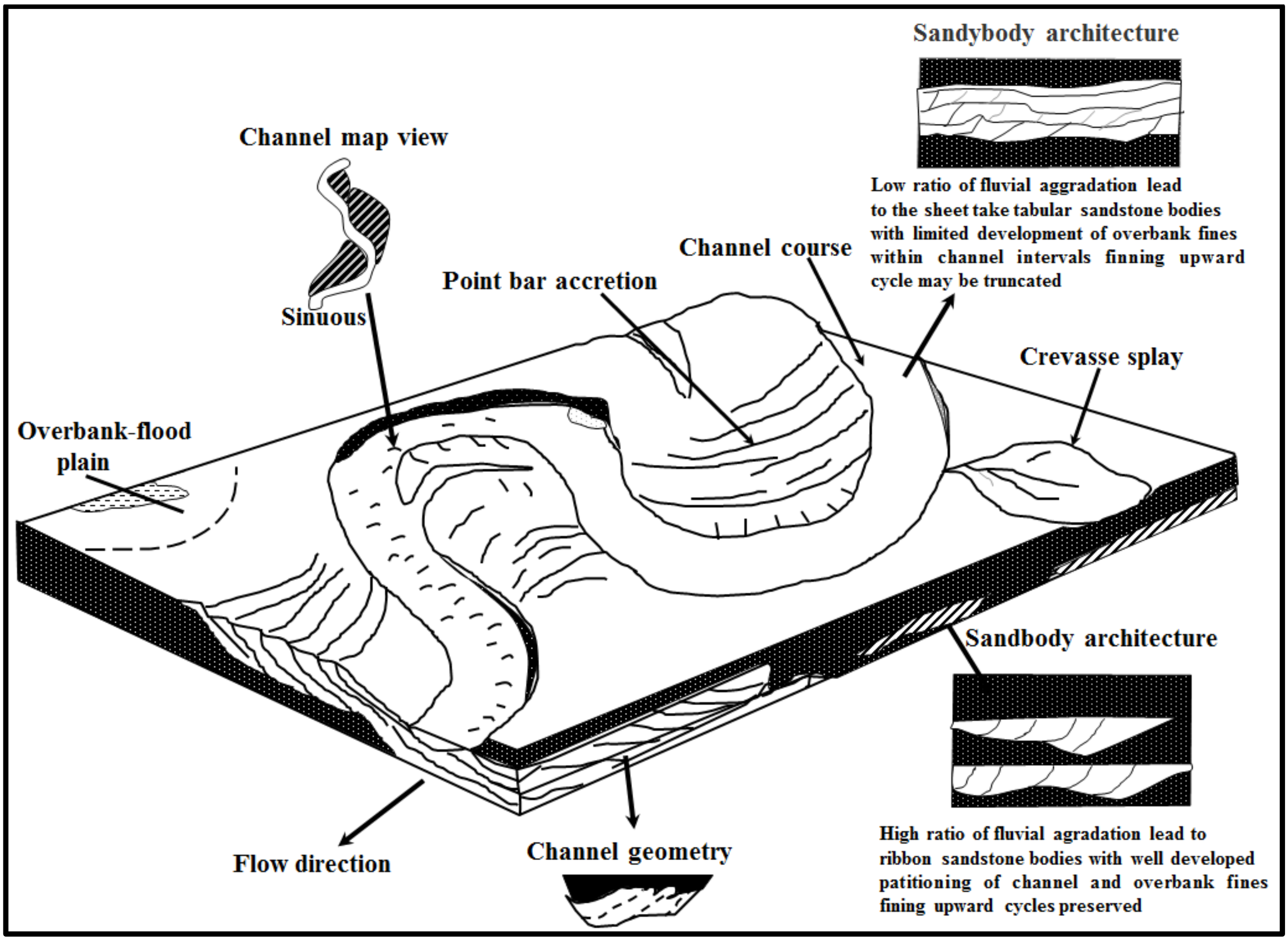


Figure 5-11: Illustrates the example of channel environment (Emery D. et al., 1996)

Also, the channels in the seismic section seems to be developed in the later stages of the Congo River, which means that the channel within the seismic section is a sediment distributary discharge channel of the main Congo River, in discharging sediment of the submarine fan as seen from present day sea level map. The fan as seen in Figure 5-12 is a discharge end product of channels. In the seismic, the channel sinuosity tells that channel tend to have a composition mix of bedload composition fine sand. The oxbow lake features seen shows the channel is the later stage of development. The channels sub facies environments are most indicative of possible location of reservoirs with channel sand and point bar. Also it could be said that if the flood plains of shaley and clay fractions are rich in organic contents that might be a good source rock of in the generation of hydrocarbon to supply this channel reservoirs of channel sand and point bars.

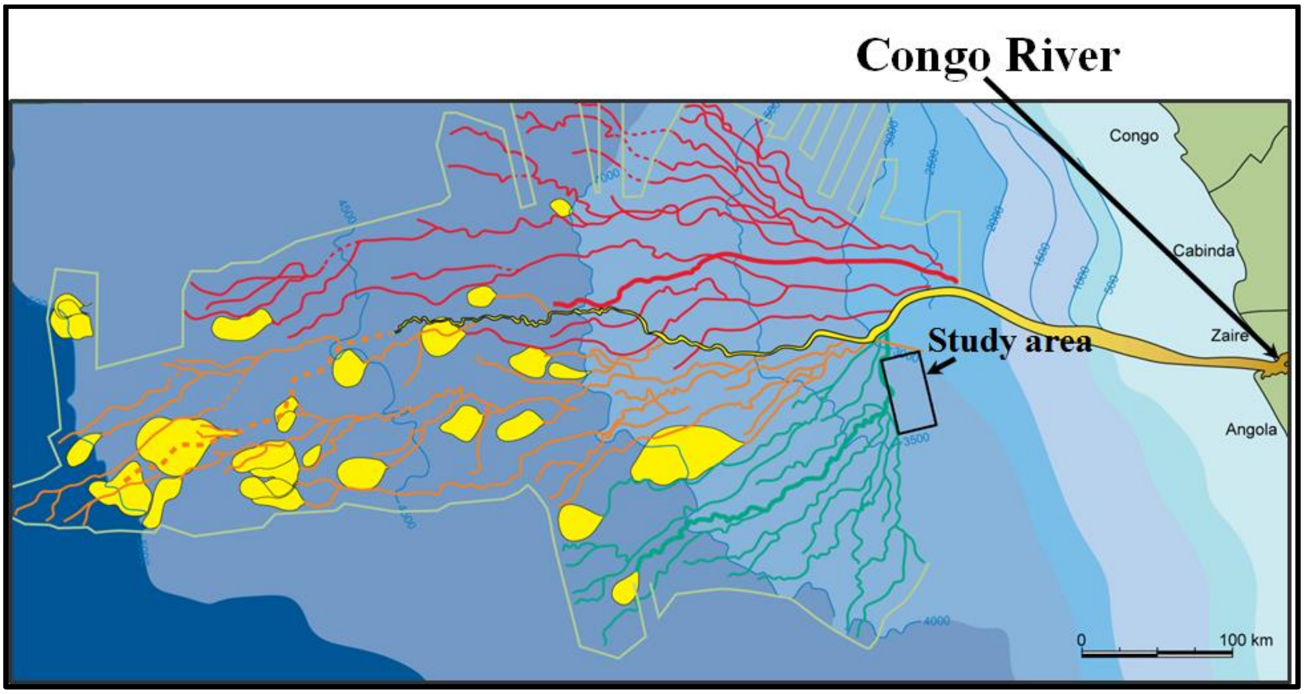


Figure 5-12: Overview map of study area black squared illustrates the many feature in the basin Lower Congo Basin offshore Angola (Modified from Droz et al., 2003).

5.7- Identification of features on the seismic section and RMS map in the unit II

On identifying a surface out crop section of the channel within the sea bed, The attribute maps was used to analyze the channel from the sea bed to the main sections of unit II . This attribute map below (Figure 5-13b) was extracted from 50ms, in reference to the surface Seabed. Amplitude reflection color shades of the channel were evident in the RMS map (Figure 5-13a). Also observed is the channel sinuosity which is flow from direction North toward West direction in part section of my studied area (Figure 5-13b). The seismic facies identified (Figure 5-13c) the feature is a channel complex in the recent age on the seabed with different meander which is characterized by high amplitude and strong/weak reflectors evident in the unit II. It should be said that the recent channel event within my near surface stratigraphic level means that at other geologic levels beneath my studied succession that the channel has developed to current lowstand progradation of recent times. The amplitudes intervals, shown in the interval 50ms displays shows result of the sub channel lithologies contrast within the units. The levee ridges and flood plain areas are easily picked out with strong amplitude reflections when compared to the channel axis with lighter amplitude reflections

(Figure 5-13c). The channel consists of several vertically and lateral stacked channels with lateral to vertical aggradational of facies units of the different channel facies that ranged from point bar, flood plain, levees, channel axis etc of different amplitude responses within the channel complex (Figure 5-13).

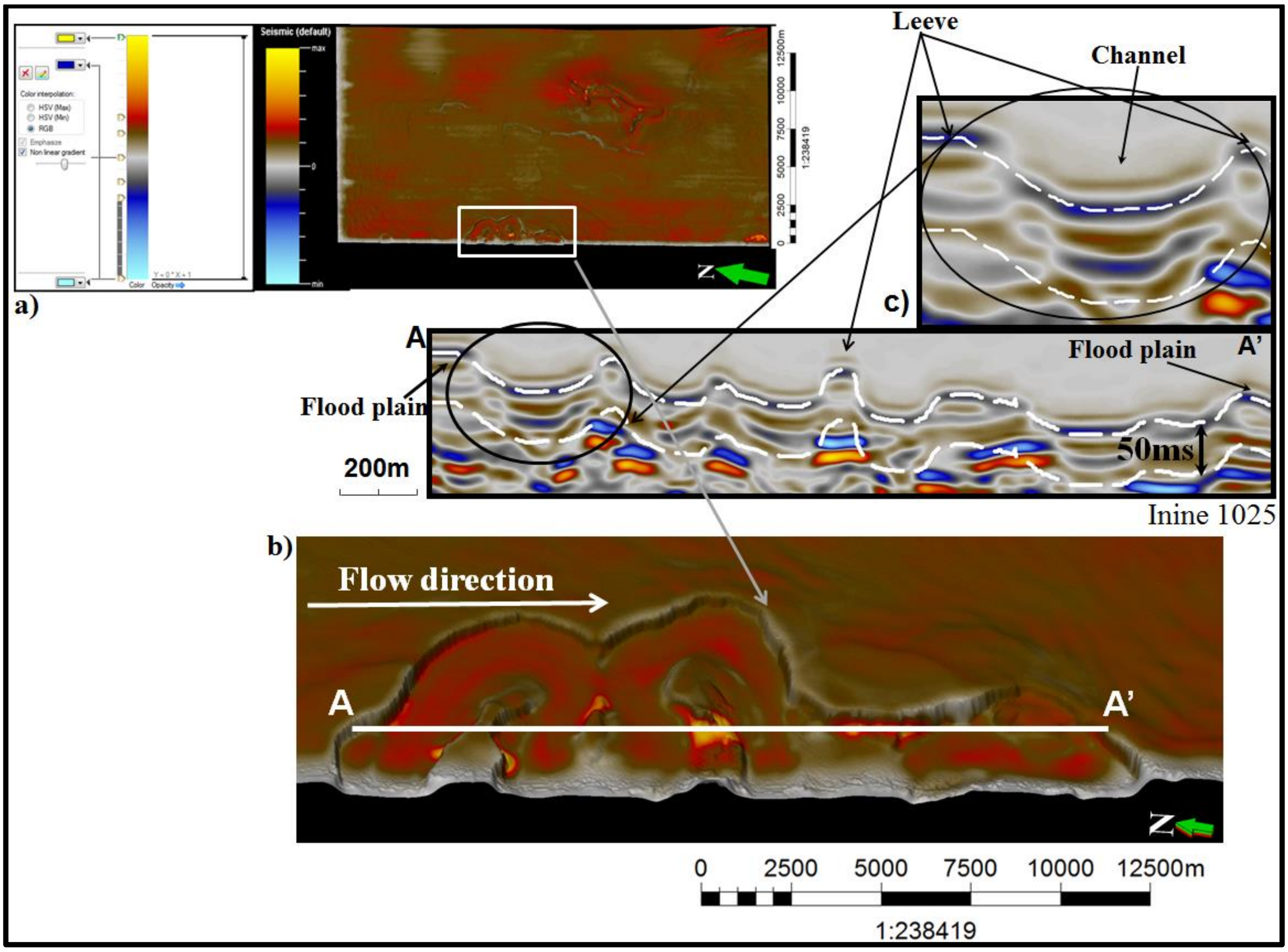


Figure 5-13: illustrates an attribute maps combined seismic facies; a) shows attribute map RMS seabed correspondent to 50ms Unit II, b) shows meander sinuosity extracted from image a, c) shows seismic facies.

Chapter 6 - Discussion

The Lower Congo basin evolution has been known to be characterized in the Tertiary times with deposition of deep water turbidites in channel dominated submarine fan system, which continued in successions to a more recent time. These events of Lowstand progradation and channel development are the main target feature in this basin (Droz et al., 2003).

The low stand progradation is due to the sea level drop where larger parts of the shelf are exposed and eroded. This erosion formed incised valley or canyons on the shelf which is continuous into the deeper water areas of the basin. Relative sea level changes strongly influence the sediment supply and architecture of submarine fan deposits (Posamentier et al., 1991). The lowstand sea level drop has led to the development of canyons fan and submarine channels. This channels fills processes resulted to channel facies units such as the channel axis, levee, flood plain and point bar facies which are noticed in the interpreted seismic units in my study succession (Figure 5-8).

The discussion is focused to the main target results of the 3D seismic data interpretation in this study which focuses on the interpreted channel and analyse other geological features in the Tertiary successions and surface sea bed features

The sea bed channel reflection was interpreted as the most recent of the channel successions developed to current sea bed erosive lowstand progradation response. This feature consists of meandering channel system of high sinuosity index of 1.6. This channel type is commonly by higher proportion of fine-grain sediments with less bed load composition, with well confined borders of levee and associated flood plains areas with accreted point bars located within the inside of the meander bend. This channel type of confined borders due has a higher fine composition to bed load it tends to have a lower net to gross of sandy composition due to the lower proportion of bed load composition (Leopold &Wolman, 1957).

Channel progradation events were also active in other Tertiary successions as their sea bed position were interpreted down into other successive units in the seismic of unit I and II, where it was noticed that the low stand progradation channel development has successive channel amalgamations with stacking architecture of channel bodies observed in seismic section across the strike and dip of the section, which could be a function of interaction between vertical or lateral amalgamation process during low stand deposition. The seismic interpretation of the units I and II it is characterized by varying amplitude and chaotic reflection, as well as continuous and discontinuous reflectors in the all seismic sections. The characteristic shingled to chaotic reflections were noticed in reflections within the channelized part of the seismic reflections which were the responses of the different channel subfacies to varying acoustic impedance contrast properties (Figure 5-7).

The high amplitude contrast of the channels in the sections were known to have stronger amplitude reflections in areas of flood plains and levee borders which confine the channel axis that are known to have lower amplitude responses according SEG standard (European). It was interesting that the channel axis with levee ridges were picked out in the surface exposure of the seismic (Figure 5-7). This interpretation made it easier to interpret the channel successions with amalgamated stacks of different sub channel facies units, which accounted for the chaotic reflection signatures. The confined channel type mainly identified in my study stratigraphic level tend to be have less sandy composition as earlier explained, this means that the reservoir potential of this channel type would be most lowered when compared to other unconfined channel events. However, the amalgamation of this channel over geologic times would mean that sand body connectivity would be higher laterally and vertically. The channel interpreted was characterized by high meander sinuosity in deep-water system. This high sinuosity meander consists of low density sediments. Where the types of sediments are characterized by fine-grain in this case levee and vertical accretion deposits that are relatively thin. Also this fine-grain sediment it is localized outside of the channel and within the channel it is filled by mixed sediments like shale-sand. Flood plains are predominately over bank deposits from the channel axis via the levee with fine compositions, vertical accretion to the point bar are found at the inside of the meander bend (Figure 6-1).

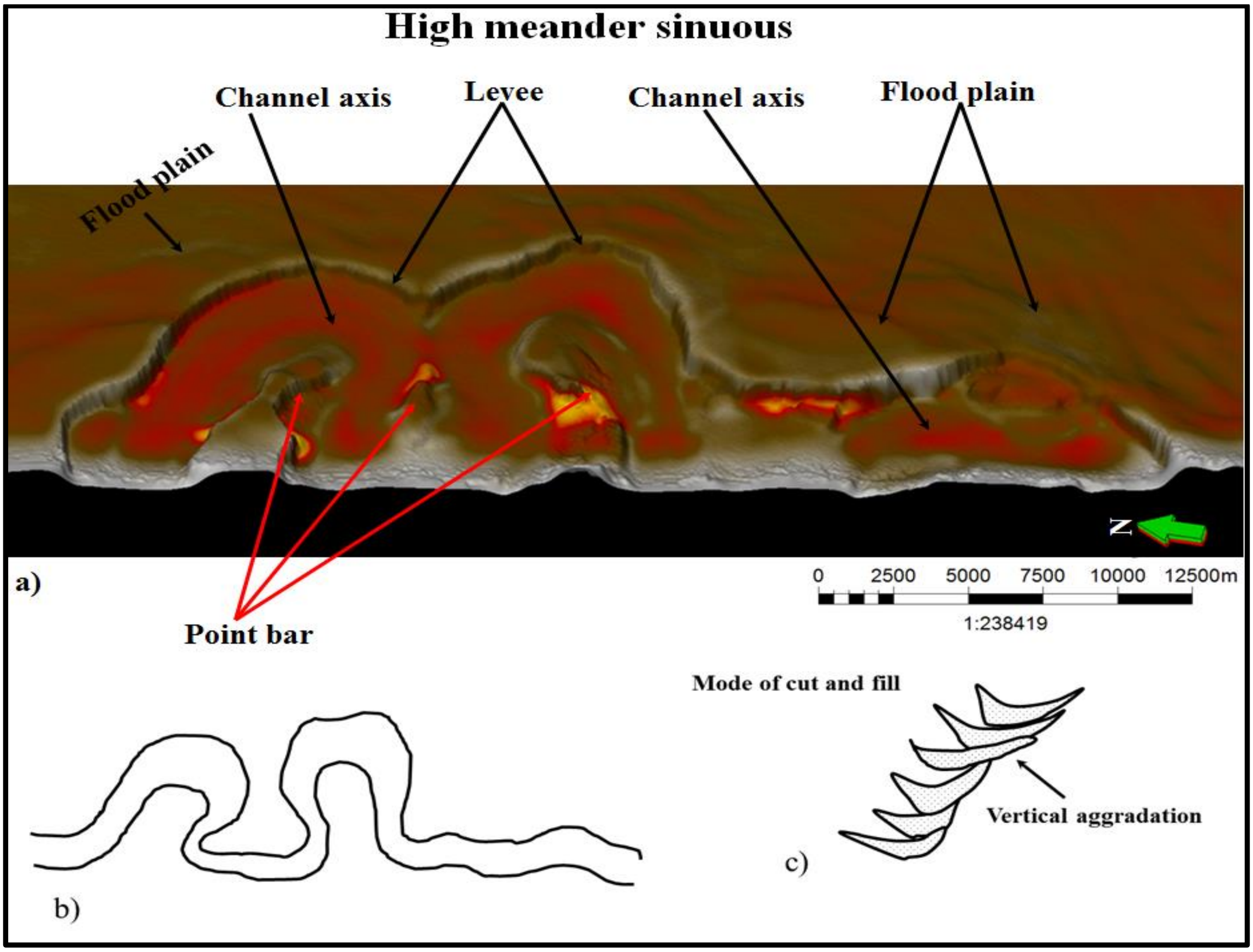


Figure 6-1:High meander sinuous channel deep-water: a) illustrates high meander sinuous; schematic sketch of b) represent Sinuous channel c) represent a vertical aggradation channel complex.

The main direction of the meandering river was known to be south-west from the main Congo River supplies which was seen to be developed in the seismic unit in the western sections of the interpreted seismic areas. This could be as a result of the salt uplift commonly found in the eastern sections of the study area, which might have caused depression areas due west to allow for submarine flow sediment to concentrate on this wedge areas for channel development, so it could be said that the channel development has been syn-tectonic to the salt intrusion in this stratigraphic level. The channel bodies in this stratigraphic level were noticed to be uniform with lateral dimension of progradation areas stretching in the sediments. This suggests that the salt had less deformational impact on the channel as spaces were mainly created by the salt presence. The presences of minor faults were noticed in some parts of the channels, which were mainly linked to the syn-tectonic salt halokinesis (Figure 6-2).

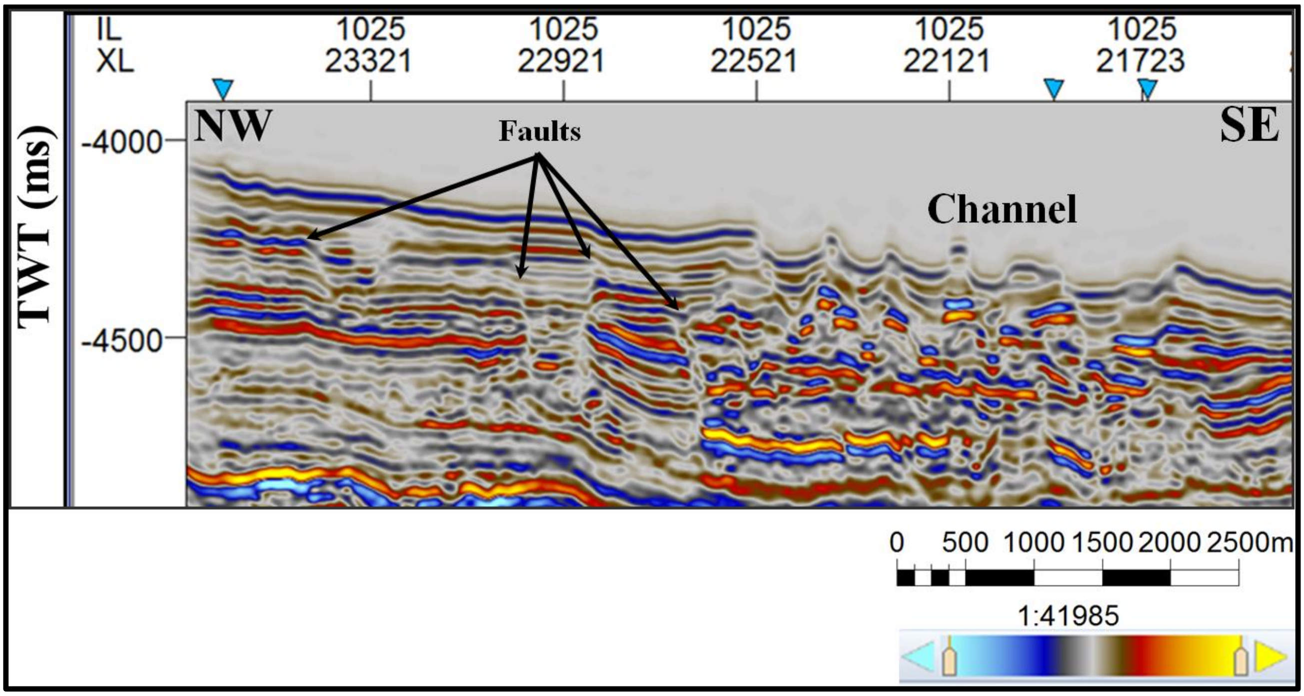


Figure 6-2: Seismic section illustrates faults and the channel.

The effect of the salt in the seismic area has mainly be linked to space creation where depressions areas of sediments were seen at the flanks and the thin veneer of sediments were also seen at the top of the salt where the sea bed topography formed ridge extensions in the eastern central section of the survey area. This higher topographic extension of the salt has triggered sediment cascade process into forming slump scar debris which was common in the sea bed surface imprints. This topographic extensions with higher ridges aid more turbiditic flows to concentrate within areas of the lower topographic extensions close to the Congo River supply. The extensive polygonal faults might be associated with desiccation process which may have be salt related as they were common in this surface stratigraphic level, linked probably to earlier sediment dewatering process (Figure 6-3).

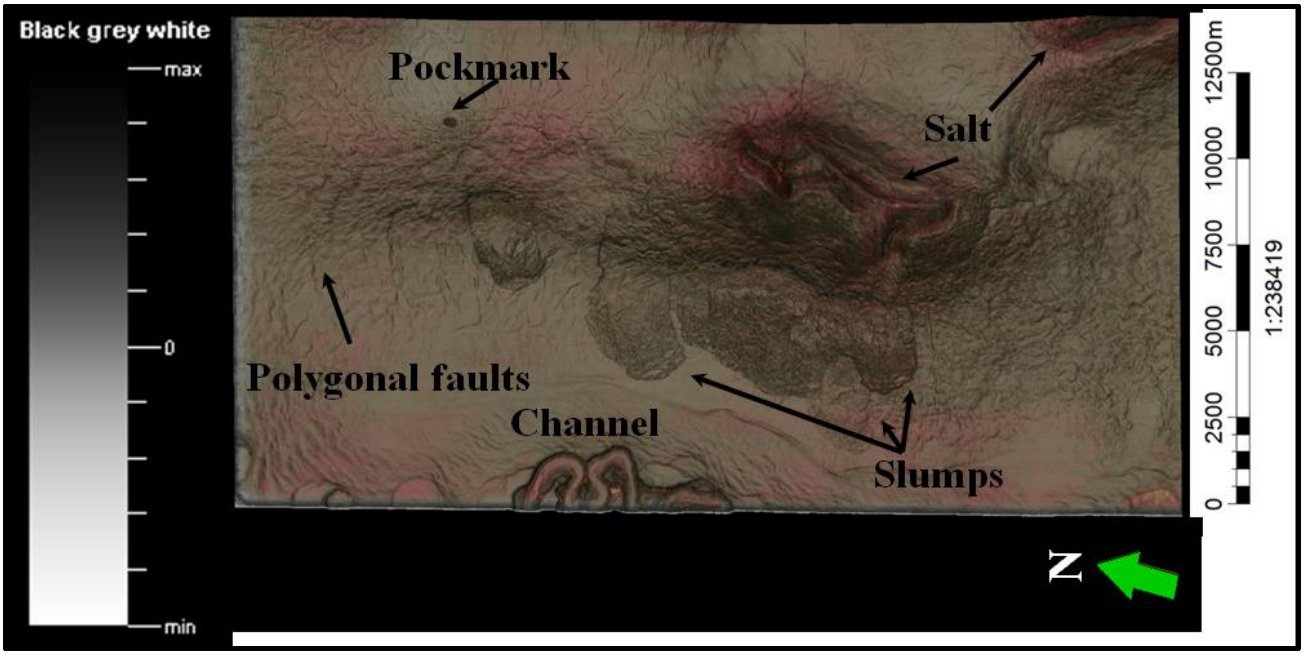


Figure 6-3: Shows the blended RMS amplitude and variance map from seabed illustrates mainly features in the map.

Also observed are pockmark features observed in the map view and noted like small hole. The pockmark is the influence of fluid escape. It is widely recognized to form by fluid explosion through the seabed. They have also been described occurring at the head scarp of a submarine slide (Gay et al., 2006). The name was coined from gasturbation as suggested by (Josenahns et al., 1978). This is interpreted and mapped to be controlled by the distribution of fluid migration pathways in the shallow buried channels. The pockmarks as was observed in RMS amplitude and variance sections, indicates that they are related with faults that extend from seabed fluid charged shallow sediments (Figure 6-3).

Finally the chronology of geologic events has been marked by the earlier salt deposition, which were tectonically active with related salt movements and diapiric features, which tend to affect the Tertiary sedimentation process of turbiditic flows from the Congo River. The low stand sea level drop has led to the Congo River supply of sediment in submarine channel systems. The channel facies were much determined by the bed load composition, flow strength, stage of the river and the provenance of the sediments. The channel amalgamation has been known to be suggesting the low stand progradation has developed at longer geologic cycles of several channel developments. The syntectonic salt events to the turbidites have been known such that the sediment wedges and large depressions adjacent the salt are location sites for the turbidite flows to concentrate. Overburden sediment reworking has also led to later polygonal planar fault events that were observed in the sections.

Chapter 7 -Conclusion and recommendation for further work

7.1- Conclusions

A 3D seismic data set from the Lower Congo basin offshore Angola shows the channel internal architecture with surface imprints of the channel developments on the sea floor. The interpretation captures the effects of the salt on the channel forming process and also how it affects other features in the area.

This interpretation was undertaken to perform detailed geological evaluation of the deep-water depositional environments contained within the uppermost stratigraphy of the Lower Congo Basin. This includes identifying and interpreting the interplay between channel development and seafloor geomorphology, to gain more insight in the depositional systems within the Lower Congo Basin.

RMS attribute amplitude and time slice maps and cross sections through 3D seismic amplitude volumes provided useful information for submarine geomorphology and geometry. It was possible to map and illustrate these internal and sea bed with the seismic interpretation, using the attribute displays in Petrel.

It was observed that the main channel type observed in this study area are the confined meandering high sinuous channels, with amalgamated facies of levee, flood plain, channel axis were noticed to cause internal chaotic reflections within the seismic units. It was also observed that the Low stand progradation cycles had repeated channel development which has amalgamated over geologic times in the Tertiary. The salt halokinetic influence was seen in the isopach sediment distributions with large sediment adjacent the salt flanks with the rising diapiric highs of the sediment affect the surface sea bed scarp with slump debris and ridges also noted.

7.2- Recommendations for further work

Other detail analysis of the channel has to be performed to know more about the fluid bearing composition of the channels. Seismic evaluation like AVO analysis would be important with fluid substitution to know which fluid could occupy the sandy channel facies. Also, a PSDM data would be important too to have accurate depth measurement of the channel dimensions. Wells data would also be relevant to mark out the horizon to well position markers, which would pin point the geologic positions of the seismic in the stratigraphy column.

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