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Integrated Subsurface Structural Interpretation of the Ordovician Succession in the South-Central part of the Concession NC186, Northern Murzuq Basin

Thesis submitted to Department of Earth Sciences as partial fulfillment for the degree for Master (M.Sc.) of Sciences

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جامعة بنغازي

كلية العلوم

قسم علوم الأرض

ربط التحاليل التركيبية التحت سطحية للتتابع الاوردوفيشي في الجزء الجنوبي الأوسط من الامتياز 186 بشمال حوض مرزق

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بسم الله الرحمن الرحيم

ثُمَّ قَسَتْ قُلُوبُكُم مِّنۢ بَعْدِ ذَٰلِكَ فَهِىَ كَٱلْحِجَارَةِ أَوْ أَشَدُّ قَسْوَةً ۚ
وَإِنَّ مِنَ ٱلْحِجَارَةِ لَمَا يَتَفَجَّرُ مِنْهُ ٱلْأَنْهَٰرُ ۚ وَإِنَّ مِنْهَا لَمَا يَشَّقَّقُ
فَيَخْرُجُ مِنْهُ ٱلْمَآءُ ۚ وَإِنَّ مِنْهَا لَمَا يَهْبِطُ مِنْ خَشْيَةِ ٱللَّهِ ۗ وَمَا ٱللَّهُ
بِغَٰفِلٍ عَمَّا تَعْمَلُونَ ﴿٧٤﴾ سورة البقرة–الجزء الثاني

In the Name of Allah, The most Gracious, The most Merciful

Then your hearts became hardened after that, being like stone or even harder. For indeed, there are stones from which, rivers burst forth. And there are some of them that split open and water comes out. And there are some of them that fall down from the fear of Allah. And Allah is not unaware of what you do (74).

Al-Baqarah (PART-2).

ABSTRACT

Ordovician is one of the challenging geological stages in the area and North Africa due to its structural and stratigraphic complexities. Since oil and gas were discovered in Murzuq Basin, the main reservoirs subjected to intensive surface and subsurface geological studies. The pre and post Ordovician tectonics all played an important role in the final configuration of the present day Ordovician structure. Resolving these tectonics complexities was only achievable by implementing data integration in regional and local scales.

This study deals with the tectonic evolution of two main oil fields (I&H) in the concession NC186 that is located in the northern part of Murzuq Basin. Differences in scale of structural and stratigraphic features in the area of study were captured using integrated workflow for high resolution and detailed subsurface structural interpretation. Large and small scale features such as faults and fractures were both studied using surface seismic and FMI* dataset by using Petrel and GeoFrame softwares.

Understanding and upgrading the polyphase tectonic variations and evolution in the studied area was developed. The observed direct and indirect tectonic impacts on the Ordovician successions from Precambrian to present day were evidently indicated by basement faults, paleohighs and paleolows, positive flower structures and folds encountered in the study area.

During Late Ordovician, glacial episode developed a regional unconformity known as "Taconic Unconformity" developed large scale paleohighs and paleolows that directly influenced the geometry of the upper Ordovician deposits.

Conceptual tectonic models of the study area were concluded in nine phases based on the detailed interpretation. The significant tectonic observations in the study area are represented by steep reverse basement faults with differential displacements separating I & H Fields. These basement faults were subjected to compressional, extensional, strike-slip and/or combination through different geological times. The Early Cambrian Extension, Late Cambrian Compression, Taconic phases during Late Ordovician, Middle Devonian inversion, Carboniferous uplifting and erosion, Mesozoic extension and Late Cretaceous compression are the main controlling tectonic episodes recorded in the area of study.

الملخص

يعتبر العصر الاوردوفيشي من أحد أهم المراحل الجيولوجية المعقدة في المنطقة وشمال أفريقيا نظرا لتعقيداتها الهيكلية والطبقية. فمنذ اكتشاف النفط والغاز في حوض مرزق، والخزانات النفطية الرئيسية تحت دراسات جيولوجية سطحية وتحت سطحية مكثفة. كل المراحل التكتونية قبل وبعد الاوردوفيشي لعبت دورا هاما في التكوين النهائي للهيكل الاوردوفيشي حتى يومنا هذا. فحل هذه التعقيدات التكتونية يكمن تحقيقه فقط من خلال تنفيذ دمج للبيانات في مقياسين إقليمي ومحلي.

تتناول هذه الدراسة التطور التكتوني لحقلين من حقول النفط الرئيسية في الامتياز NC186 الذي يقع في الجزء الشمالي من حوض مرزق. تم تحديد الاختلافات في حجم وسمات التركيبات الهيكلية و الطبقية في منطقة الدراسة باستخدام نموذج عمل للحصول على أعلى دقة وتفصيل مفسر للتركيبة التحت سطحية. تمت دراسة الظواهر التركيبية الكبيرة والصغيرة مثل الصدوع والكسور باستخدام البيانات الزلزالية السطحية وبيانات التصوير الرقمي الدقيق وبمساعدة برامج حاسوبية تسمي بترل (Petrel) وجيوفريم (GeoFrame).

من خلال هذه الدراسة وضع تصور لفهم وتطوير الاختلافات التكتونية والتطور التكتوني. وحللت في هذه الدراسة التأثيرات التكتونية المباشرة وغير المباشرة على التتابع الاوردوفيشي من عصر ما قبل الكمبري إلى الوقت الحاضر والمتمثلة بالصدوع في صخور القاعدة والمرتفعات والمنخفضات القديمة وما يعرف بالطيات الموجبة.

تكون سطح لا توافقي خلال أواخر العصر الاوردوفيشي بفعل الجليد عرف باسم السطح اللاتوافقي التاكوني "Taconic Unconformity" والذي نتجت عنه مرتفعات ومنخفضات قديمة ذات حجم كبير والتي أثرت بشكل مباشر في الشكل النهائي لرسوبيات العصر الاوردوفيشي الاعلى.

تم طرح مفهوم النموذج التكتوني لمنطقة الدراسة في تسع مراحل و على أساس تفسيري مفصل. وتتمثل المشاهدات التكتونية الهامة في منطقة الدراسة بصدوع عكسية في صخور القاعدة حادة تفصل بين الحقلين مع فرق نسبي في الإزاحة الراسية. هذه الظواهر التكتونية كانت عرضة لقوى ضغطية أو شد أو إزاحة جانبية أو لاتحاد قوتين في أن واحد خلال العصور الجيولوجية المختلفة. من أهم المراحل التكتونية التي سجلت في منطقة الدراسة هي: الشد و الضغط في العصر الكمبري و المؤثرات التاكونية في نهاية العصر الاوردوفيشي و الانقلاب الحركي منتصف العصر الديفوني و الرفع والحث في العصر الكربوني و إعادة الشد في الدهر الوسيط والضغط نهاية العصر الطباشيري.

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First and for most, I thank Allah who allows me to fulfill and commit such work and gives me the strength to proceed and accomplish this thesis.

Second, my great gratitude and appreciation goes to my family for their encouragement and support throughout different stages of my life.

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

During the last decades and due to intensive oil exploration, Murzuq Basin became one of the largest profitable basins in North Africa and especially in Libya. The petroleum system of the basin is represented by Hawaz and Mamuniyat Formations (Middle to Upper Ordovician deposits) as the main reservoirs and Hot Shale Member (Base Silurian deposits) as the main source rock. The Ordovician sequence, especially the Upper Ordovician, is characterized by structure and stratigraphic complexity due to tectonic instability and glacial event. However, understanding the regional geology of Murzuq Basin is a key for understanding the area of subject study which is located in the northern part of the basin.

This thesis is dealing with pure structural evaluation of the H and I fields in the Concession NC186 that located in the northern eastern part of the Murzuq Basin within the main axis of Awbari Trough. Therefore, focusing on the structural evolution is key element for resolving the structural complexity in local and regional scale by using different subsurface dataset.

The latest comprehensive integration of the surface and subsurface geology of Murzuq Basin was published by Sola and Worsley (2000) after the geological conference on Exploration in the Murzuq Basin held in Sabha (1998). In addition, Hallet (2002) gathered a huge dataset using both surface and subsurface information of the whole Libyan basins. Moreover, many geological activities and researches have been established in the basin focusing on the Ordovician and Silurian deposits. These deposits represent the main reservoir system in the area especially after the 90's where oil intensively discovered and produced.

Through time the main objective of combining and integrating of geological and geophysical data and information was and still the main target for the geoscientist in the oil companies for better understanding of the reservoir properties. Therefore, analyzing of the subsurface structural configuration in this part of Murzuq Basin may adds to the geological details and helps to open the area for future academic research.

1.2 Location of the Study Area

Murzuq Basin is located at the southwestern part of Libya and covering an area of about 350,000 km^2. The basin is bounded from the north by Gargaf Arch, to the west by Tihemboka Arch and to the east by Tibesti Uplift and to the south extended into Niger and known there as Djado Basin (Figure-1.1). The present day Murzuq Basin is confined between latitudes 22° 30`N and 27° 30`N and longitudes 11°E and 16°E.

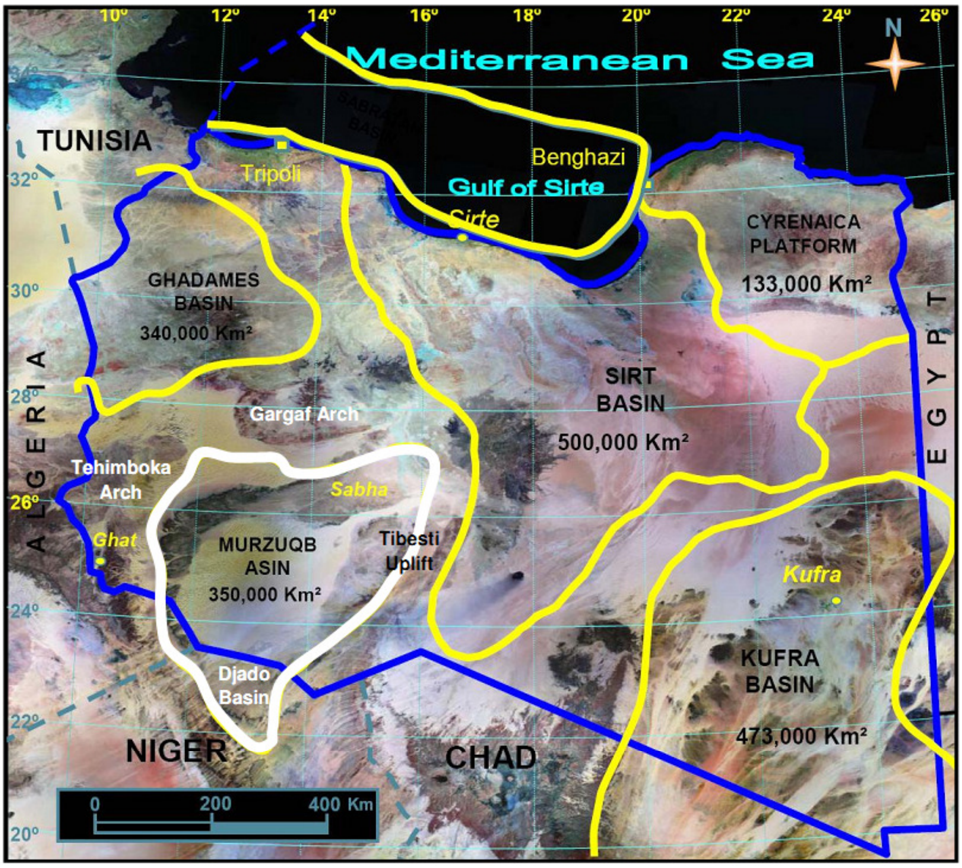


Figure-1.1: Location of Murzuq Basin in the southwestern part of Libya and the bounding features.

Geologically, the area is located in the Awbari trough that developed during extensional phase in the early Paleozoic and was connected with the Idhan depression till the end of the Paleozoic. The nearest exposures to the area of present study are the Messak escarpment of Cretaceous age to the south and the Qargaf Arch to the north (Figures-1.1 & 1.2).

The study area is represented by two major producing oil fields, namely H & I and located in south central part of the Concession NC186. The Concession NC186 is located in the northeast of Murzuq basin of southwest Libya between the latitudes 27° 00` to 26° 40` N and longitudes 13° 9` to 12° 00`E and it covers an area of about 3400 km^2. In the two fields (H & I), only five wells are chosen to be included in the subject study hence they cover the boundary of the two fields (Figure-1.2). The exact locations of these wells are as follow:

Well	Latitude	Longitude
I1-NC186	26°41'32.40"N	12°28'05.70"E
I2-NC186	26°41'01.56"N	12°26'29.91"E
I3-NC186	26°44'00.92"N	12°25'19.71"E
H1-NC186	26°45'56.36"N	12°30'51.37"E
H3-NC186	26°41'21.40"N	12°34'00.80"E

Table-1.1: List of the wells and their exact locations in the study area.

Repsol Exploration Murzuq SA (REMSA) began a new exploration campaign in the area following the award of NC186 during 1996. Six exploration wells were drilled between 1999-2002, three wells were declared as a discovery with A1-186 the first discovery, one suspended and two wells were declared as dry holes. Total oil in place discovered to date in the area is significant and considered as a large discoverers, two of them founded in the middle Ordovician Hawaz formation with only one being found in the upper Ordovician Mamuniyat formation.

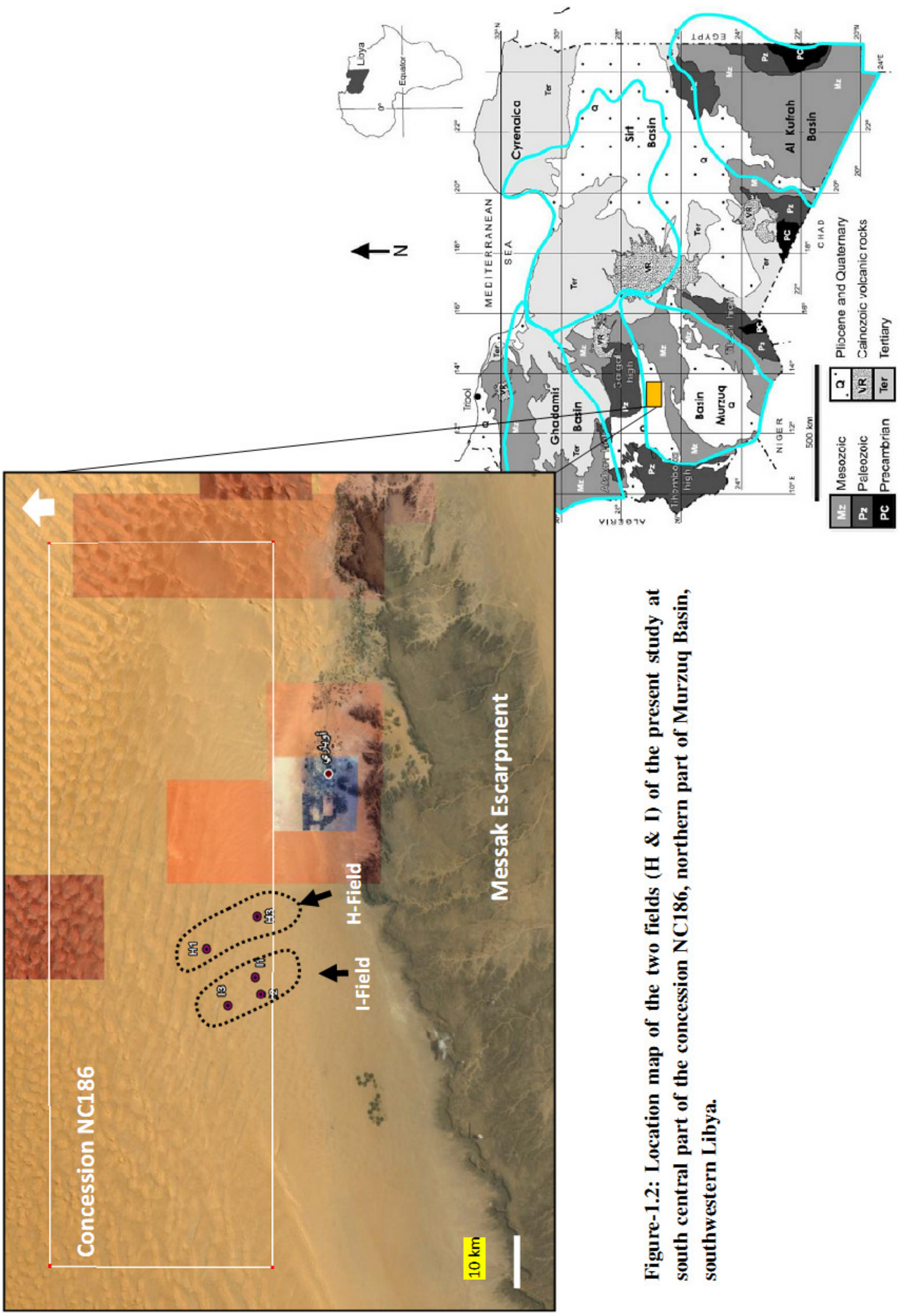


Figure-1.2: Location map of the two fields (H & I) of the present study at south central part of the concession NC186, northern part of Murzuq Basin, southwestern Libya.

1.3 Objectives of the Study

Multiple reactivations of structures is common, often following basement zones of weakness, and many faults were subjected to alternating compression/transpression and extension/transtension during the geological time. Due to this complexity, the detailed structural history of many composite present-day structures is still unclear. Therefore, the following sequence of objectives was considered:

1. Identification and evaluation for the main structural elements in both H and I fields in the Concession NC186 and connect the interpretation results with the regional tectonic evolution of Murzuq Basin.
2. Detailed evaluation of faults (especially the basement faults), their rejuvenation during geological time (i.e. from Precambrian to Present day) and their impact on the Ordovician successions.
3. Resolving the Ordovician complexity by analyzing the tectonic evolution and rejuvenation mechanisms including possible later retro-deformations.
4. Identifying the geometrical variations of the Ordovician sequences as a response of both structural and/or stratigraphic controls.
5. High resolution reconstruction model of structure and stratigraphic evolution in the two fields will be proposed in this study.

1.4 Study Background & Previous work

With the arrival of Oil Companies in 1955, a new phase of investigation began, with the acquisition of large amounts of subsurface data. The Petroleum Exploration Society of Libya emerged as the focus for oil company activity, and played a key role in publishing new data during the 1960's. The Society organised the First Saharan Symposium in 1963 which included notable stratigraphic papers such as by Klitzsch (northeast Murzuq and Dur a1 Qussah). The Society also organized annual field excursions. Other authers have played an important role in that stage such as Massa and Collomb (1960), Collomb (1962), Havlicek and Massa (1973). By 1987 oil companies had begun to release large amounts of data and this was reflected in the third symposium on the Geology of Libya which presented key well information from the Kufrah and Murzuq Basins, and from the Cyrenaican offshore.

In 1998 a conference on geological exploration in the Murzuq Basin was held in Sabha, and the proceedings were published in 2000 by Sola and Worsley. This volume included new data on the Silurian hot-shales, the Mamuniyat glacial episode and the stratigraphy of the Murzuq Basin. It also represents the comprehensive geological collection for Murzuq Basin where many important papers have changed the vision of the Geology of Murzuq Basin. Authors included in this volume such as Echikh and Sola (2000) and Davidson et al., (2000). Hallet (2002) gathered also one of the largest databases of the petroleum geology of Libya including the geological and economical information in all the basins. In the Petroleum Geology of Libya, tectonic evolution, structural framework, stratigraphic succession, hydrocarbon system and other valuable information all are available for each basin in Libya.

In the recent decades, many publications were intensively written especially about the northern part of the basin after the huge discoveries in the concessions NC174 and NC115. Most of these papers were concentrated about the reservoir and source rock succession in the area (Ordovician–Silurian sequence). The upper Ordovician succession in Murzuq Basin (Mamuniyat Formation) is considered as the major reservoir accumulation in Murzuq Basin. Therefore, high detailed surface and subsurface studies conducted during the previous years on the late Ordovician stage in order to investigate the reservoir complexity. However, both Le Heron and Craig published in 2006 and 2008 good paper work referring to the Late Ordovician glaciations in Murzuq Basin. The Middle Ordovician succession in Murzuq Basin (Hawaz Formation) is considered as the second major reservoir accumulation in Murzuq Basin. Ramos et al. (2006) studied the stratigraphy and sedimentology of the oil-bearing Hawaz Sandstone.

CHAPTER TWO

TECTONIC EVOLUTION & MAIN STRUCTURAL ELEMENTS OF MURZUQ BASIN

2.1. Tectonic Evolution of Murzuq Basin

The basin is defined as an intracratonic basin that developed during the Last stage of the Pan African Orogeny (i.e. Late Neoproterozoic to Early Paleozoic) and it's considered as one of the major Paleozoic Basins in North Africa (Figure-2.1).

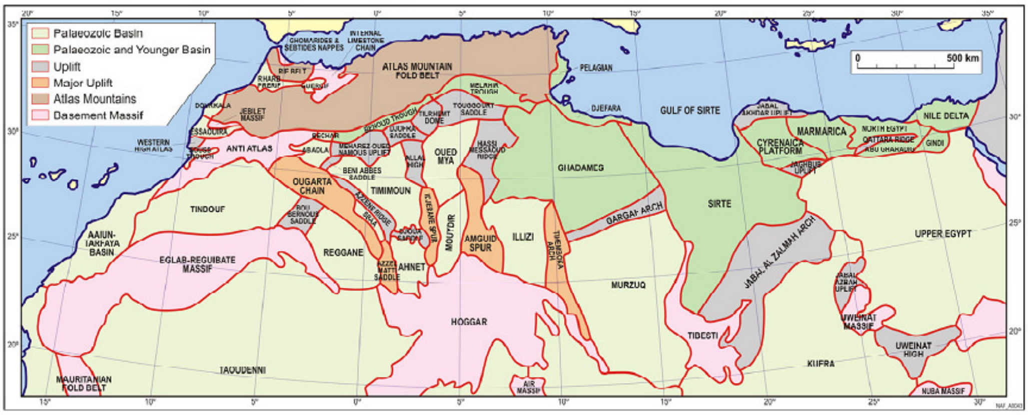


Figure-2.1: Map of the major Paleozoic sedimentary basins in North Africa. (Source: Craig et. al., 2006)

In Early to Middle Paleozoic times the evolution of Gondwana controlled the development of Libyan tectonics and Pangaea in the Late Paleozoic to Mesozoic. In addition, the evolution of Tethys Ocean primary controlled the tectonics of Libya during the later Mesozoic and Cenozoic. A brief summary of the tectonic history of Murzuq Basin was carried out in details in this study. New idea was implemented to subdivide the regional tectonic history of the basin based on timing into six stages (Figure-2.2) as follow:

1. ***Precambrian (Rodinia, Pan African Orogeny and Gondwana assembly).***
2. ***Early Paleozoic (Murzuq Basin, Regional Unconformities & Glacial episodes).***
3. ***Middle Paleozoic (Transition from Extension to Compression Episodes).***
4. ***Late Paleozoic (Hercynian Orogeny, Assembly of Pangea).***
5. ***Mesozoic (Extension by Breakup of Pangea, Tethyes Ocean, Austrian & Santonian Upliftiing).***
6. ***Cenozoic (Uplifting and Inter-plate stresses during Alpine Orogeny to present).***

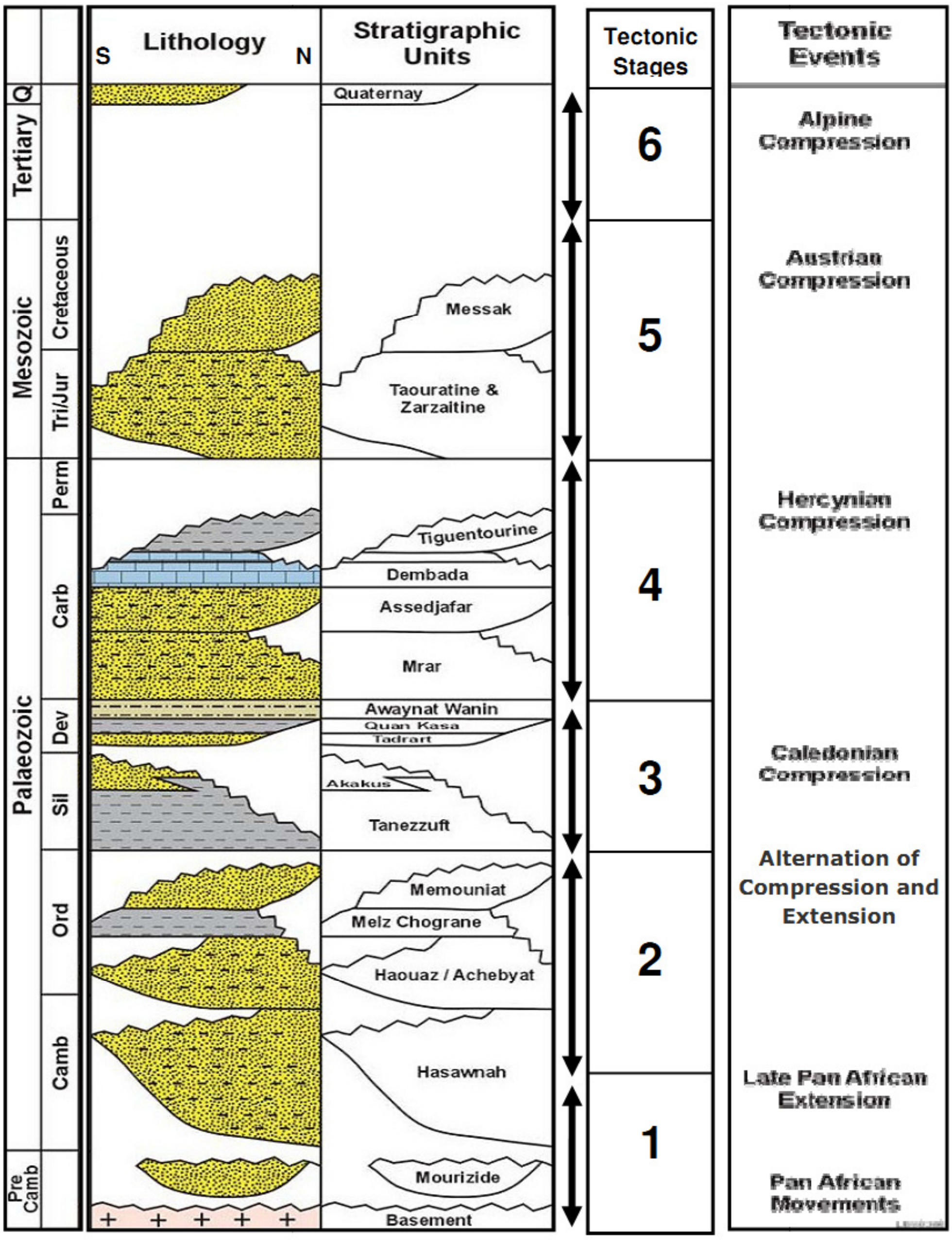


Figure-2.2: General Stratigraphic Column of Murzuq Basin shows unconformity and tectonic events. Modified from Echikh and sola, 2000.

2.1.1. Precambrian (Proterozoic)

During this eon, two major tectonic episodes occurred, these are; 1) Assembly and breakup of Rodinia supercontinent and 2) Development of the North African crust at the end of the eon (Pan African Orogeny).

2.1.1.1. Rodinia Supercontinent (Assembly & Breakup)

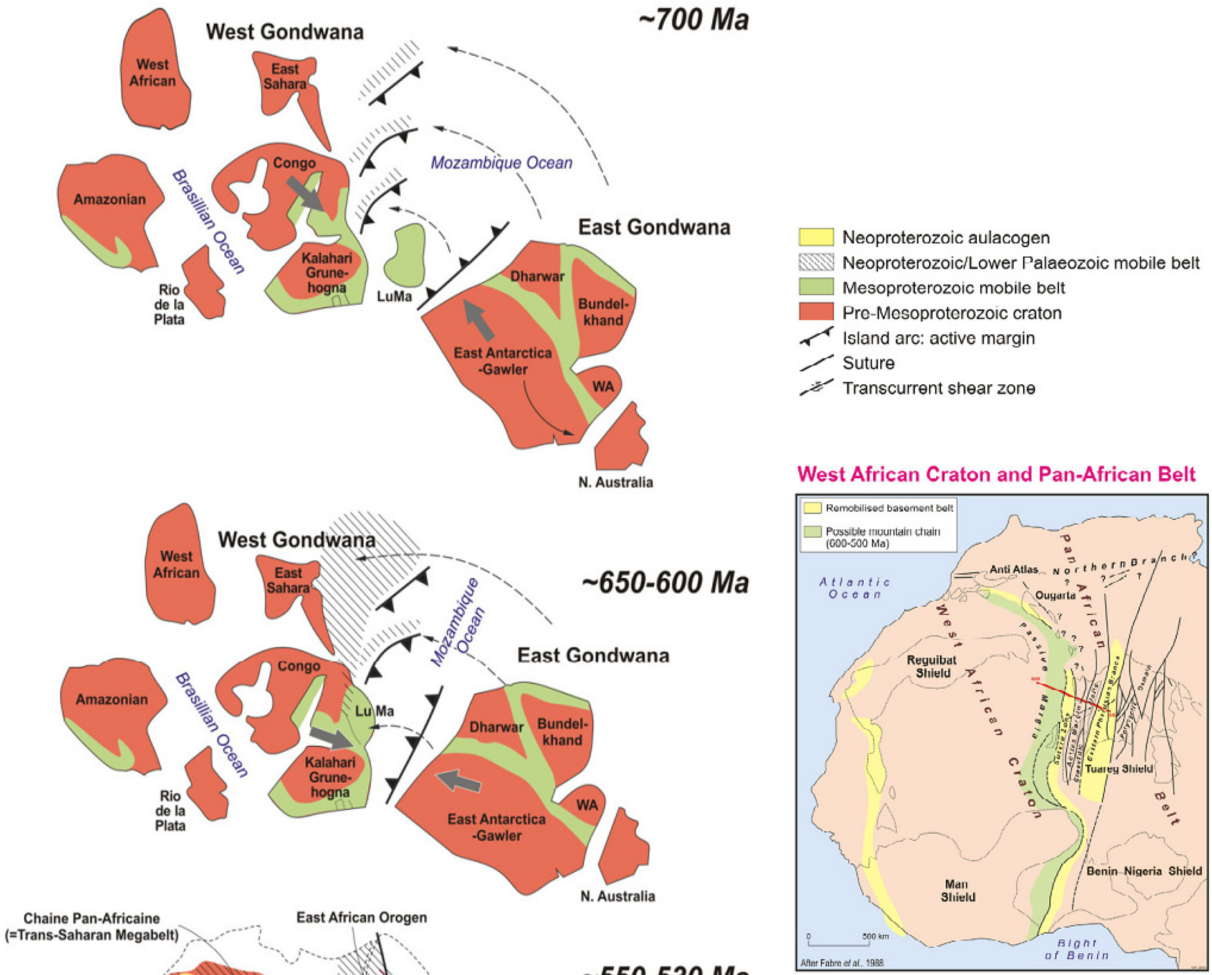
According to Ettalhi *et. al.,* (1978), the Rodinia was assembled during the ***Meso-Proterozoic*** from about 1600 to 1000 Ma and the break apart began in the ***Early Neo-Proterozoic*** from about 1000 to 500 Ma. The break apart axis trending N-S moving splitting the cratons from each others with two different directions; clockwise and anticlockwise. Available evidence suggests that, Rodinia was composed of about twenty identifiable Archaean and Palaeo-Proterozoic cratons. In Libya, rocks of averaging age from 2900 to 2600 Ma found in Jabal Awaynat, on the border with Sudan, and have also been found in eastern Tibisti Mountains.

The period from 700 to 500 Ma was marked with the final break-up of Rodinia and the reassembly of a new supercontinent which was given the name Pannotia by Powell (Hallet, 2002). The start of this assembly has major tectonic event in the development of North Africa which is known as Pan African Orogeny where Murzuq Basin believed started to be developed.

2.1.1.2. Pan African Orogeny (Building North Africa)

The North African crust was developed during an oblique continent to continent collision, between the West African and East Saharan Cratons (Figure-2.3). The rearrangement, rotation and alignments of the cratons are accompanied by intensive shearing and deformation, called Pan-African Orogeny, in which the cratonic nuclei of present-day Africa were, fused together (Caby et al. 1981; Vail 1987; Jacobs and Thomas, 2004).

The collision occurred between the West African and East Sahara cratons and more than twenty other terranes led to the development of Trans-Saharan Megabelt (Craig et. al., 2006) (Figure-2.3). As a result of the Pan African Orogeney; Africa is made up of more than twenty terranes (Hallet, 2002) (Figure-2.4). Basement terranes within the Hoggar Massif are separated by major northsouth vertical shear zones representing crustal scale terrane boundaries that underwent transpressional reactivation during oblique Pan-African collision (Hallet, 2002). These wrench fault systems provide weaknesses within the North African continental crust that were exploited repeatedly during subsequent tectonic events.



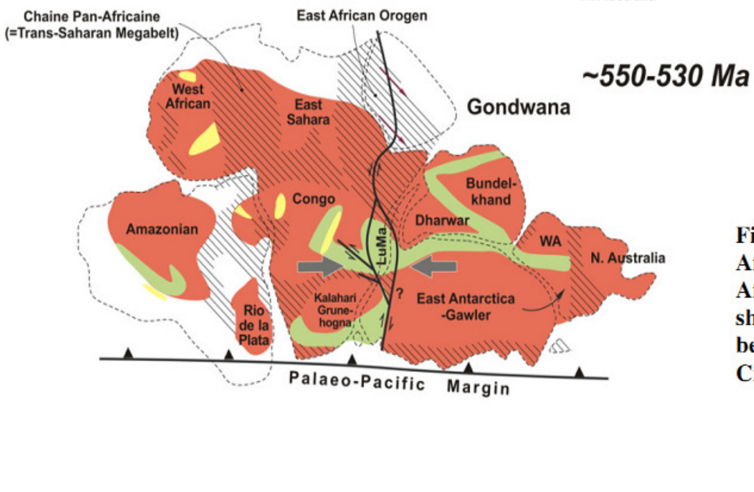


Figure-2.3: Shows the Evolution of Pan Africa Orogeny and the assembly of the African continents. Note also the megabelt shear zone that developed after the collision between the West African and East Sahara Cratons. (*Source: Craig et. al., 2006*).

An extension occurred in Late Neoproterozoic to Early Cambrian period between c. 1000 Ma and c. 525 Ma, in North Africa and a sequence of "Infracambrian" conglomeratic and shaly sandstones and siltstones deposited. In Murzuq Basin, south-west Libya, these sediments exposed at outcrop in the Mourizidie area on the eastern margin of the basin. The basement in Murzuq Basin is mainly composed of high-grade metamorphic rocks associated with plutonic rocks, as well as low grade metamorphic to unmetamorphic rocks of Precambrian age (Mourizidie Formation).

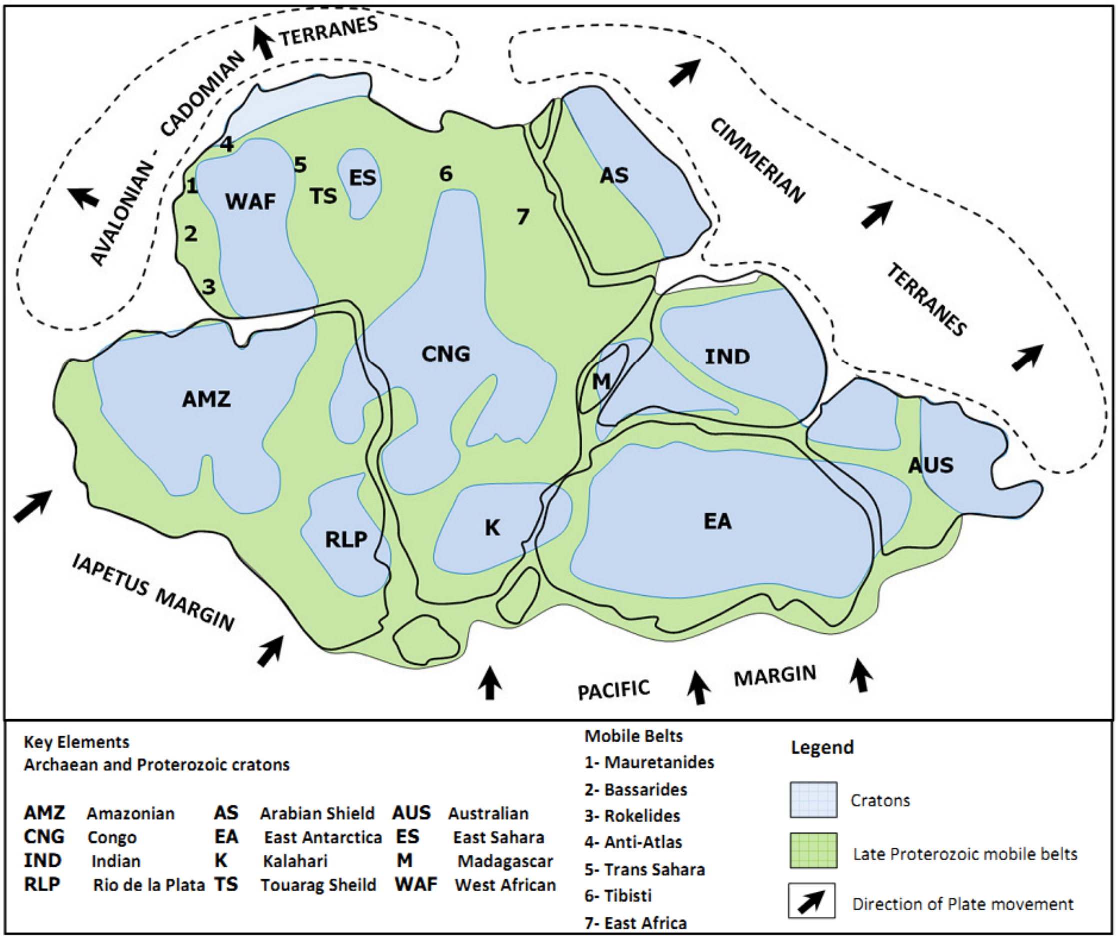


Figure-2.4: Plate Tectonic Reconstruction: Gondwana assembled, 450 Ma. ***After Unrug (1996)***

Following the separation of Laurentia the Pan-African Orogeny fused together the cratons to form Gondwana. The southern margin of Gondwana became an active margin with subduction of oceanic crust beneath the continental edge and the northern margin became a tensional passive margin.

2.1.2. Early Paleozoic (Cambrian & Ordovician)

The Early Paleozoic (Cambrian-Ordovician) represents the earliest stage in the tectonic and stratigraphic history of Murzuq Basin and the final phases of Pan-African Orogeny. At this time, in Early Paleozoic, a strong NW-SE extensional structural grain imposed across much of North Africa (Figure-2.5). This structural trend influenced the depositional pattern of the Paleozoic successions during the Cambrian, Ordovician and Early Silurian sequences towards the NW. The major NNW-SSE trending structures dominated the Early Palaeozoic evolution of eastern Algeria and western Libya seem to have been initiated as horsts in the late Cambrian (Klitzsch and Ziegert, 2000) and subsequently formed the weaker zones of later "Caledonian" uplifts in the middle Devonian.

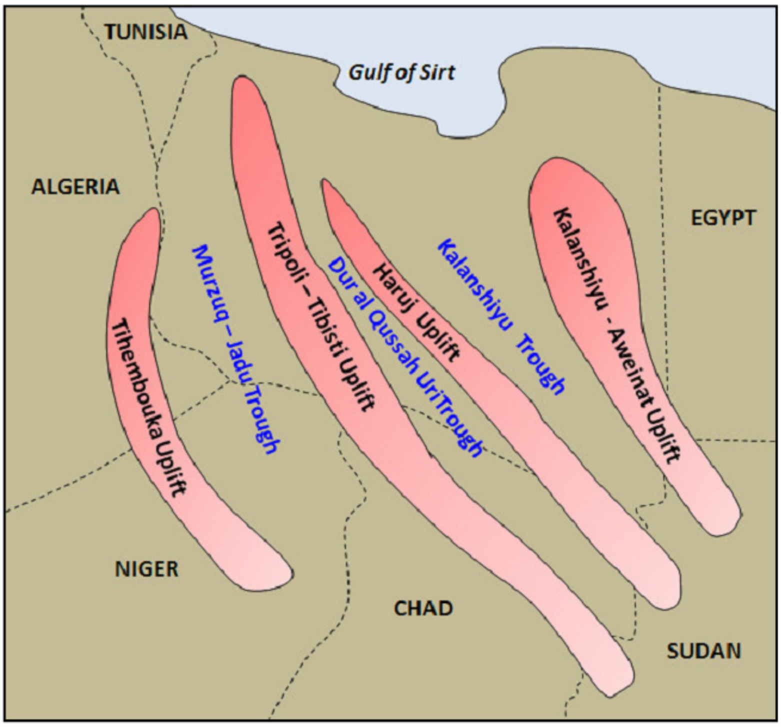


Figure-2.5: Post Pan-African Structural Trends in Libya (Early Paleozoic). After Klitzsch (1971).

Pan-African tectonism welded together the cratonic blocks of Africa **as** they are known today with remobilized belts separating the cratonic nuclei. Following the de-coupling of Laurentia from Pannotia Libya was located on the passive margin of West Gondwana. The final phase of the Pan-African orogeny in the Cambrian produced a series of north-south to northwest-southeast uplifts and troughs which controlled sedimentation in the early Palaeozoic.

Instability during the Early Ordovician is indicated by the absence of Cambrian strata over several main Paleozoic uplifts in central North Africa. An indication is located locally by development of an angular unconformity between the Cambrian and Ordovician successions in the outcrops as in Jabal Dur al Qussah at the eastern margin of the Murzuq Basin (Figure-2.6). This unconformity related to the Late Cambrian compression in the basin. During the Middle to Late Ordovician, separation of Avalonia and Armorica from Gondwana (Figure-2.7) was occurred. This separation initiated intensive extension of the northern margin of Gondwana was accompanied by basaltic volcanism and a northward tilting of the Saharan Platform (Beuf *et al*., 1971).

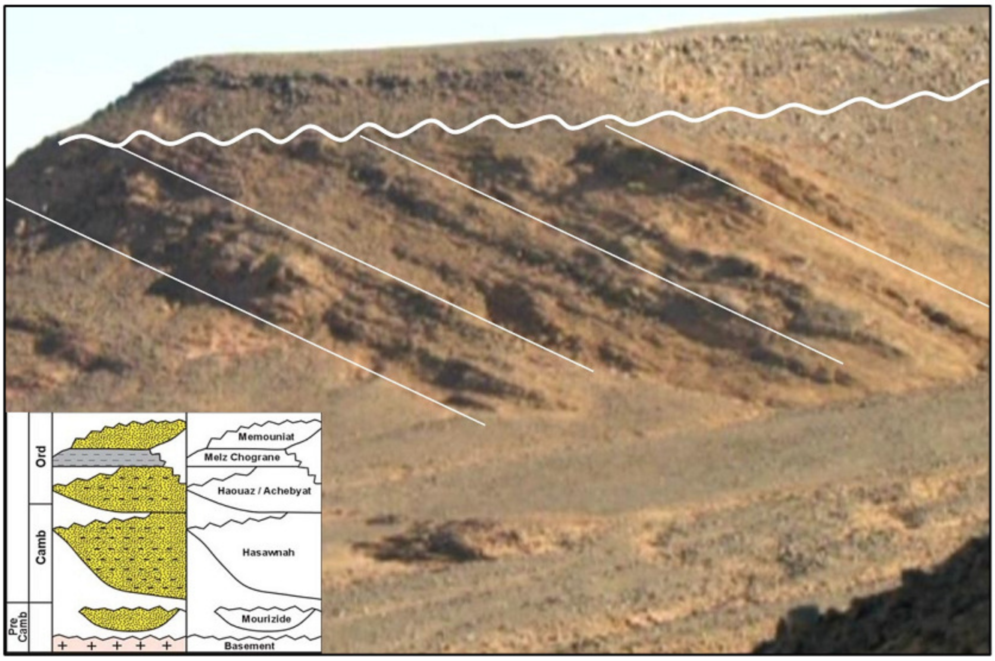


Figure-2.6: An angular unconformity between the Cambrian and Ordovician Successions in Jabal Dur Al Qussah at the Eastern margins of Murzuq Basin. After Klitzsch (1971).

During the Late Ordovician, Murzuq Basin was located on the southern pole ~ 60° S and glacial processes were dominated (Figuer-2.7). A widespread 'Taconic' polygenetic unconformity surface developed in Late Ordovician as a result of the combined effects of the glacially induced sea level fall and of subglacial erosion (Craig *et al*., 2006). However, this unconformity locally cuts down through older Ordovician and Cambrian strata as observed in the seismic data (Figure-2.8).

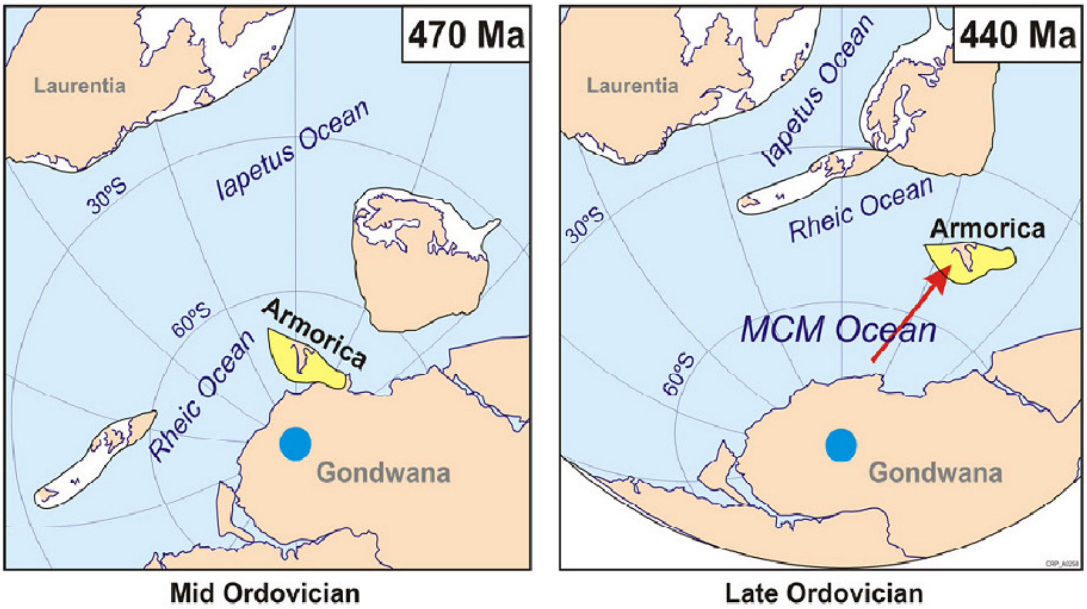


Figure-2.7: The separation of the Armonica from northern Gondwana generated the major extension phase at the Middle to Late Ordovician. Source: Craig et. al., (2006)

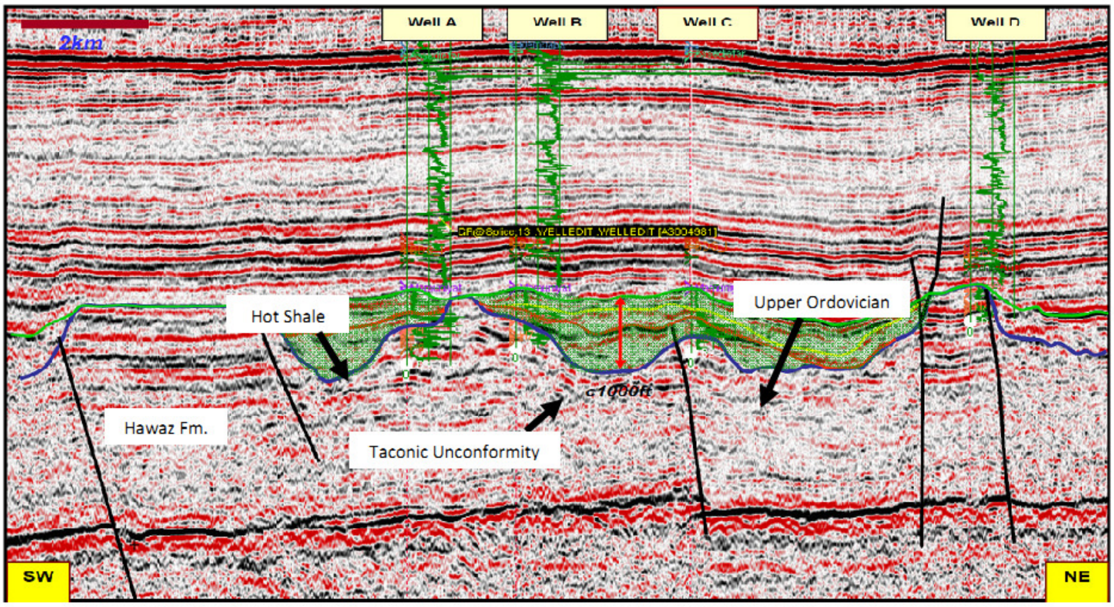
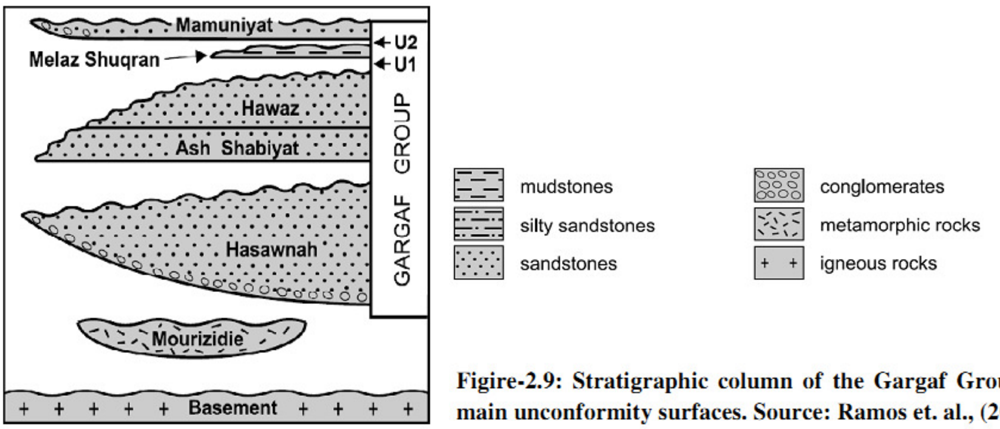


Figure-2.8: Seismic section southern of the concession NC186 shows the huge paleovalleys crossing the area towards the Concession NC186 with width of 2 to 8 km. These paleovalleys have the same trend of the basement faults NW-SE, while mainly these basement faults are rejuvenated. Taconic unconformity is cutting down to the Cambrian which is considered as Caradocian to Ashgillian Late Ordovician in age. Source McDougall et. al., 2008.

The Avalonian and Cadomian Provinces broke away during the Ordovician and drifted northwards and collided with Laurentia and Baltica respectively, resulting in the Caledonian orogeny, which did not directly affect Gondwana (Hallet, 2002). However, the term "*Caledonian Orogeny*" has one of the main contradictions in many literatures in the structural history of Libya. Craig *et. al.,* (2006) wrote; *"many authors refer to the Late Silurian – Early Devonian compressional phase in North Africa as the 'Caledonian Orogeny' while Gondwana was located thousands of kilometres to the south at this time and was separated from the collisional zone by a major ocean (Stampfi and Borel, 2002)"*. Tectonic events in North Africa during post-Infracambrian to pre-Hercynian times were independent of those in the collision zone to the north and the term 'Caledonian Orogeny' is inappropriate in North Africa (Jackson, 1997). Time-descriptive terms may be preferred instead. Consequently, in this project, timing was selected to avoid contradiction as "Middle Devonian Compression".

Stratigraphically, the lower Paleozoic rocks in Murzuq Basin are represented by the Gargaf Group. From the base to the top the Gargaf group (Figure-2.9) consists of five formations, these are: *Hasawnah, Ash Shabiyat, Hawaz, Melaz Shuqran and Mamuniyat*. All of these formations have been established by Massa and Collomb (1960). All boundaries between these formations are unconformable apart from the one between Ash Shabiyat and Hawaz Formations.



Figire-2.9: Stratigraphic column of the Gargaf Group and the main unconformity surfaces. Source: Ramos et. al., (2006)

2.1.3. Middle Paleozoic (Silurian & Devonian)

The Silurian to Devonian stage represents a significant tectonic phase in Murzuq Basn. Change from extensional to compressional regimes within Murzuq Basin occurred during this stage. These changes took place by the drifting of terrans from north Gondwana and collision between Gondwana and Laurasia that persisted till Jurassic. The earliest Silurian relief may have been controlled, at least in parts, by the Cambro-Ordovician tectonic movements, in combination with Late Ordovician glacial and post-glacial processes. The western part of Murzuq Basin was especially underwent a significant subsidence during the Early Silurian, whereas the central part of the basin was positive feature at that time. Thick black shales were deposited following the ice melting which form the major source rocks for the Paleozoic oil accumulations of North Africa.

During the Middle to Late Devonian, the northwestern margin of Gondwana collided with Laurasia and the effects of the collision became progressively evident throughout North Africa. During Middle to Late Devonian; continental conditions were established, extensive erosion took place, and the North African platform was deformed into a series of swells and sags extending from Morocco to western Egypt (Hallet, 2002). In Libya, the *Nafusah Uplift*, *Gargaf Arch*, *Sirt Arch*, *Ennedi-A1 Awaynat Uplift* and their associated troughs were formed which are trending NE-SW (Figure-2.10). The superimposition of the Hercynian trend over the Lower Palaeozoic trend led to the separation of the Ghadamis from the Murzuq Basin.

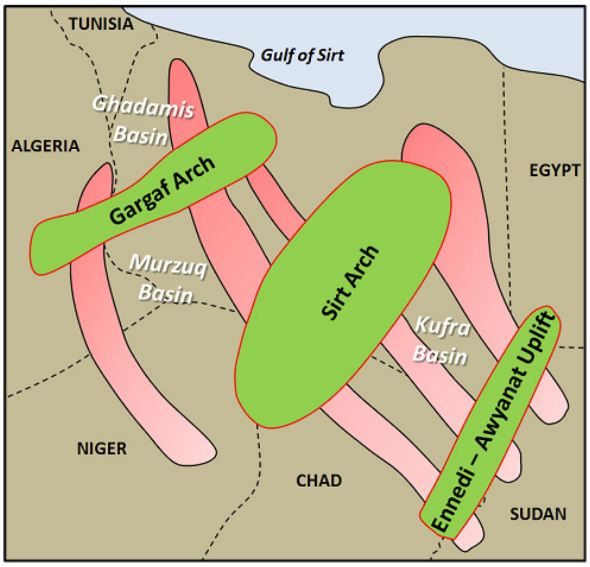


Figure-2.10: Middle to Late Devonian structural elements. After Klitzsch (1971).

Middle to Late Devonian compressional episode persisted to Carboniferous as result of collision between Gondwana and Lurasia. Basin configuration and isolation is started within this stage and totally separated at the Paleozoic-Mesozoic contact.

The timing of the compressional episode at the Middle Devonian is known in some literatures as "Mid Devonian Inversion". The passive continental margin of the early Paleozoic was replaced during the Devonian by a sheared margin, reflecting the first episode of the *Hercynian Orogeny* (Hallet, 2000).

In Murzuq Basin, the Hercynian Orogeny was mainly characterized by major strike slip rejuvenations of older faults. The fault kinematics during the Silurian to Devonian was subjected to numerous compressional/transpressional forces along the basement faults. These are identified from the seismic data in Murzuq Basin as reverse faults with positive flower structures (Figure-2.11).

Stratigraphically, the Silurian and Devonian are generally the thickest Paleozoic accumulation in Murzuq Basin. However, six clastic formations were deposited these are; *Tanzuft*, *Akakus*, *Tadrart*, *Wan Kasa*, *Awaynat Wanin* and *Tahara*.

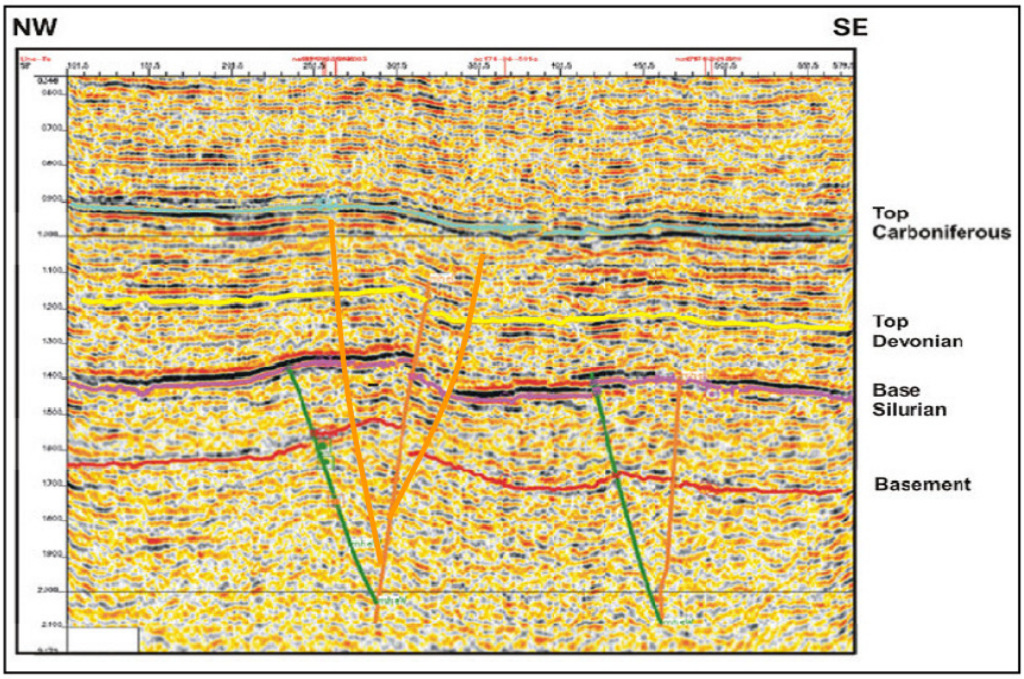


Figure-2.11: Surface seismic line in Murzuq Basin, Concession NC174, indicates the Silurian-Devonian transpression growth fault within Positive flower structure. It is clear that these are rejuvenated basement faults. Source; Craig et. al., (2006).

2.1.4. Late Paleozoic (Carboniferous & Permian)

The Middle Devonian compressional event was persisted to the end of the Jurassic with differential forces and reach it is peak within the Permian (i.e. Hercynian Orogeny). In Murzuq Basin, development of positive features such as Gargaf Arch was a key for separating the Murzuq from Ghadamis Basin to the north and changing of the depocenter of Murzuq Basin to Idhan depression. In addition, the collision involved significant strike-slip movements and a major dextral shear-zone developed along the line of contact.

In Murzuq Basin, major NE-SW en echelon folds along with NNE-SSW trending wrench faults. These faults indicate stage of transpresional tectonism during the Middle Carboniferous on the Tiririne High such as the Birtazit wrench faults. It is proposed by Craig *et. al.,* (2006) that across-fault thickness changes of the Carboniferous sequences identified in the Murzuq Basin of western Libya are caused by strike slip faulting. However, structural kinematic analyses and seismic interpretation undertaken in the Murzuq Basin of Libya indicate a *Hercynian transpressional* origin for the structure of the giant 'Elephant' oil field, Concession NC174 (Glover, 1999). Stratigraphically, at the end of the Paleozoic time Marar, Assedjefar, Dimbabah & Tiguentourine Formations were deposited.

2.1.5. Mesozoic (Triassic, Jurassic and Cretaceous)

Following the Hercynian uplifts, Gargaf Arch played an important role separating the Ghadames and Murzuq basins and became a barrier for the marine transgressions from the north. Consequently, deposition in the Murzuq Basin to the south of the arch was entirely continental in character from Permian to Early Cretaceous times. During the Early Triassic rifting and volcanic activity throughout the Saharan Platform were dominant.

NW-SE striking faults in Murzuq Basin underwent sinistral transpressional reactivation at the Late Cretaceous (Glover, 1999). The fault bounding the F-field (Elephant structure) in the northern Murzuq Basin has a significant component of Alpine movement, as indicated by folding of the youngest Lower Cretaceous reflectors. At the Middle Cretaceous, major compressional episode (Aptian compression) caused a rejuvenation of the North-south trending Pan African faults, with the Hassi Touareg Horst, the Tihemboka Arch and the Hassi Messaoud ridge all undergoing significant uplift. Collision between the African and European Plates occurred at the Late Cretaceous – Tertiary stage which is known as "Alpine Orogeny". In Murzuq Basin, nearby the area of the present study a cretaceous escarpment of Messak sandstone formation is exposed as a result of post Cretaceous uplifting.

In the Triassic and Jurassic, marine rocks, deposited on the southern margin of the Tethys Ocean during the breakup of Pangea. These deposits are largely confined to the northern areas of Libya, whilst the interior is dominated by continental rocks, which form part of the "Continental Post-Tassilien sequence". In the Murzuq Basin the "Continental Post-Tassilien sequence" has been subdivided into three formations: the Tiguentourine Formation (mentioned previously) of the late Carboniferous-Early Permian age, the Zarzaitine Formation of Triassic age, and the Taouratine Formation of Jurassic age (Kilian, 1931). Continental conditions dominated the interior of Libya from the Permian to the mid- Cretaceous age in Murzuq Basin are missing and only Messak Formation of Cretaceous age was deposited.

2.1.6. Cenozoic (Tertiary & Present)

During the Early Cenozoic (Paleocene & Eocene), Alpine Orogeny that persisted from Cretaceous was well developed in the mid of the Eocene. At this time, shortening and inversion of many of the basin in Libya was established. Most of these compressional movements are of strike slip (transpressional) taking over the weak zones of the older faults. The final rift phase affected North Africa area during the Oligocene-Miocene time. Intense volcanic activity accompanied rifting in the central and eastern parts of North Africa such as Jabel Haruj in central Libya and Tibesti volcanoes in southern Libya and northeast Chad. Only quaternary lose sandstone sediments are despited with the basin at the present day and covering large areas.

The present day stress field over onshore of the North Africa is dominated by E-W compression associated with "ridge-push' from the Atlantic and Indian Oceans. In Murzuq Basin, the present day stress is mainly trending towards the NW-SE direction. This section was carried out in more details using FMI data in analyzing the present day stress (section-6.9, page-94).

2.2. Main Structural Elements in Murzuq Basin (Present Day)

The main structural elements in Murzuq Basin were gathered by Fürst and Klitzsch (1963) as *Tiririne High* separating *Al Awaynat* and *Awbari* troughs and *Traghan High* (Also named in this chapter by Barak Ben Ghanimah Arch of Klitzsch, 1963) between *Awbari* and *Dor Al Qussah* troughs (Figure-2.12).

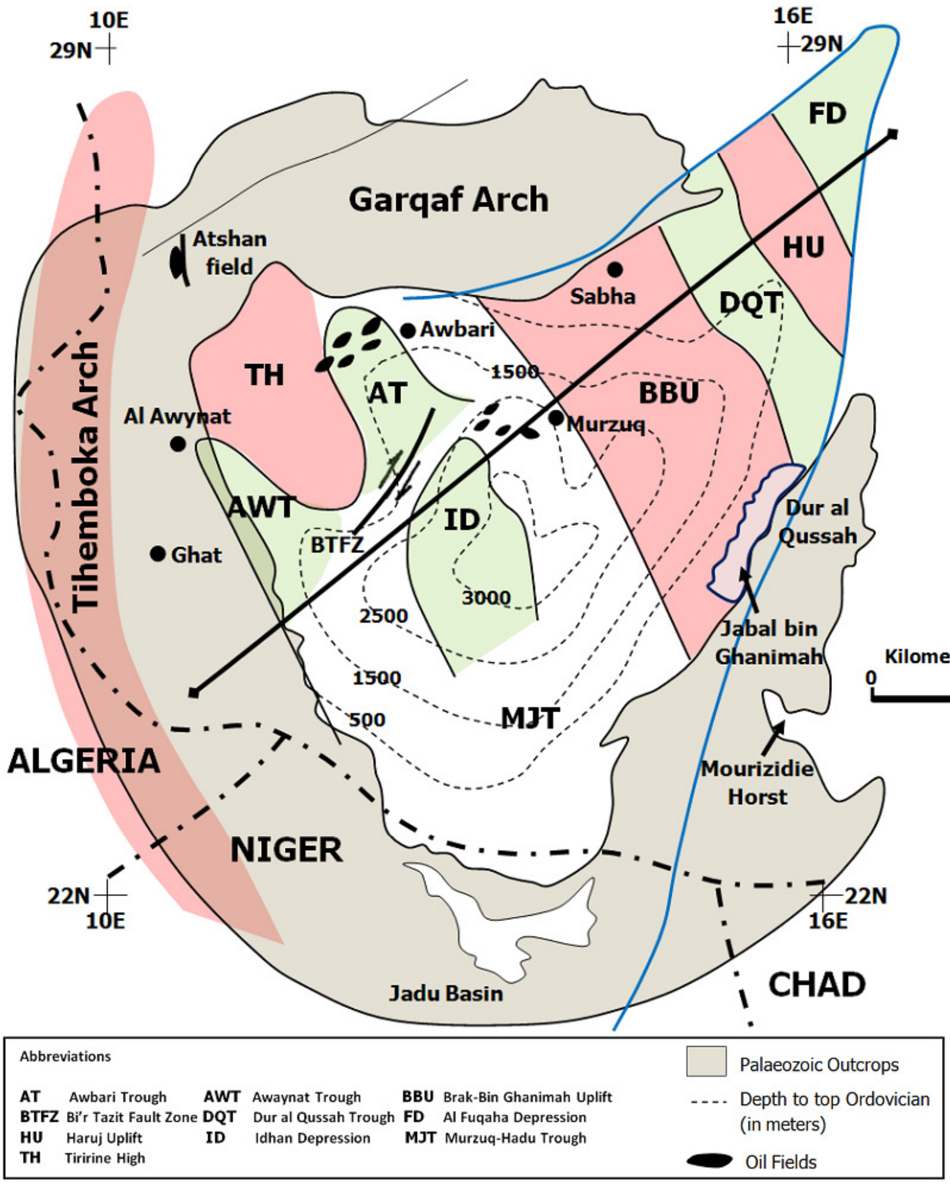


Figure-2.12: Shows the main structural elements in Murzuq Basin. SW-NE cross section, see figure-2.13. Highs are coded with red color. Source: Klitzsch, (1966), Contours modified from Echikh and Sola, (2000).

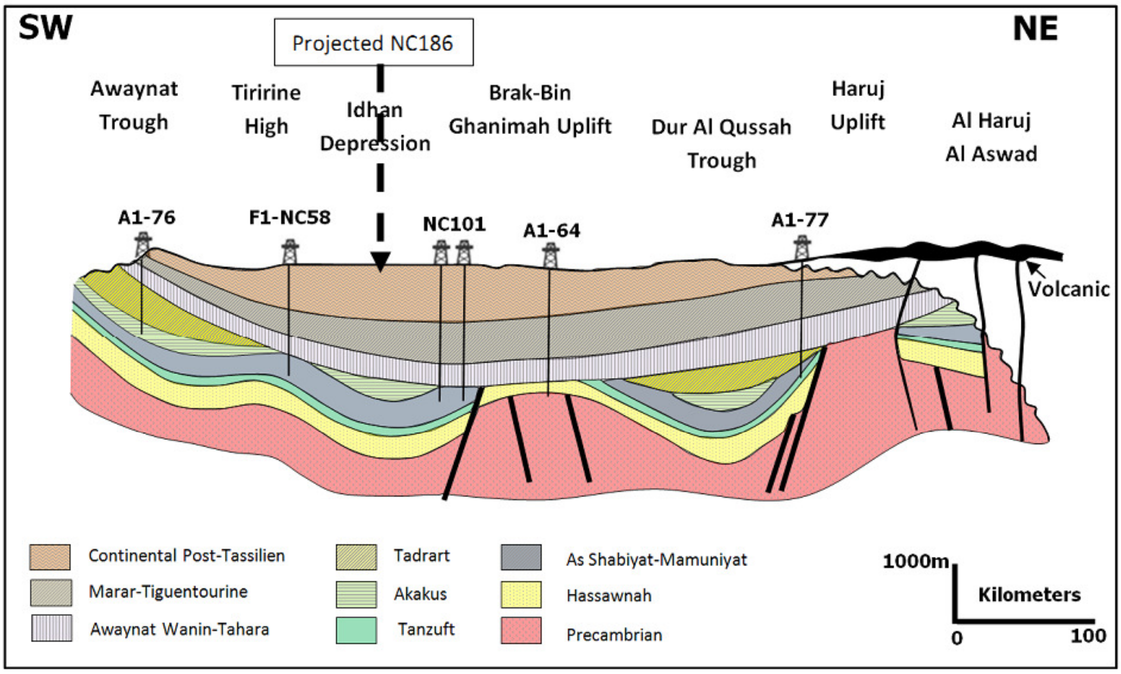


Figure-2.13: Cross section crossing the main structural elements in Murzuq Basin. Source: Klitzsch, (1971), Pierobon, (1991), Echikh, (2000) and Sutcliffe et.al, (2000).

The present day configuration of Murzuq Basin did not develop until the end of Mesozoic and prior to that the Paleozoic the basin was mainly comprised of a serious of NW-SE directed horsts and grabens (Klitzsch, 1963). The most important structural elements of the present study are Tiririne High, Awbari trough and Traghan High since they are confining the present area of study. The major oil discoveries in the basin are within Awbari trough as well as the area of the present study.

2.2.1. Tihemboka Arch

Tihemboka Arch is one of the oldest features in Murzuq Basin that located at its western margine. This features has been a positive feature since early Palaeozoic times (Figures-2.12&2.13) during the shearing between the West African and East Sahara cratons. It has affected the sedimentation throughout the Palaeozoic and has been intermittently reactivated since then. By uplift during the Devonian shifted the main depocentre of the Murzuq Basin from the Al Awaynat Trough to the Idhan Depression, and reactivation during the Hercynian Orogeny separated the Murzuq Basin from the Illizi Basin.

2.2.2. Awaynat Trough

In the area east of Al Awaynat a narrow trough is preserved in the re-entrant between the Tihemboka Arch and the Tiririne High. It contains a significant Lower Devonian section which is not present on the Tiririne High to the east. Southwards it passes into the Idhan Depression, and to the north it is cut by the "*Tumarolin wrench fault*". The Awbari trough is separated from the Idhan Depresssin with major fault known as "*Bi'r Tazit Fault Zone*" (Fgiure-2.12).

2.2.3. Tiririne High

The Tiririne high is considered as the most intensely affected structural element in Murzuq basin with large scale rejuvenated basement faults, in other words, wrench faults (Figure-2.13). The Tiririne high is defined as an asymmetrical NW-SE trending structure that is down-faulted to the West parallel to Tihemboka Arch. However, there is a remarkable change in faults from the northwestern part of the high to its southeastern part. This change is represented by change in the faults geometry and kinematic from dextral to sinsitral strike slip faulting from the NW to the SE parts of the Tiririne High respectively (Figure-2.14).

Only the northwestern part is confined by regional wrench fault called "*Tumarolin Fault*" that is trending NNE-SSW of right-lateral displacement while left-lateral displacement at its southeastern part (Echikh and Sola, 2000). Many operating companies have mapped many surface normal faults those are trending NW-SE in the center of the Tiririne high such as Haghe and Geramna structures. However, seismic surveys in the area show also reverse-faulted structures (Figure-2.15B). In the central part of the Tiririne high, shifting of the structural crests positions and absence of oblique en echelon fold pattern suggest the absence of wrench faulting in this part. In this part, possible purely compressional movements have taken place between the northern and southern parts of the high.

In summary, a right lateral displacement (dextral) of 10 km at Cambro-Ordovician level is recorded in Atshan area (NW of Tiririne High). While a left lateral displacement (sinistral) trending NNE-SSW of Hercynian compression reactivated the southern part of the Tiririne High. Therefore, the southeastern part of the Tiririne High is the most affected by the Hercynian compression while the middle part is purely compression of transitional zone to the northwestern part which is Cambro-Orodovician features.

2.2.4. Awbari Trough

The Concession NC186, present area of study, is located on the main axis of the Awbari Trough (Figure-1.16) in the northern part of Murzuq Basin. However, the area between the Tirirene High and the Brak Bin Ghanimah Uplift is occupied by the Awbari Trough. The major oilfields in Murzuq Basin are located in this trough (e.g. NC186, NC 115 and NC 174). In the eastern part of the trough reverse faults with a northwest orientation perhaps represent *reactivation of "Pan-African fault zones"* (Hallet, 2002). These reactivation processes in Awbari trough will be examined in details in local prospect within the H and I fields, Concession NC186. The Ordovician sequence thins on the up thrown side of the reverse faults and in many cases roll-over is present on the overriding fault block. The trough subsided during the mid-Devonian, and formed the main axis of the basin during the later Paleozoic.

2.2.5. Barak Ben Ganimah Uplift (Traghan High)

The Brak-Bin Ghanimah Uplift, known also as the Traghan High, forms part of the Tripoli-Tibisti Uplift of Klitzsch. This feature originated during the extension of the early Palaeozoic and remained active until the mid-Devonian. The uplift subsequently became inactive and thereafter the area formed part of the greater Murzuq Basin. This high is affected by several fault-sets (Echikh and Sola, 2000); these dip westwards with trends changing from NW-SE to NE-SW in its northern parts.

2.2.6. Idhan Depression

The Idhan Depression marks the main depocentre of the basin from mid-Devonian times when it subsided rapidly. It is separated from the Awbari Trough only by the disturbed zone of the Bi'r Tazit wrench fault (Figures-2.12 & 2.13).

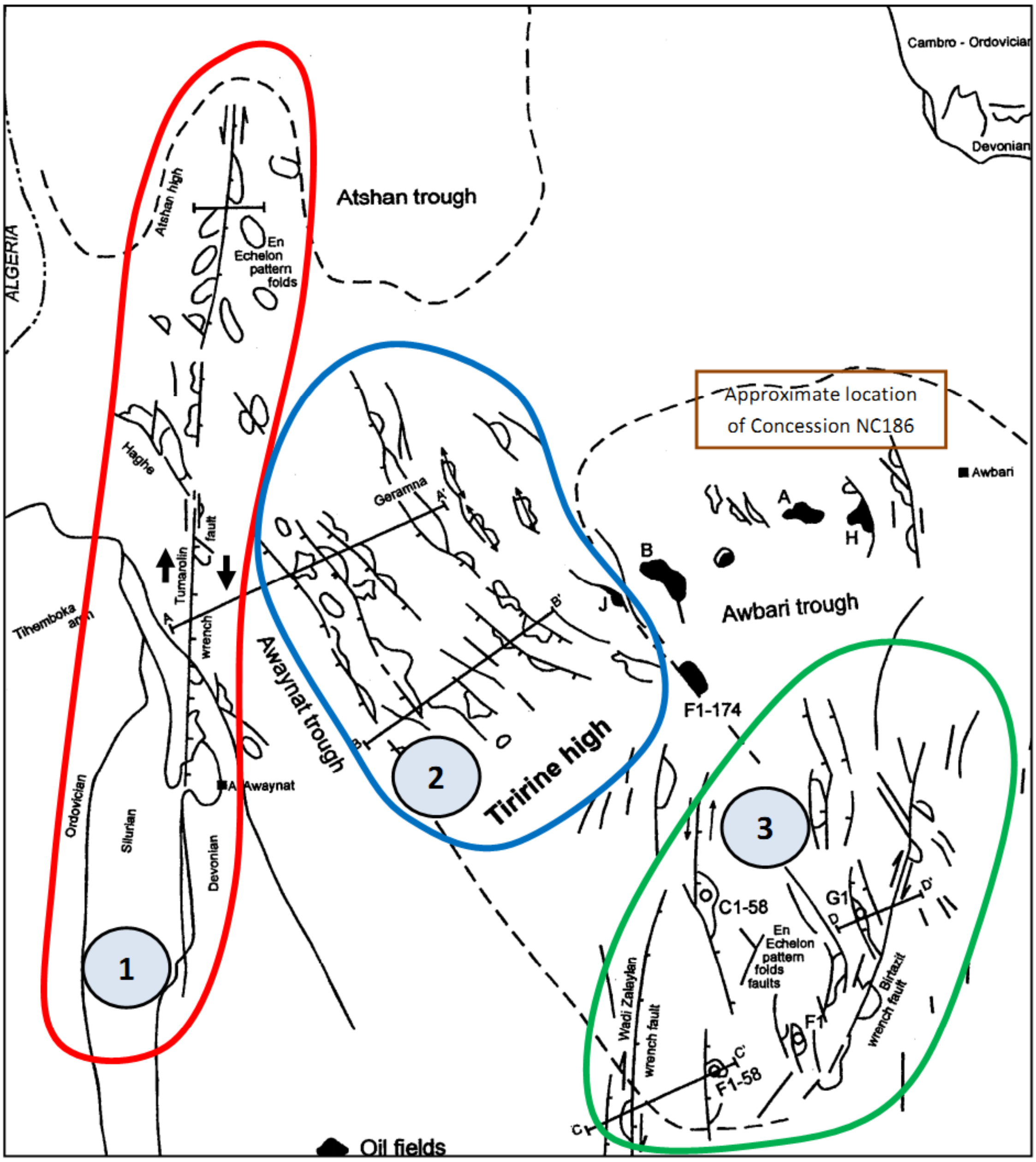


Figure-2.14: (A) Structural configuration of the NW part of Murzuq Basin. The structural and fault styles changes from NW to SE parts of the Tiririne high (1, 2 &3). Cross sections taken cross the high (see Figure-2.15). Sources: Echikh and Sola, (2000).

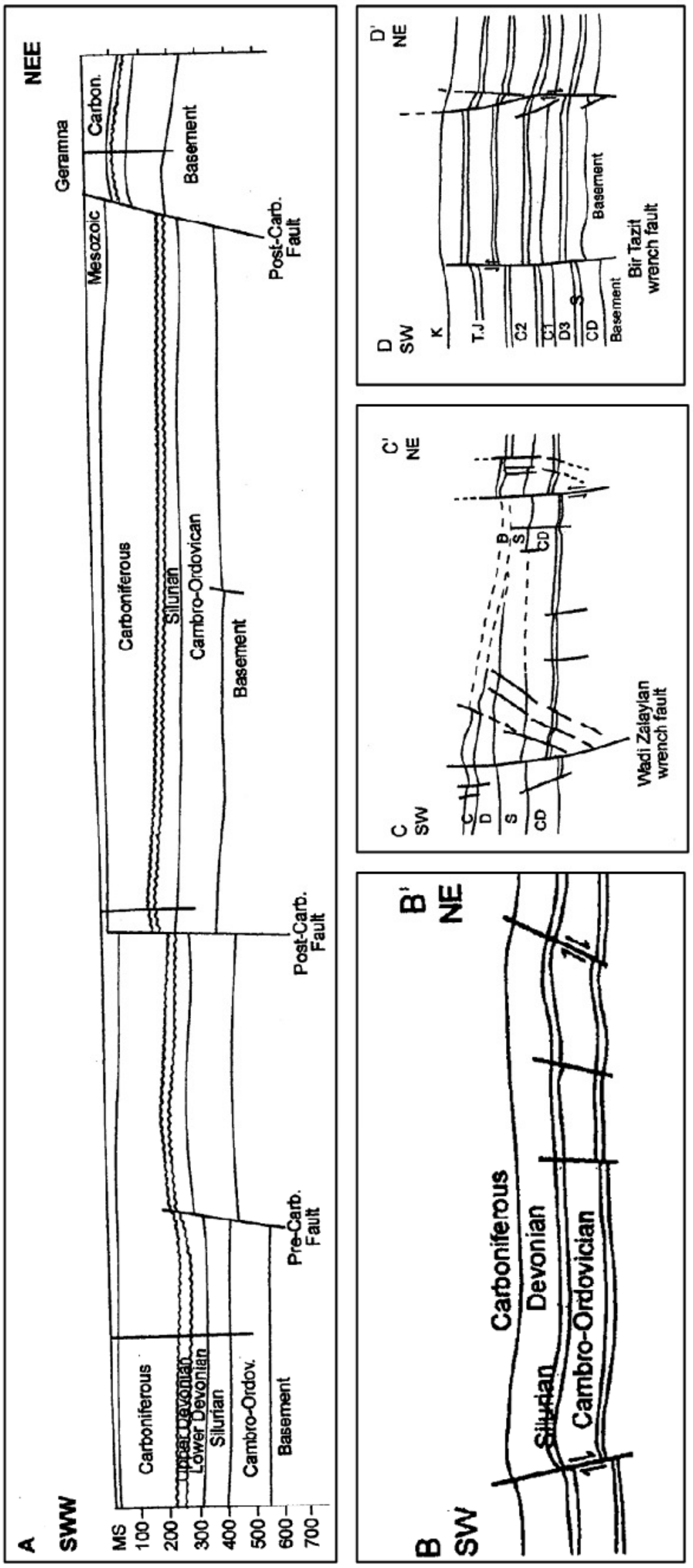


Figure-2.15: Structural styles over the Tiririne High, cross sections shown in Figure-1.16. A-A': Geoseismic profile showing different fault ages. B-B': Geoseismic profile through the central part of the Tiririne High showing reverse faults. C-C' and D-D': Geoseismic profile showing the southern part of the Tiririne High with indication of wrench faulting.

2.2.7. Dur Al Qussah Trough

As originally defined by Klitzsch; the Dur al Qussah Trough forms a counterpart to the adjacent Tripoli-Tibisti Uplift. It trends northwest-southeast and was active during the early Palaeozoic when thick sequences of Cambro-Ordovician, Silurian and Lower Devonian rocks were deposited. Like the Brak-Bin Ghanimah Uplift it became inactive following the mid-Devonian tectonism and became part of the greater Murzuq Basin during late Devonian and Carboniferous times. Numerous northeast-southwest oriented structures are present in this area, affected by a group of wrench faults visible on the Devonian outcrops (Echikh and Sola, 2000). The most prominent feature of the southern part of the Murzuq Basin is the *Mouride Fault* with a throw of 1000 m (Thompson, 1960), dipping westward along a 70 km trace and juxtaposition the Devonian with the Cambro-Ordovician succession. Further to the south, in Jabal Al-Marokma, the Paelozoiz rocks are intensively affected by a series of NE-SW trending faults. Westward of this area a number of folds is aligned ENE-WSW, the most prominent of these being the 60 km long Tumu anticline.

CHAPTER THREE

METHODOLOY & INTERPRETATION TECHNIQUES

3.1. Introduction

Implemented methodology and specific techniques were used in this study to reveal high resolution subsurface structural interpretation. Dataset available in this project is covering both large and small scale structural and stratigraphic features for better evaluation and interpretation of both H and I Fields. Petrel* and GeoFrame* were used mainly to interpret the surface seismic data and the FMI* images respectively. This chapter is divided into three main sections as follow:

1- *Dataset of the present study,*
2- *Project Data Management (Workflow),and*
3- *Softwares and interpretation techniques.*

3.2. Available Dataset

Dataset has been requested and released from REMSA Company and NOC (National Oil Corporation) as follow:

1- Surface seismic data cross five wells in the H and I field, Concession NC186 (Figure-3.1).
2- Formation tops (Table-3.1).
3- FMI data in the wells H1, H3, I1, I2, and I3.
4- Open hole logs in the previously mentioned wells.
5- Core images in the wells I1 and I3.

Other dataset was also available such as surface maps of the area and satellite images those were utilized within the current study. The methods and techniques used to refine the structural evolution of the H and I fields are believed to be covering various structural scales. Seismic data was used mainly to analyze large scale structural and stratigraphic features such as; faults and paleotopographic variations. While the FMI images (Schlumberger, 2004) were used mainly to interpret the small scale structural and stratigraphic features such as; fractures and sedimentary structures.

*Trade mark of Schlumberger Oilfield Services Company.

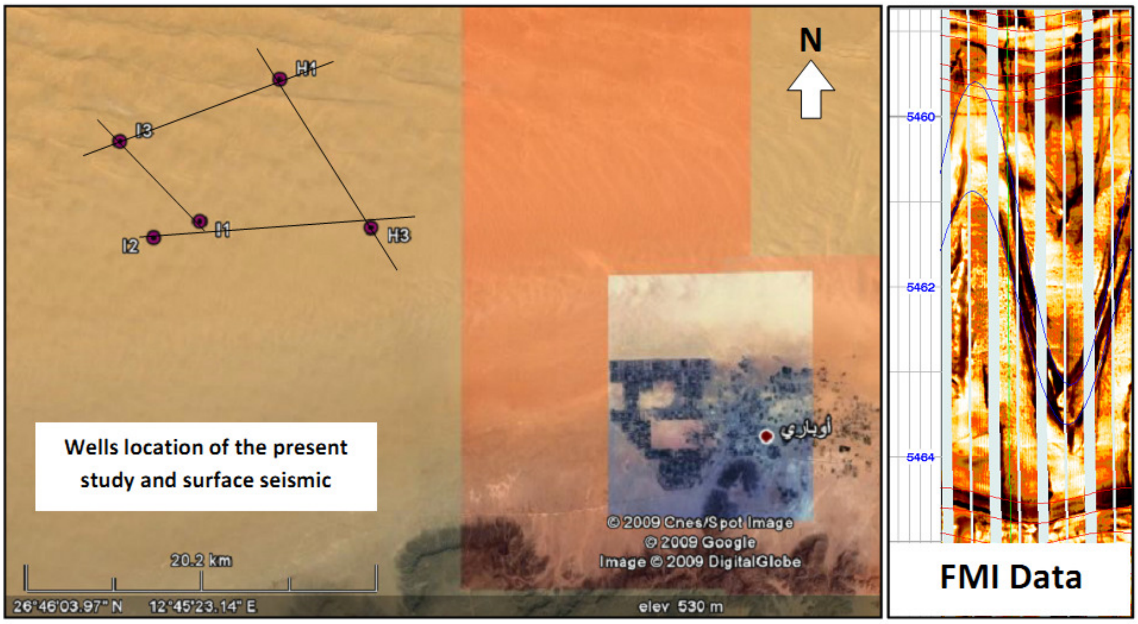


Figure-3.1: Location of the five released wells of the present study and an example of FMI image.

Age		Formation/ Member		Depth (MD_feet) from KB					
				I Field			H Field		
				I1	I2	I3	H1	H3
Carboniferous	Up	Tiguentourine	Covered with 2D & 3D Seismic Data and Open Hole Logs		635	722	429	441	861
		Dembaba			1594	1718	1385	1558	2008
		Assedjefar			1698	1824	1504	1639	2085
	Lr	Marar CB			1786	1920	1600	1760	2234
		Marar			1920	2073	1799	1954	2363
		Marar.Lw			2597	2754	2499	2654	3034
Devonian	Up	Awaynat_Wanin			3231	3384	3154	3318	3663
	Lr	BDS_II			3517	3673	3425	3605	3940
		BDS_Sh			3584	3741	3506	3663	4017
		BDS_I			3646	3803	3562	3729	4074
Lower Silurian		Tanezzuft			3762	3908	3690	3848	4203
		Hot Shale			4457	4700	4577	absent	absent
Upper Ordovician		Mamuniyat		Covered with FMI images	4505	4759	4647	absent	absent
		Melaz Shuqran			4693	4881	4801	absent	absent
Middle Ordovician		Hawaz			5400	5628	5235	4361	4611
Lower Ordovician		Ash Shabiyat			5400	5628	5235	4998	5239
Cambrian		Hasawnah			5578	Not Drilled	Not Drilled	Not Drilled	Not Drilled

Table-3.1: Formation tops of the five released wells as provided by REMSA Company.

3.3. Project Data Management (Workflow)

Workflow was developed and implemented to manage the available dataset using Petrel and GeoFrame softwares as well as to be used as guidance for conducting subsurface structural analysis using these softwares (Figure-3.2).

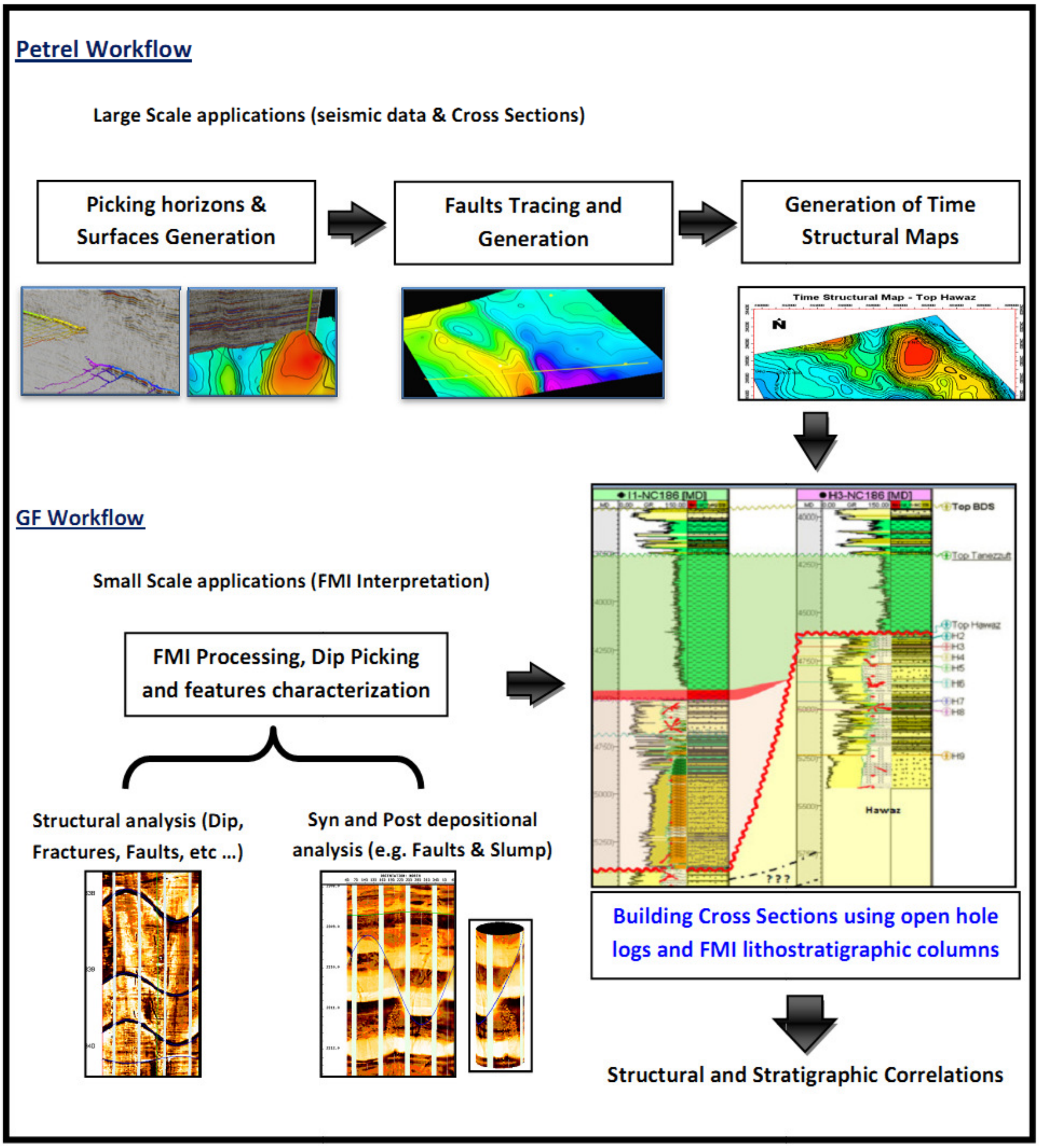


Figure-3.2: Workflow of the present study from seismic to FMI using Petrel and GeoFrame Softwares.

3.4. Softwares & Interpretation Techniques

Two softwares (i.e. Petrel and GeoFrame) were used in this project for the purpose of performing high resolution structural interpretation in the H and I fields, Concession NC186. Both Petrel and GeoFrame are Schlumberger Softwares those designed especially to handle subsurface data (i.e. from seismic to reservoir simulation). However, in this project, the analysis was divided into two sections; petrel used to visualize and analyze surface seismic data and GeoFrame used to process and interprets FMI data. Both softwares were used and integrated for building cross sections. Therefore, simplified outputs from both seismic and FMI data integrated in context of large and small scale of outputs.

3.4.1. Petrel Software

Petrel is software owned by Schlumberger Company and operated by the SIS (Schlumberger Information Solutions) department and considered as one of the major well known softwares in the oil industry. Petrel can handle all the related subsurface data from seismic to simulation that can be operated using Windows/PC.

3.4.1.1. Seismic Interpretation Workflow

This workflow can be illustrated in four main steps (Figure-3.3) as follow:

1. ***Loading and visualization of 3D seismic data into petrel.***
2. ***Picking seismic horizons and surfaces generation.***
3. ***Faults Generation.***
4. ***Generation of time top structural maps.***

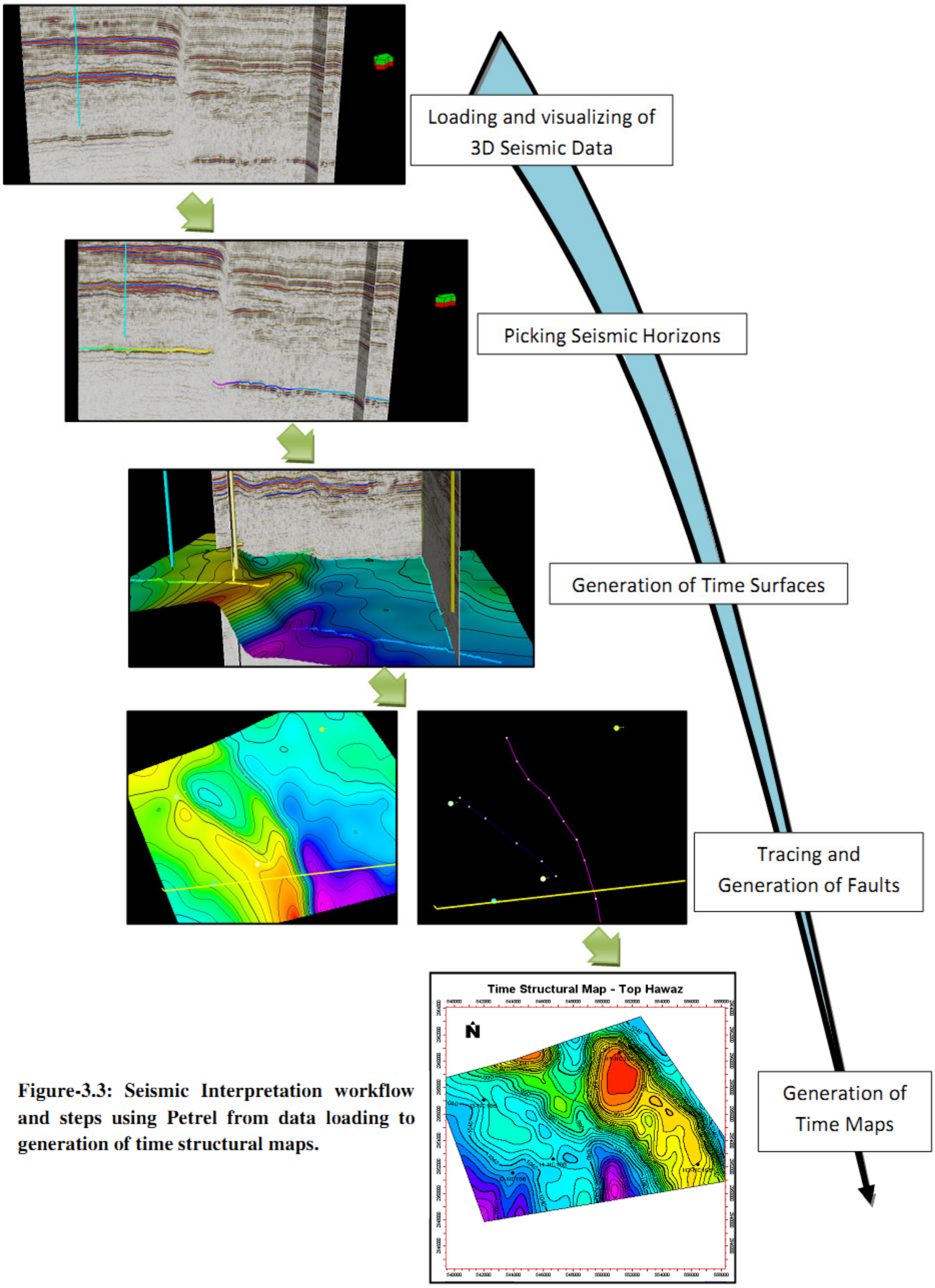


Figure-3.3: Seismic Interpretation workflow and steps using Petrel from data loading to generation of time structural maps.

3.4.1.2. Seismic Terminologies and Interpretation Techniques

Using the seismic data becomes an essential technique in the oil exploration for identification of the subsurface economic targets. Terminologies for seismic interpretation implemented to understand the stratigraphic truncations and terminations. These terminologies such as; Onlap, Downlap, Toplap and Truncation. These treminolgies were mainly used with the stratigraphic terminations in the subject study. An example of these terminologies is the onlap of the upper Ordovician and Silurian deposits on the Paleohighs ridges of the Middle Ordovician deposits (Figure-3.4).

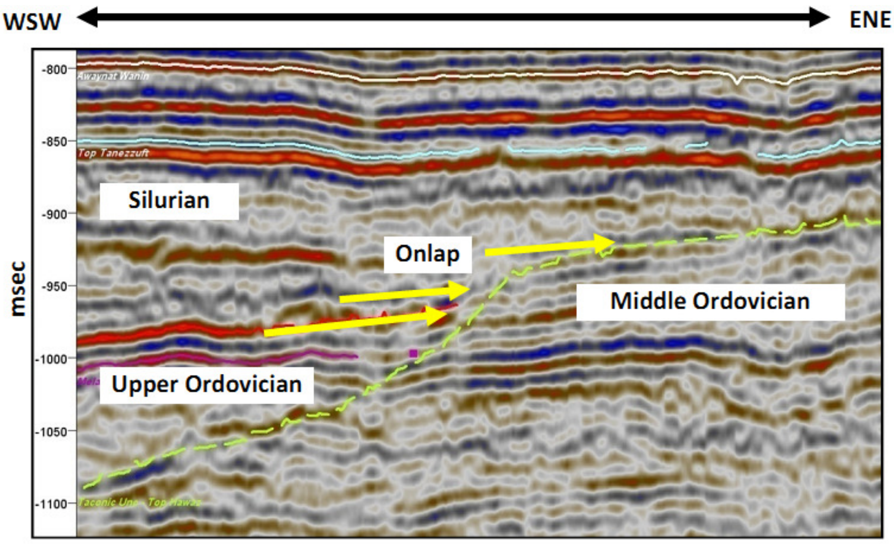


Figure-3.4: An example of onlap truncation of the Upper Ordovician and Silurian deposits on the edges of the Middle Ordovician in the southern part of the study area.

3.4.1.3. Building Cross Sections

Building cross sections for structural and stratigraphic interpretation is one of the main geological applications for correlation between offset wells using seismic data and/or openhole logs. Over the Ordovician successions, different cross section lines were constructed using the available softwares to emphasize the vertical and lateral variations (Figure-3.5).

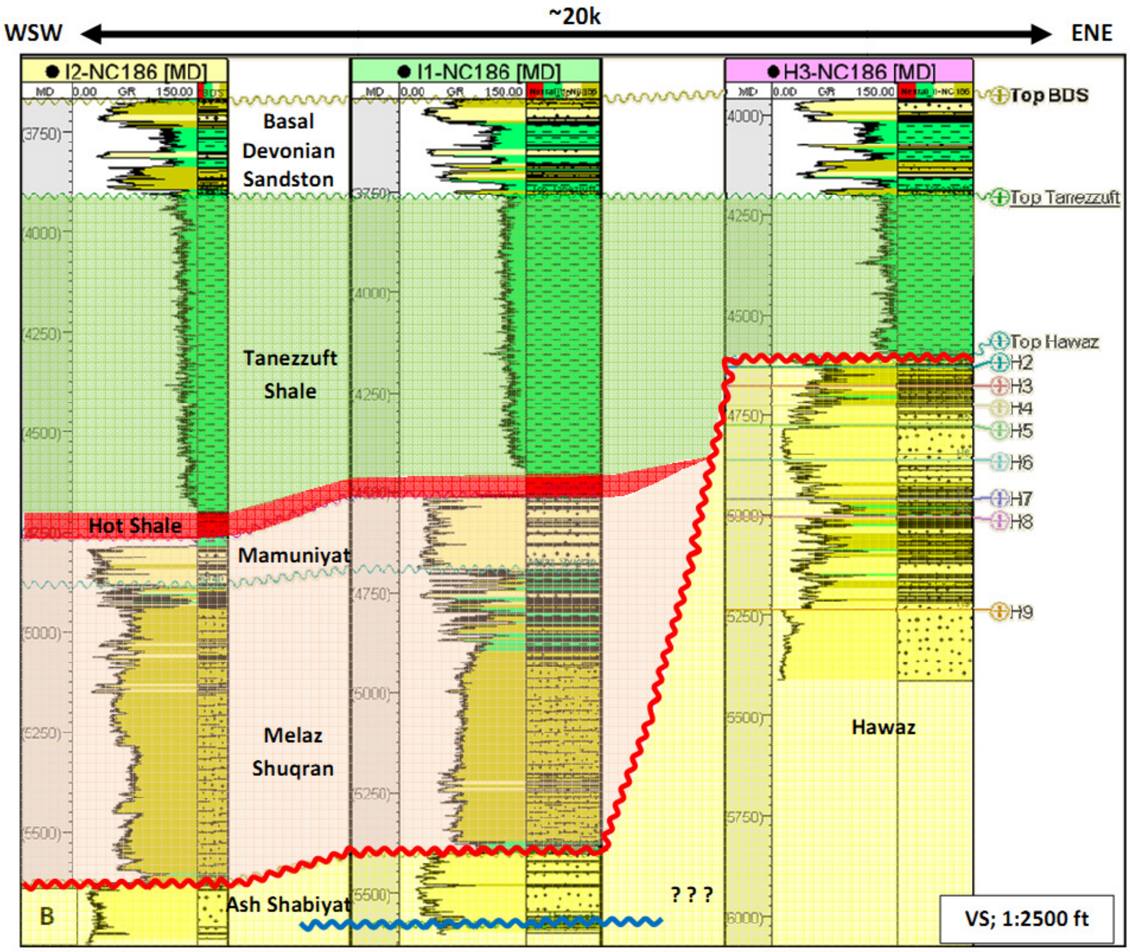


Figure-3.5: Example of stratigraphic cross section between H3-NC186, I1-NC186 and I2-NC186 wells.

3.4.2. GeoFrame Platform

GeoFrame is a Platform contains many types of softwares that mainly deal with the processing and interpretation of the subsurface data including Geophysics, Geology, Reservoir and other applications. In GeoFrame, only processing and interpretation of the FMI* data (see appendix-B) was conducted in this project for full geological interpretation (i.e. Structures, Sedimentology and Stratigraphy).

In this project, FMI is mainly used for interpreting small scale geological features those are beyond the resolution of seismic data. This interpretation is represented by identification of:

1. Structural Dip (magnitude and azimuth) over the logged intervals.
2. Fractures picking and identification into two types namely, conductive and resistive.
3. Sub-seismic faults (known as micro-faults).
4. Present day stress analysis using drilling induced fractures and breakouts as well as using CALIBAN module.
5. Deformation features (slumps, load cast, sand joints, etc …).
6. Sedimentary structures and stratigraphic column.
7. Paleocurrent interpretation over the Ordovician successions.

3.4.2.1. Image Interpretation

After the image generation an interpretation is carried out using BoreView module. ***Borview*** is a GeoFrame module that is included under the interpretation chain of FMI images. It is mainly consists of three sub-modules namely, Image View, StrucView and Stereonet. These three sub-modules are the main interpretation windows where generating of dips, plotting them on stereonets and building cross sections out of them is performed. In the *ImageView* we can display images and other open hole logs. The main usage of Image View is to pick geological features from the images. The dip picking process is mainly done from FMI images (both dynamic and static) using Image View sub-module. However, to pick any feature from FMI, unwrapped and oriented images must be available to plot sinusoid (Figure-3.6). On the other hand, the use of stereonets which including rosettes and histograms give a statistical analysis of the features picked such as fractures, faults, etc.

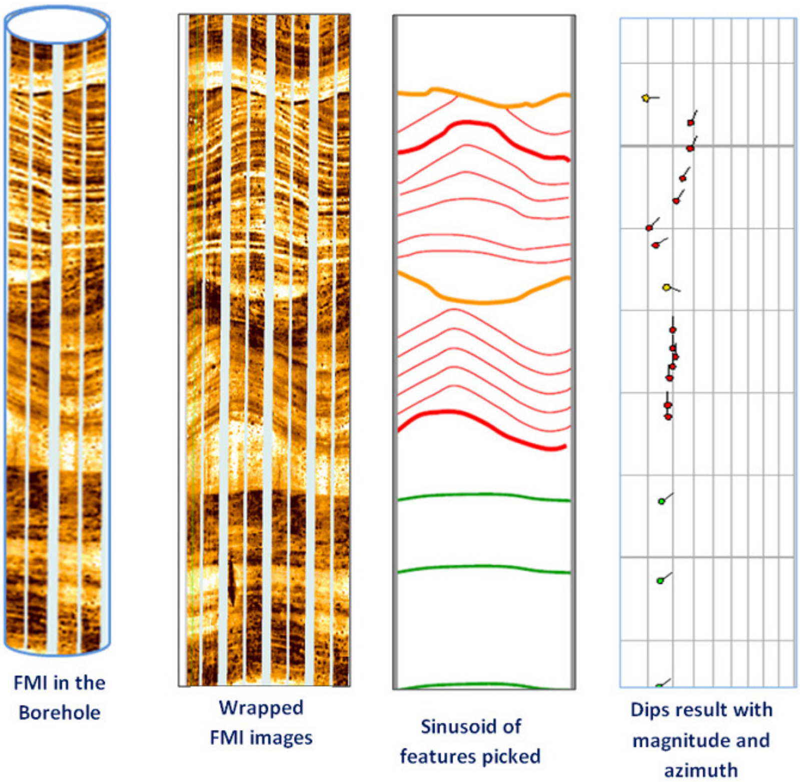


Figure-3.6: Shows example of workflow for features picking from FMI images. To pick features out of the FMI images unwrapped image must be available to pick sinusoid and compute dips.

3.4.2.2. CALIBAN for In Situ Stress Analysis

CALIBAN* module is used for borehole shape analysis using dual caliper tools, such as FMI, in present study. After drilling a well, hydrostatic pressure inside the borehole generated and one of the three principle stress magnitudes is eliminated. Only two principle stresses will remain stressing the borehole called maximum and minimum horizontal stresses (Figure-3.7). These two main horizontal stresses can be used to indicate the *In Situ Stress* direction. According to mud weight used in the borehole, one or two failures will take place either tensile and/or shear which also called *Drilling Induced Fractures* and *Borehole Breakouts* respectively. If the mud weight is low borehole ovalization will take place with shear failure in strike direction of the minimum horizontal stress (i.e. borehole breakouts, see figure-3.8). On contrast, if the mud weight is too high, tensile failure will take place (i.e. drilling induced fractures) parallel to the maximum horizontal stress.

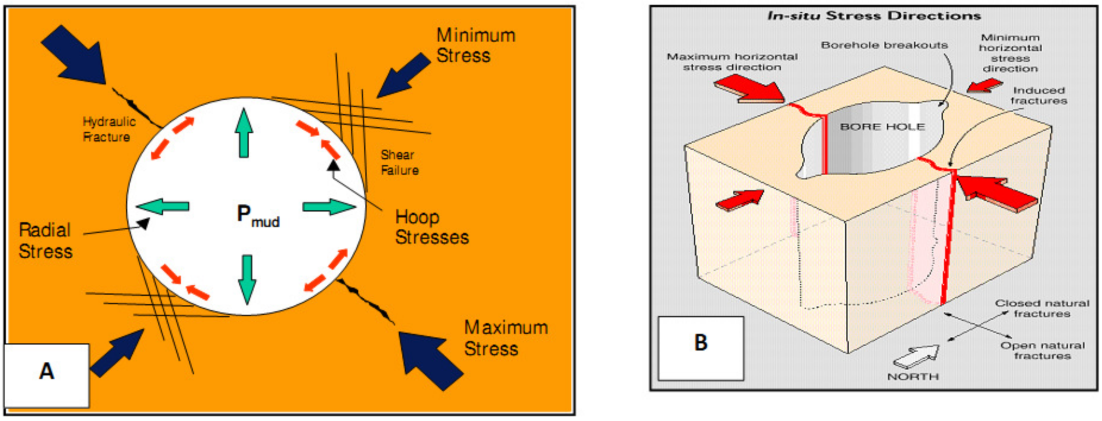


Figure-3.7: Mechanism of Drilling Induced Fractures and Borehole Breakouts generation in the borehole.

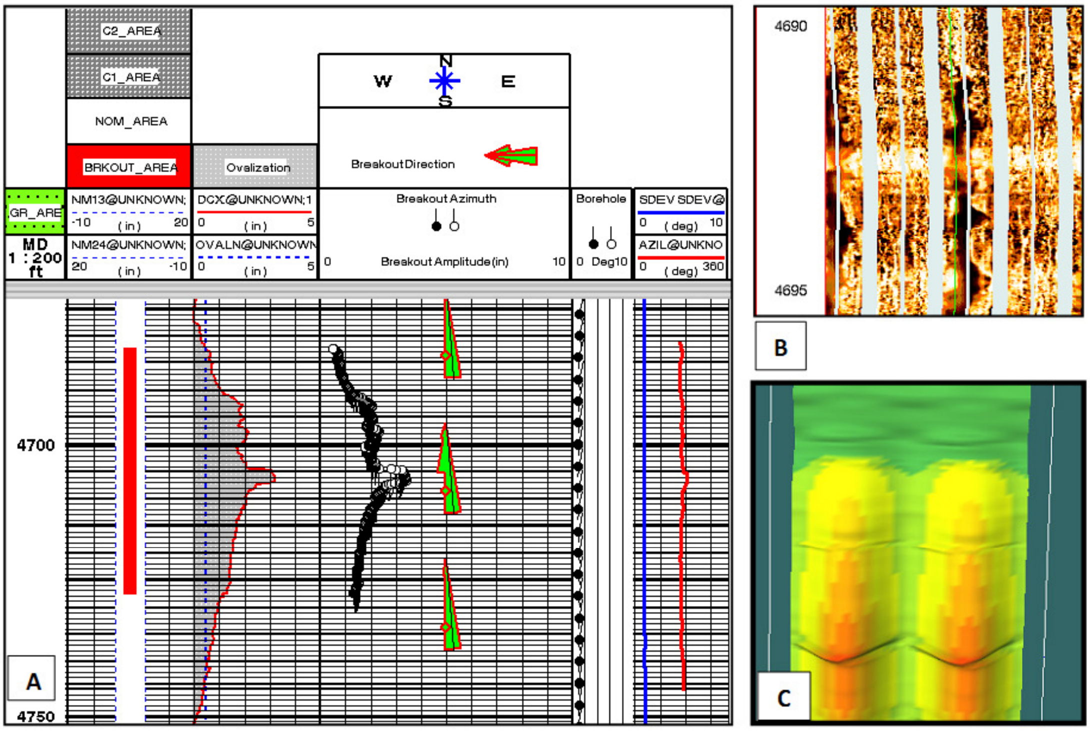


Figure-3.8: (A) Main display of the CALIBAN module shows the ovalization trend of the borehole towards the South (well H1-NC186) which refers to the direction of the minimum horizontal stress. (B) Example of FMI image showing the borehole breakouts. (C) Cross section of the borehole showing the borehole ovalization.

CHAPTER FOUR

STRATIGRAPHYOF H & I FIELDS, CONCESSION NC186

4.1. Introduction

Understanding the stratigraphic succession and distribution of the study area is important for comprehensive evaluation of the tectonic evolution. Defining the stratigraphic distribution at the contact between the Cambrian and Ordovician strata in the study area was difficult due to; 1) Poor surface seismic data quality at the intervals of the Cambrian and Ordovician and 2) The studied wells did not penetrate the Cambrian-Ordovician contacts except in I1-NC186 well. Using enhancement of the seismic data was crucial to define these contacts.

The stratigraphic column of the study area include Basement to Cretaceous deposits and covered with Quaternary lose sand sediments. The stratigraphic record of the study area was constructed using surface seismic and FMI dataset as well as open hole logs. Four seismic lines crossing five wells in both H and I fields were well utilized for the stratigraphic interpretation. The major stratigraphic difference between these two fields is represented by the occurrence and absence of both Middle and Upper Ordovician successions.

The stratigraphic column of the Ordovician succession in the study area consists of *Ash Shabiyat, Hawaz, Melaz Shuqran, and Mamuniyat* Formations. Detailed stratigraphic description of the Ordovician succession was possible by utilizing FMI logs in the provided five wells. The stratigraphic description has included sequence patterns, facies description, paleocurrent analysis and depositional setting interpretation. For higher resolution and better evaluation of the Ordovician succession; previous surface studies were integrated with subsurface dataset.

The correlation of the upper Ordovician deposits (i.e. Melaz Shuqran and Mamuniyat Formations in I-Field) shows extreme variations of both vertical and lateral stratigraphic distribution. On contrast, the Middle Ordovician deposits (i.e. Hawaz Formation in H-Field) shows homogeneous distribution of both vertical and lateral stratigraphy. During the Late Ordovician time, I-Field and H-Field were considered as the paleolow and paleohigh in the studied area. Hence, the Upper Ordovician deposits of Melaz Shuqran and Mamuniyat Formations were deposits within paleolow areas.

4.2. Seismic Stratigraphy (Geometry & Distribution)

Four seismic lines, named H1-I3, I1-I3, H3-I2 and H1-H3, crossing the area of study averaging of 10km each reveal large scale stratigraphic variations and decreased the uncertainty of using only open hole logs dataset for well to well correlation (Figure-4.1). The seismic data shows that all the stratigraphic sequences of Murzuq Basin are present within the studied concession from *Basement* to *Cenozoic* (Figure-4.2). The observations, from the seismic data, exhibit that paleohighs and paleolows in the area of study are evident. The typical seismic line to represent the study area succession is H3-I2 line which is trending East–West direction.

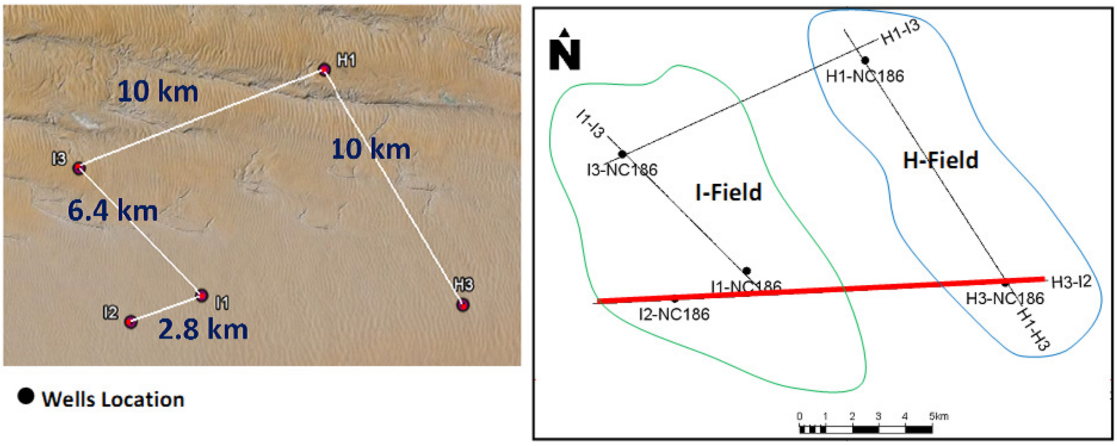


Figure-4.1: Distance and names of surface seismic lines in the area of study. H3-I2 seismic line is indicated by red line (Figure-4.2 for more details) crossing the two main fields in Concession-NC186 (H & I Fields).

The stratigraphic records are essential for structural interpretation as they are indicators of uplift, subsidence and relaxation. All of the stratigraphic units are extended over the area of study with identical distribution apart from the Ordovician successions which are the main interest of this study. Instability of both tectonic and eustasy during the Late Ordovician led to generation of multiple unconformity surfaces (known as Taconic and/or Polygenic Unconformity for Craig *et.al.* 2006). Consequently, this led to differential erosion of different intensities as observed from the seismic section (Figures-4.3 & 4.4).

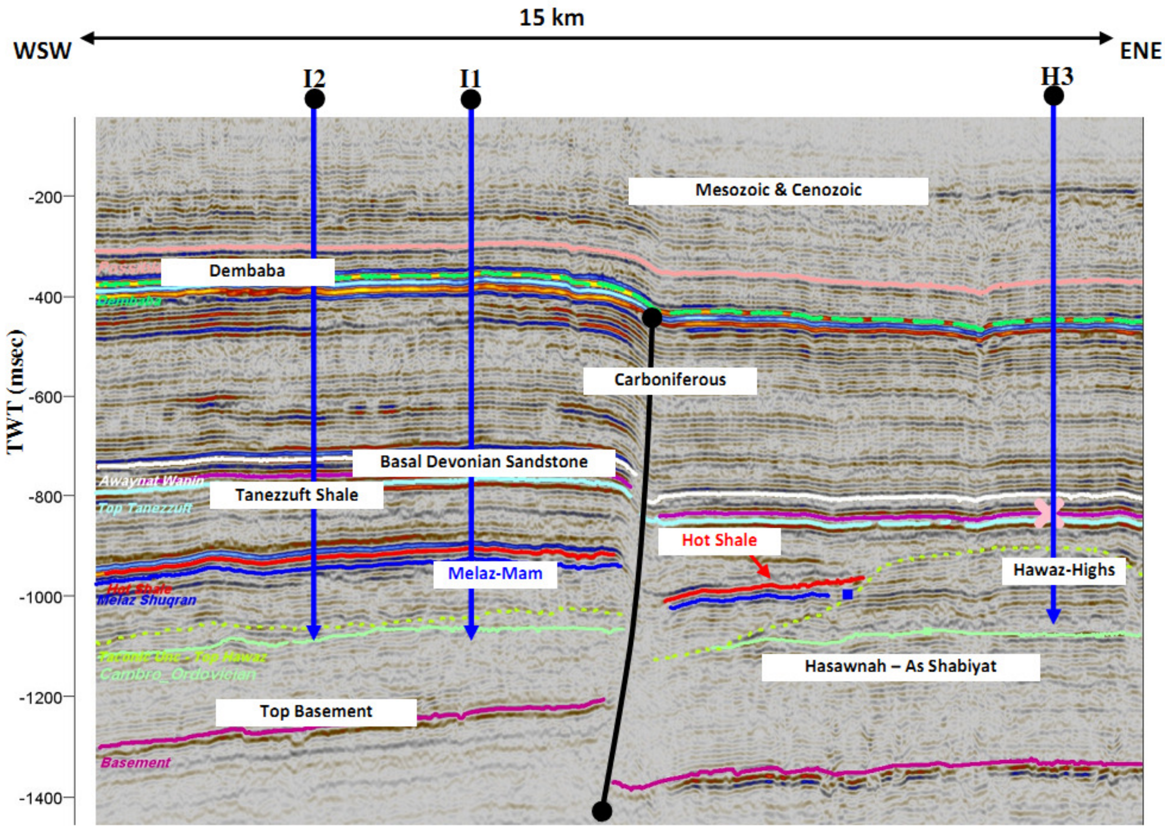


Figure-4.2: The main representative surface seismic line in the study area crossing the wells H3 and I2 trending E-W. The defined Seismic Horizons from bottom to top are; *Basement, Cambro-Ordovician Contact, Taconic Unconformity (between Middle-Upper Ordovician), Top Melaz Shuqran, Hot Shale, Tanezzuft Shale, Basal Devonian Sandstone, Awaynat Wanin, Dembaba and Possible Cretaceous,* which are all overlaid by Mesozoic and Cenozoic deposits. I1-NC186 well is projected on the seismic line hence it is located nearby the line (see figure-4.1 for wells location).

The interpreted seismic stratigraphy of the Ordovician is represented by paleohighs (i.e. Hawaz Formation) and paleolows (i.e. Melaz Shuqran and Mamuniyat Formations). This is mainly developed during the known glacial episode at the end of the Ordovician by large glacial valleys of alternative erosion and deposition. Melaz Shuqran, Mamuniyat, Bir Tlacsin, Hot Shale and Tanezzuft Shale Formations were deposited within the paleolows of the Taconic Unconformity and truncated/onlapped at the edges of the paleohighs of Hawaz Formation. All of the Ordovician successions in the study area are capped by the thick Silurian shale (Figures-4.4).

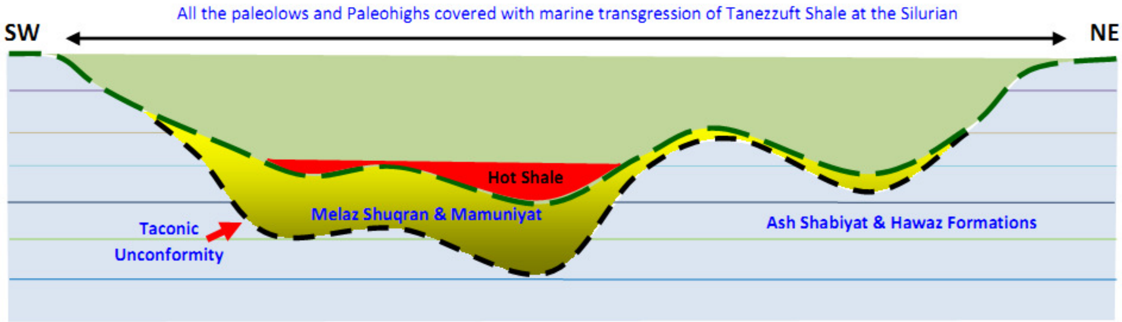


Figure-4.3: Sketch illustrates the main stratigraphic distribution and geometry of the Ordovician successions in the study area. Note the erosion variations at the Middle to Upper Ordovician contact (i.e. Taconic).

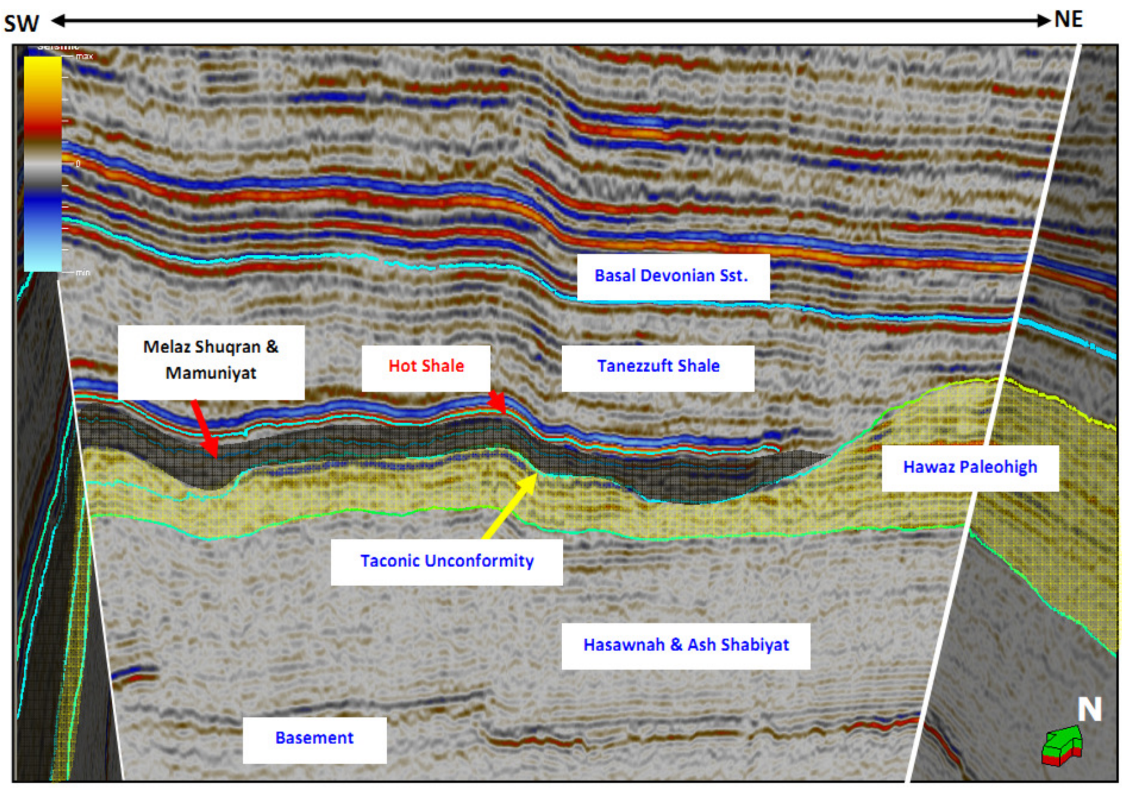


Figure-4.4: 3D view of the interpreted H1-I3 seismic line (looking NW) shows the vertical and lateral distribution of the Ordovician formations in the area of study. Differential erosion (Taconic Unconformity) between the middle and upper Ordovician succession encountered at the seismic lines trending toward E-W direction. This is directly related to the paleovalleys trending NW-SE. Additionally, Tanezzuft Formation is covering the whole sequences and thinning over the paleohighs areas. Vertical exaggeration is 20 times.

4.3. Stratigraphic Correlation of Ordovician Successions

Stratigraphic correlation lines were constructed to cover the study area for further interpretation. The main purpose of this correlation is to delineate the stratigraphic extend of each formation within the Ordovician stratigraphy. The stratigraphic correlations constructed in four correlation lines crossing the subject wells in the studied area (Figure-4.5).

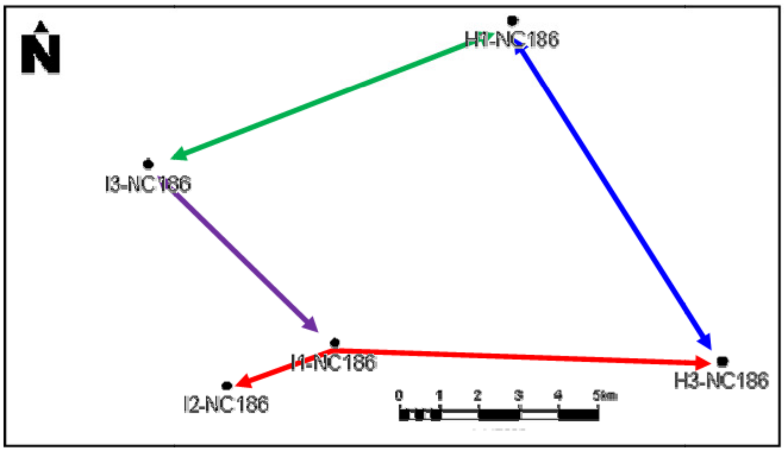


Figure-4.5: Alignment of the cross sections in the study area.

4.3.1. Cross Section H1 – H3 (H-Field)

This correlation line is crossing the H1 and H3 wells, which is the best trend to represent the H-Field stratigraphy. Only the Lower and Upper Ordovician deposits, Ash Shabiyat and Hawaz Formations, are existed in this field while the upper Ordovician successions are totally absent (Figure-4.6). Flattening of seismic data at the top of Tanezzuft Formation indicated uniform distribution of the Middle Ordovician successions in H-Field. This uniform distribution has indicated the stability of both structure and accommodation space during the deposition of Hawaz Formation. In addition, the observed increased thickness of Tanezzuft Formation towards H1-NC186 Well location indicates structural instability during Early Silurian times.

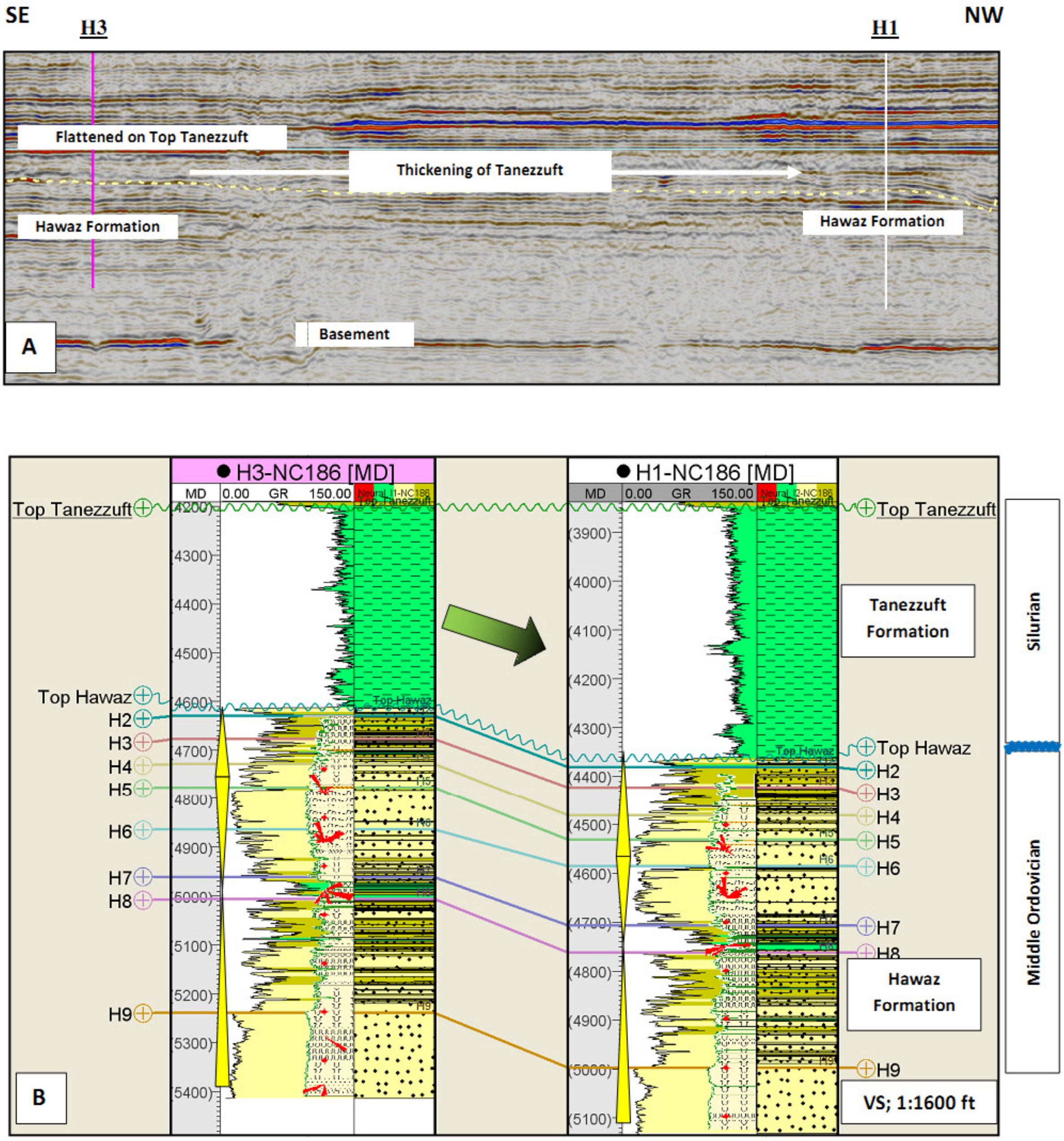


Figure-4.6: (A) Surface seismic line crossing the two wells H1 & H3 in NW-SE direction flattened on top of Tanezzuft Formation. Note the thickening of the Tanezzuft shale towards the NW. (B) Stratigraphic cross section between H1 & H3 wells in the H-Field. Lithofacies description and paleocurrent direction are extracted from FMI images. Both stratigraphic successions indicate homogeneous lateral distribution. Note that REMSA classifying the Hawaz Formation into nine units from H9 at the bottom to H1 at the top.

4.3.2. Cross Section I1 – I3 (I-Field)

It is a representative cross section of I-Field correlating I1 and I3 wells which is parallel to H1-H3 cross section (Fiure-4.5). From the Ordovician successions, only the Upper Ordovician units (Melaz Shuqran & Mamuniyat Formations) are present. These units or formations are deposited within paleolows of the study area. Flattening at the top of Tanezzuft Formation using seismic data shows that the Upper Ordovician deposits are thickening towards the SE (Figure-4.7) which is also indicated by the open hole logs. Lateral Changes in stratigraphic successions and sedimentary structures between these two wells indicate a depositional setting change from NW to SE (Figure-4.8). Tanezzuft Formation is thickening towards the NW which is directly related to the extension event during the early Silurian time.

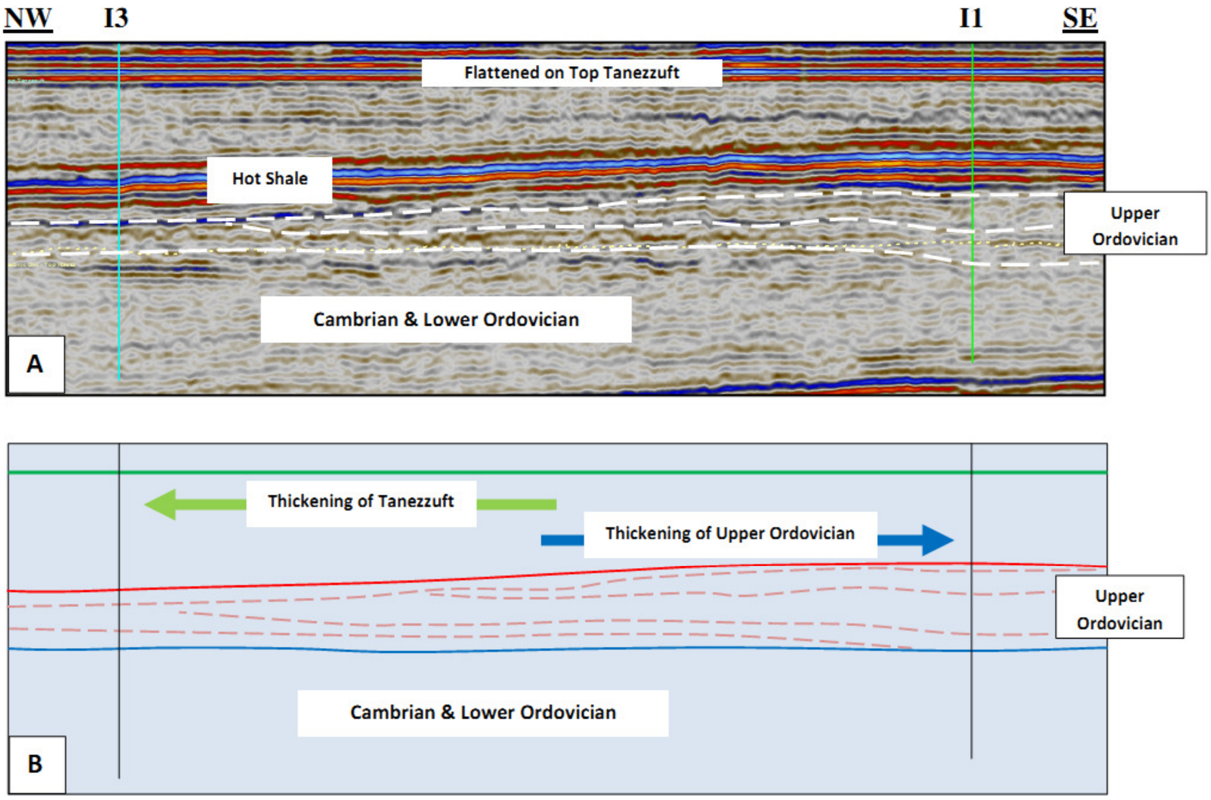
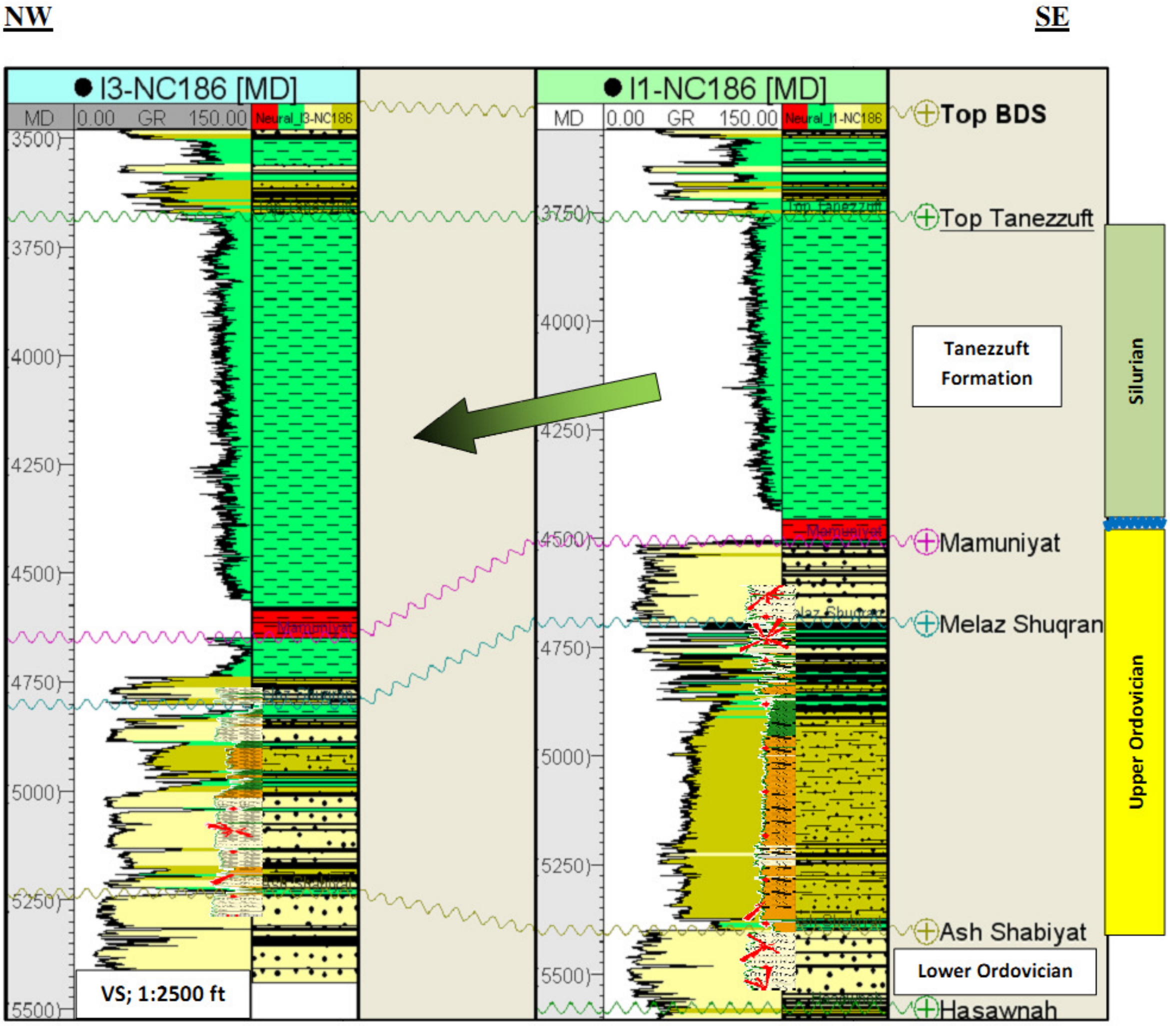


Figure-4.7: (A) Seismic line crossing the I3 & I1 wells in NW-SE direction flattened on top of Tanezzuft Formation. Note the thickening of the Upper Ordovician stratigraphy towards the SE. (B) Sketch illustrates the lateral discontinuity of Upper Ordovician stratigraphy as indicated by dashed lines.



Figuew-4.8: Stratigraphic correlation between I1 & I3 wells in I-Field shows the stratigraphic distribution and variations from NW to SE. These variations are mainly represented by change in lithology and thickness.

4.3.3. Cross Section I2 – H3

Cross sections in the study area were built through H and I Fields to establish detailed stratigraphic variations within the Ordovician successions. Seismic line trending East-West direction is chosen for this purpose (Figure-4.9). Large scale of erosion was observed, almost 400 meters, and developed wide glacial valley as accommodation space for the Upper Ordovician deposits represented by Mamuniyat and Melaz Shuqran Formations (Figure-4.10). Both seismic and open hole logs dataset exhibited large scale of paleohigh and paleolow topography that separate the Middle and Upper Ordovician successions. Truncation or onlapping of the Upper Ordovician and Silurian successions to the paleohighs topographic of the Middle Ordovician, Hawaz Formation, identified using seismic data.

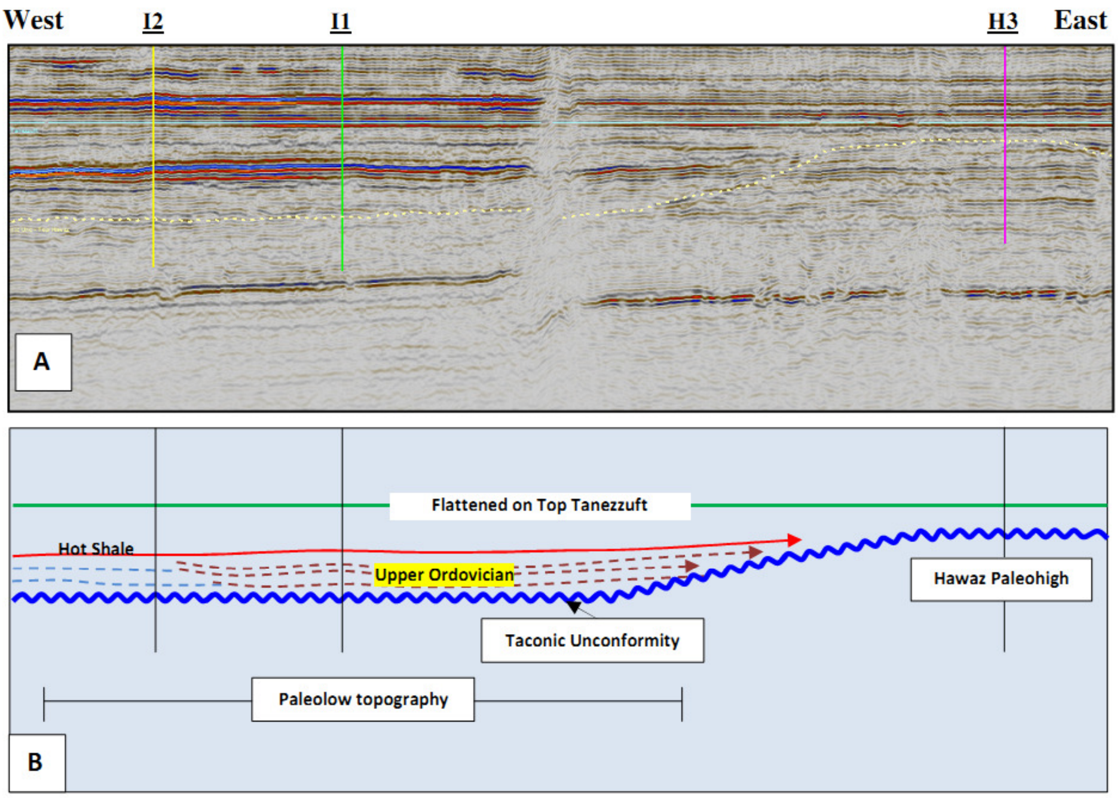


Figure-4.9: (A) Seismic line crossing H and I Fields through the wells I2, I1 & H3 (East - West direction) and flattened on top of Tanezzuft Formation. This cross line is a representative seismic line of the topographic variation of the Ordovician succession in the study area. The Upper Ordovician stratigraphy shows discontinuity between the I1 and I2 wells which is also encountered from the open hole logs. (B) Sketch illustrates the seismic data interpretation between the I2, I1 and H3 wells.

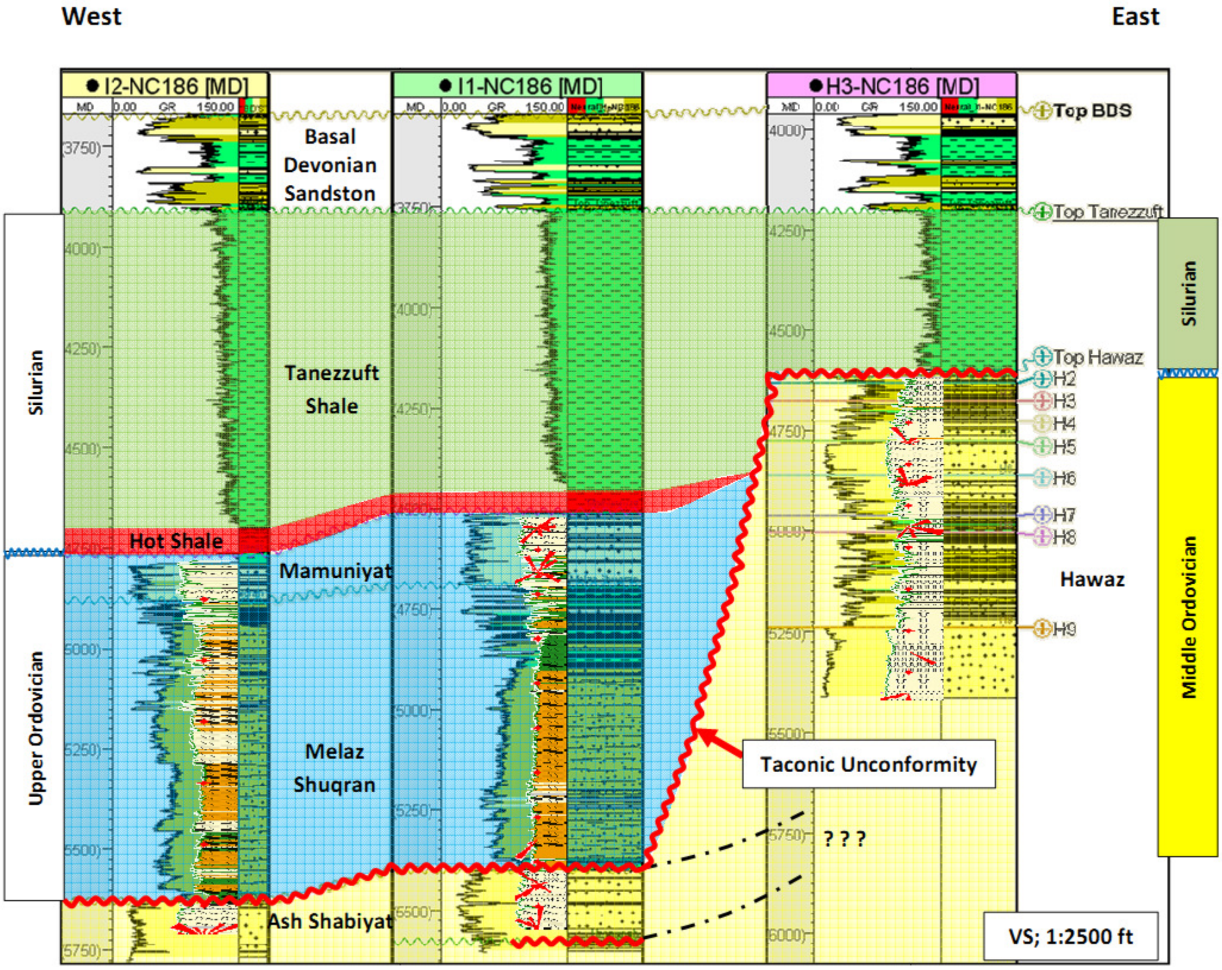


Figure-4.10: Key Stratigraphic Correlation crossing the two fields of the study area (H&I Fields) towards the E-W direction. The stratigraphic relationship between the Middle and Upper Ordovician succession is represented by paleohigh and paleolow of glacial influences during the Taconic.

4.3.4. Cross Section I3 – H1

Parallel to I2-H3 cross section, NE-SW cross section between the well I3 and H1 is constructed for higher stratigraphic resolution to control the structural interpretation at the northern part of the study area. This cross section is also crossing the two fields (Figure-4.5, green line). Good match was observed between I3-H3 and I2-H3 cross sections results in terms of paleo-topographic patterns except some lateral variations occurred due to differential erosion intensities (Figures-4.11&12). These intensive differential erosions are represented by north-south alignment where the southern part is more eroded than the northern part of the study area. These observations illustrate the paleotopograhy during Middle to Upper Ordovician time that the northern part of the area was emergent with respect to the southern area. This is also approved by the SE and SW dipping of the unconformity surfaces between Melaz Shuqran and Ash Shabiyat Formations (see Figure-4.13). Tanezzuft Formation in the I-Field is thicker than H-Field, which indicates large topographic variation at the Ordovician-Silurian times.

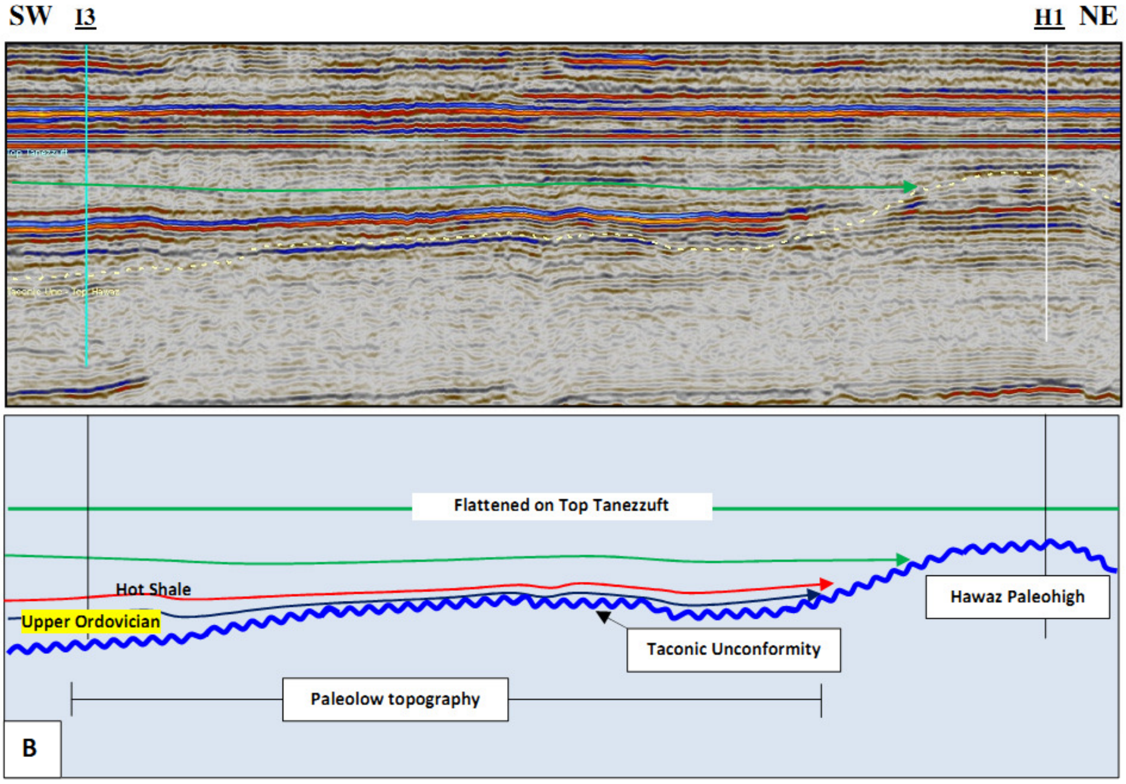


Figure-4.11: (A) Surface seismic line crossing the H and I Fields through the I3 & H1 wells (NE-SW direction) and flattened on top of the Tanezzuft Formation. This is a representative seismic line of the Ordovician topographic variation in the Concession NC186. (B) Sketch illustrates the seismic data interpretation between the I1 and H3 wells.

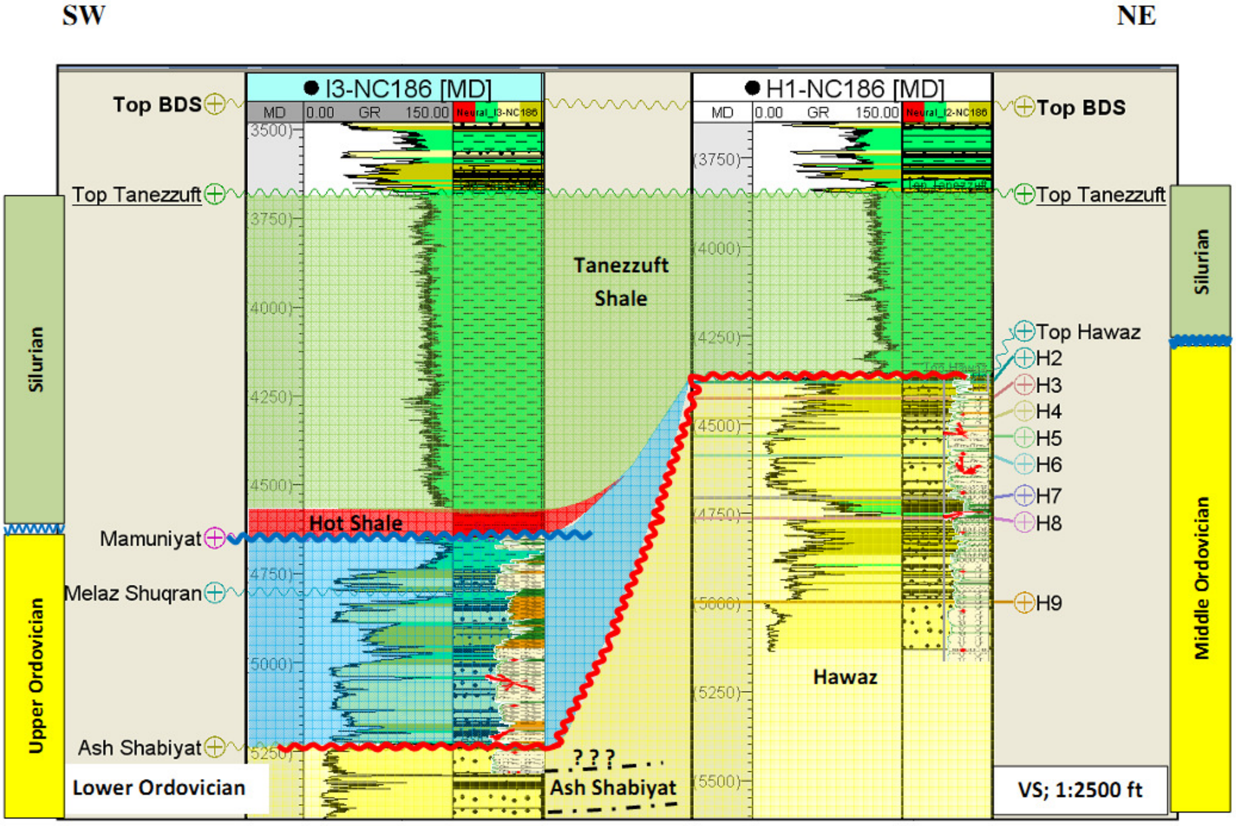


Figure-4.12: Stratigraphic Correlation crossing the two main fields (H&I) in NE-SW direction through the wells I3 and H1 at the northern part of the study area. Both seismic and open hole logs indicate large incised valley between the Middle and Upper Ordovician successions. Due to the lack of data below Hawaz Formation in H1 and I3 wells it was difficult to correlate Ash Shabiyat Formation between H to I Fields.

4.4. Stratigraphic Analysis of Ordovician Successions Utilizing FMI Data

The Ordovician stratigraphic column was constructed using FMI data with other open hole logs such as; GR, Density, Neutron and PEF (Photo Electric Factor). For geological description, FMI data can be used as an outcrop. The stratigraphic column of the Ordovician Successions in the study area subdivided into:

Lower & Middle Ordovician (Shallow Marine): *Ash Shabiyat & Hawaz formations.*

Upper Ordovician (Glacial Episode): *Melaz Shuqran & Mamuniyat formations.*

4.4.1. Lower & Middle Ordovician (Shallow Marine)

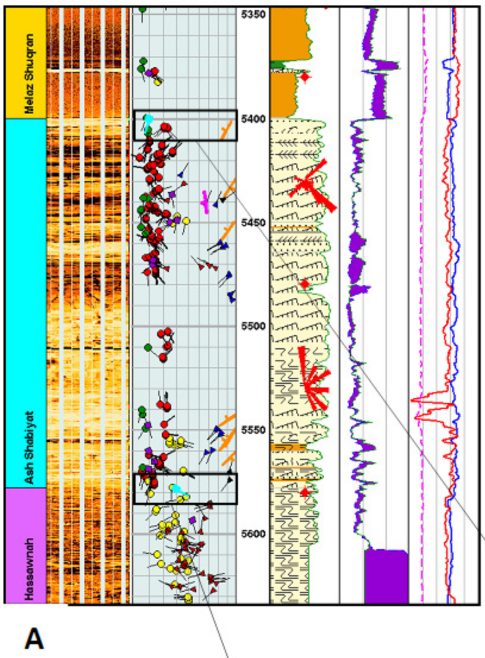
4.4.1.1. Ash Shabiyat Formation

As Shabiyat Formation was encountered in I-Field only where some wells drilled into Hasawnah Formation such as in I1-NC186 well. Both lower and upper contacts of Ash Shabiyat Formation are unconformable as in the well I1-NC186 (Figure-4.13). These unconformity surfaces are dipping towards SW and SE which indicate general south tilting. This formation is mainly comprised of cross-bedded and bedded sandstone facies. The typical log of Ash Shabiyat Formation in the area of study was encountered in I1-NC186 well. Stratigraphic and sedimentological description of Ash Shabiyat Formation was described in details (see appindex-B).

4.4.1.2. Hawaz Formation

The stratigraphic column of Hawaz Formation shows mostly uniform homogeneous distribution over Murzuq Basin including the concession NC186. However, using REMSA Company standards, the Hawaz Formation was subdivided into nine members or units namely, H1 to H9. In H-Field of the study area, Hawaz Formation was logged using FMI over the units from H9 to H2 Units (i.e. both top and bottom of the formation not acquired). Hawaz Formation in I-Field is eroded with different scales as explained in Figure-4.4. A typical log of Hawaz

Formation is constructed from the well H3-NC186 and was described in details (see appindex-B).



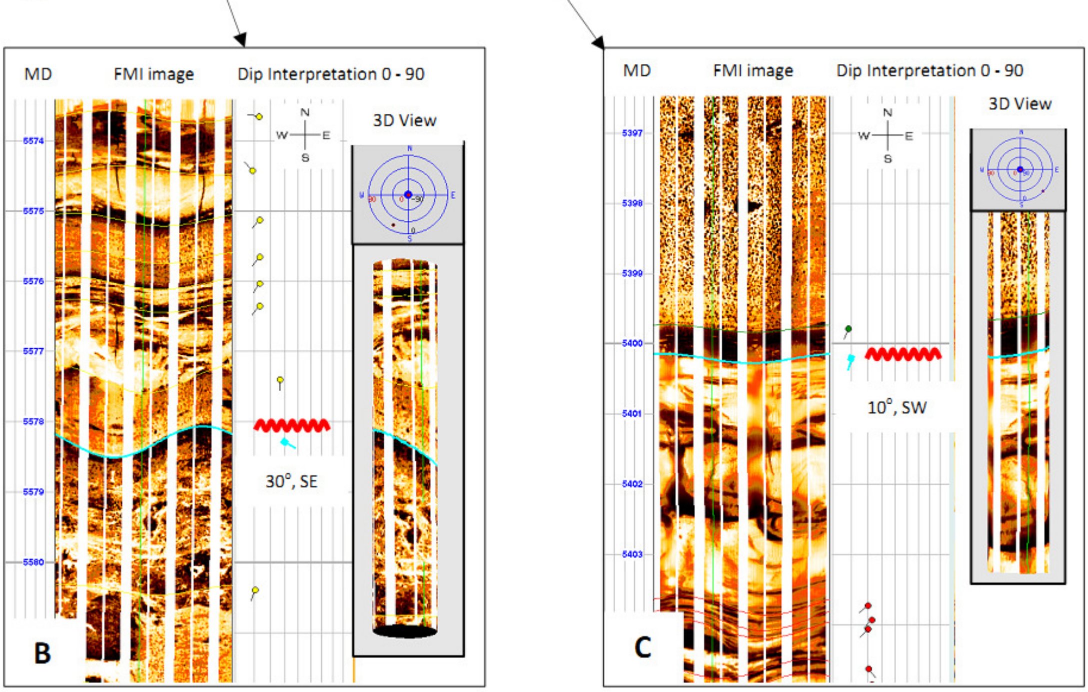


Figure-4.13: (A) Composite display of Shabiyat Formation. (B) An example of unconformity surface between Ash Shabiyat Formation (Middle Ordovician) and Hasawnah Formation (Cambrian) dipping 30°, ESE. (C) An example of unconformity surface dipping 10°, SSW between Ash Shabiyat Formation (Middle Ordovician) and Melaz Shuqran (Upper Ordovician) Formation where Hawaz Formation is totally eroded, both examples from well I1-NC186. The dipping of the unconformity surface in all wells in I-Field is toward the south indicate the dipping of the formation (See Appendix-B for more details).

4.4.2. Upper Ordovician (Glacial deposits)

During Late Ordovician (i.e. Hirnantian), Murzuq Basin was lying along the continental margin of west Gondwana. The possible maximum extent of the ice-sheet during glacier advance events approached north Al-Qarqaf and Wadi Anlalin areas. Therefore, Ghat area represents the ice-proximal (shallow water) areas, whereas the Wadi Anlalin represents the ice distal (deep water) area and Al-Qarqaf was located in the intermediate area with respect to the ice-sheet center (El-Ghali, 2005). The glaciogenic rocks are subdivided into two formations; (1) The mud-dominated Melaz Shuqran Formation, and (2) The sand-dominated Mamuniyat Formation.

4.4.2.1. Melaz Shuqran Formation

The stratigraphic continuity (i.e. lateral and vertical) of Melaz Shuqran Formation in the study area is interrupted. This formation is defined and covered by FMI images in the available wells from I-Field. It is mainly comprised of contorted and deformed clastic facies. Its thickness various from well to another where it reaches a maximum of 800 ft (~240 meters). In well I3-NC186, sandstone percentage is more than in the other wells which indicates lateral stratigraphic discontinuity. The unconformity surfaces separating Melaz Shuqran and As Shabiyat Formation are dipping to SSE and SW directions.

In the three wells of I-Filed; Melaz Shuqran Formation shows general fining upward sequences. In I3-NC186 well, fining upward cycles are the dominant with cross-bedded sandstone at the base of the cycles. Several features observed within the formation have clear indication of glacial depositional environment (see appendix-B for more details).

4.4.2.2. Mamuniyat Formation

The Mamuniyat Formation in the study area is not thick as it's exposed at the surface. From the studied wells, a maximum thickness of 188 ft (~56m) was observed. It is comprised of cross-bedded sandstone facies in I1-NC186 and I2-NC186 wells and contorted sandstone facies in I3-NC186 well (see appendix-B for more details).

CHAPTER FIVE

STRUCTURAL ANALYSIS OF ORDOVICIAN SUCCESSIONS IN H & I FIELDS, CONCESSION NC186

5.1. Introduction

Intensive studies were carried out in the main concessions of the basin (e.g. NC174, NC115 and NC186) using both surface and subsurface datasets due to the exploration activities in the area. In this thesis, this is the first comprehensive published work on the subsurface geology of the Concession NC186 by integrating the regional studies in the basin with the present area of study.

Data integration and utilization for both large and small scale subsurface dataset available (i.e. seismic to FMI) were used to interpret and analyze the structural elements in the study area. It was difficult to analyze the tectonic evolution of the Ordovician successions separately due to the affect of multiple tectonic events occurred before and after the Ordovician. These events have direct and indirect impacts on the last structural configuration of the succession. The study area, as part of Murzuq Basin, passed through various tectonic events from PreCambrian to Cenozoic.

High resolution identification and interpretation of the structural elements in the area of study carried out using different datasets. Time structural maps for all horizons were generated from seismic data and used for structural interpretation in the study area. These maps are very important where they played a key element in identification of the main structural elements.

5.2. Main Structural Elements in the study area

The structural elements in the study area were classified into large scale and small scale features as follow:

1. *Large Scale Structural Features:*
    - *Paleohighs and Paleolow.*
    - *Basement Faults.*
    - *En Echelon Folds.*
    - *Positive Flower Structures.*

2. *Small Scale Structural Features:*
    - *Micro-Faults*
    - *Fractures.*

5.2.1. Large Scale Structural Elements (Seismic Scale)

5.2.1.1. Paleohighs and Paleolows of Ordovician

The largest and most important structural features in the Concession NC186 are the *Ordovician paleohighs and paleolows*. These features observed in the study area trend NW-SE direction with thickness variations from north to south (Figure-5.1). The paleohigh and paleolow are represented by H and I Fields, where H-Field refers to Paleohigh and I-Field refers to Paleolow. This paleo-topographic complex occurred as a result of preexisting highs and lows of the last stage of Pan African Orogeny (Klitzsch and Ziegert, 2000) and juxtaposition glaciations processes during late Ordovician.

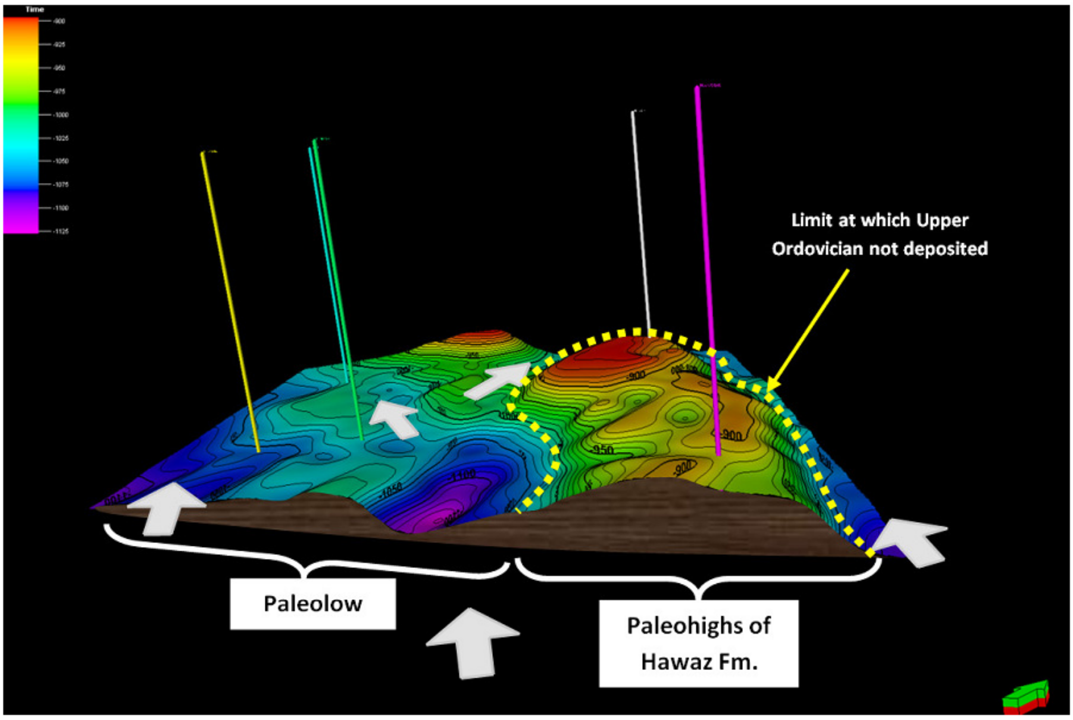


Figure-5.1: 3D view, looking NW, of Hawaz Formation time top structural map illustrates the paleo-topographic variations. These features are trending NNW & NW directions. (See also Figures- 4.4 & 4.10). white arrows indicate the directions of ice streams during the upper Ordovician.

Paleo-ice streams mapped by Le Heron and Craig (2008) indicate NW trend of the glacial flow (Figure-5.2). Due to glaciations processes a polygenic regional unconformity occurred (i.e. *Taconic Unconformity*) and eroded deeper into older Paleozoic deposits along same trend.

Truncation of the upper Ordovician succession is observed on seismic data against the Hawaz Paleohighs (Figure-4.4). In the nearby areas, Concession NC174, these paleohighs and paleolows features are also present (Figure-5.3). They are mapped using seismic data and shows mainly NNW and NW paleo-valleys trend.

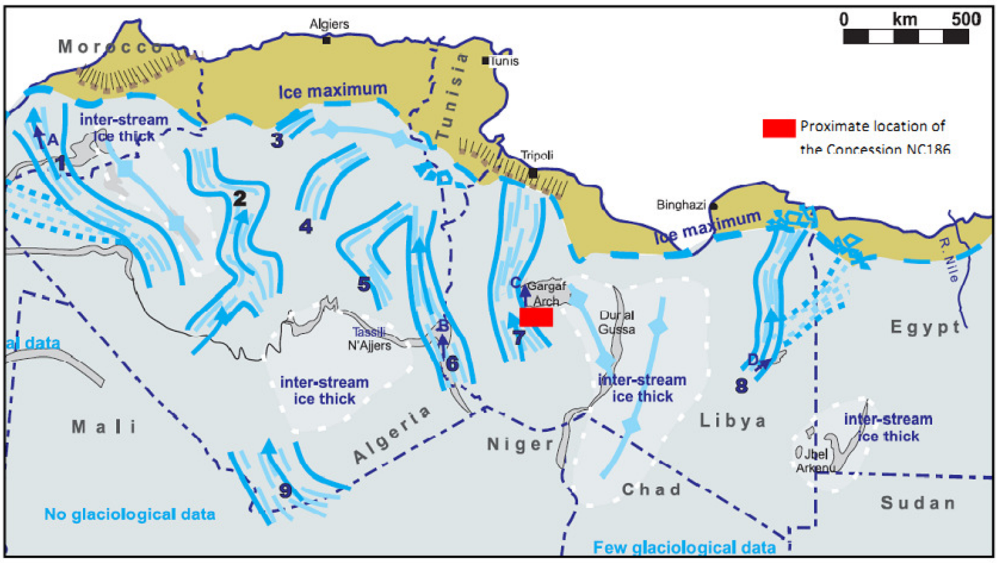


Figure-5.2: Palaeo-glaciological reconstructions of the Late Ordovician Saharan ice sheet. Ice sheet configuration at glacial maximum position, showing widespread occurrence of ice streams separated by wide inter-stream areas. Note that the large glacial trend over Murzuq Basin crossing the area of study is mainly towards the NW direction. After Le Heron and Craig (2008).

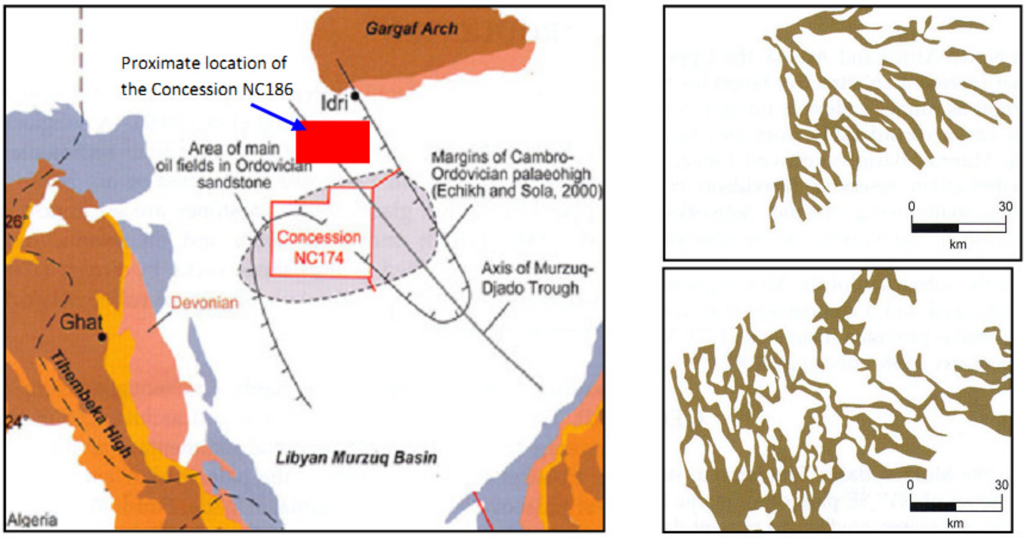


Figure-5.3: Location and distribution of glacial paleo-valleys, Concession NC174, Murzuq Basin. Drainage pattern indicate NW trend of the glacial valleys encountered within the paleolows of Ordovician.

5.2.1.2. Basement Faults

5.2.1.2.1. Identification of Basement Faults in the area of study

The study area is located over the main axis of the Awbari trough (at the uppermost northern part of Murzuq basin) which was an important depocenter for Murzuq basin during the Early Paleozoic (Figure-5.4). In Awbari trough, the basement faults (also known as wrench faults) are mainly trending NNW-SSE and NW-SE directions.

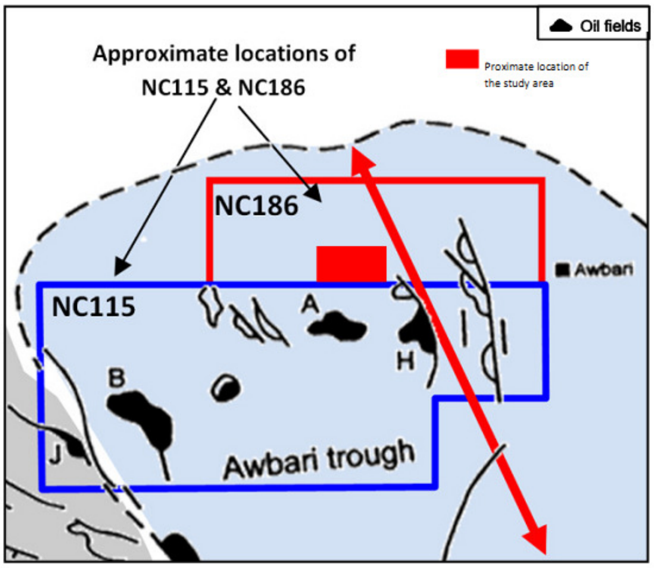


Figure-5.4: Location of the study area within Awbari trough. Main trend of the basement faults in Awbari trough are towards NNW-SSE and NW-SE directions as indicated with the red arrow. After Echikh and Sola (2000).

Observation and interpretation carried out for the major basement faults in the study area those can be summarized as following:

1. There is no effect or structural signature of faulting in H-Field (Figure-5.5).
2. All the basement faults observed in the area of study are thrust faults (i.e. Reverse Faults) with differential vertical displacement from the northern to the southern parts and trending mainly in NNW-SSE and NW-SE direction and dipping to the west. In addition, they are only encountered within the paleolow area (i.e. I-Field).
3. The largest vertical displacement observed in the basement rocks reaches up to 300 meter at the southern part of the area which indicates tearing fault pattern.
4. These basement faults extend upwards from basement up to Carboniferous.

5. Thickening of formations on the downthrown sides of the reverse faults indicates syn-depositional faulting (growth faults) during evolution.
6. Features of en echelon folds, tearing, positive flower structures coincide with the faults indicate simple shear along the major basement faults in the study area.

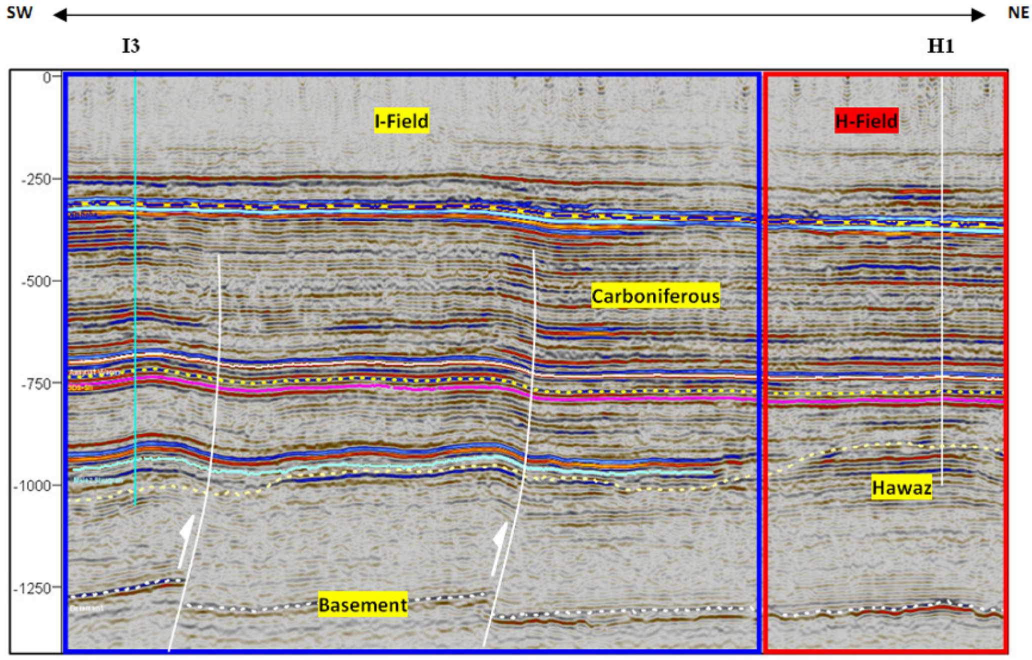


Figure-5.5: Shows the H and I Fields in seismic line. Note that reverse basement faults observed only over the I-Field and dipping WSW.

5.2.1.2.2. Generation and Rejuvenation of Basement Faults

All faults observed within the area of study were picked on various seismic horizons show that faults generated and rejuvenated with different mechanisms and developed along the same fault planes toward NNW-SSE and dip westerly (Figures-5.6, 5.7 & 5.8).

The dip magnitudes of the basement faults in the area of study were almost steep since the time of generation. Therefore, differential fault kinematic were active through time from extension to compression to strike-slip along their planes. The largest vertical displacement of basements faults in the study area averaging of more than ~ 300 m.

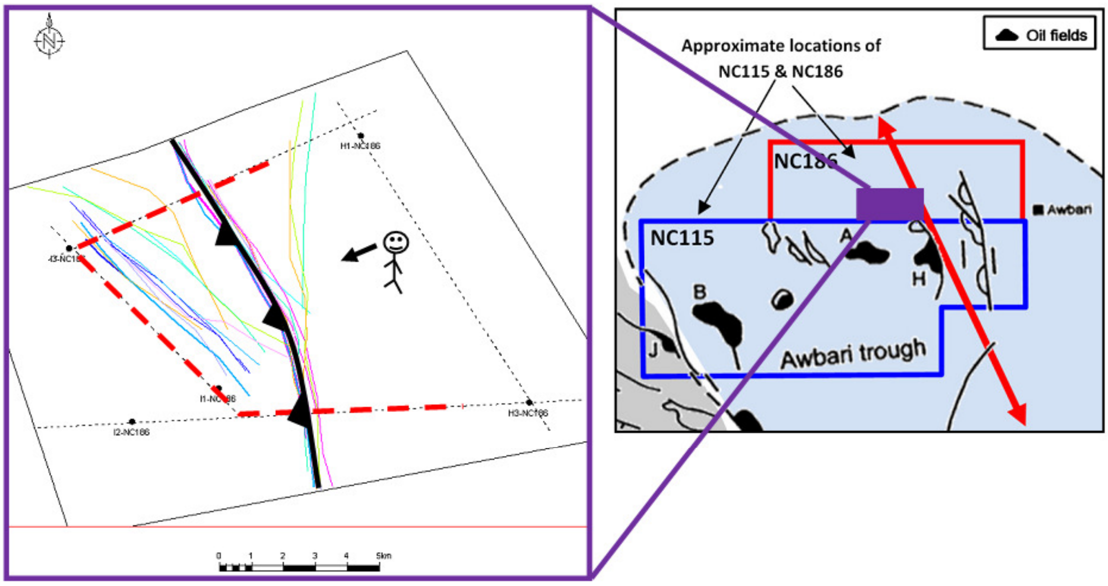


Figure-5.6: Plan view of the major faults in the study area which is matching in direction with the major faults of Awbari trough. Seismic lines covering the study area shows the direction of the 3D view looking towards SW. Red dashed line indicates the view profiles of the 3D view (Figure-5.7).

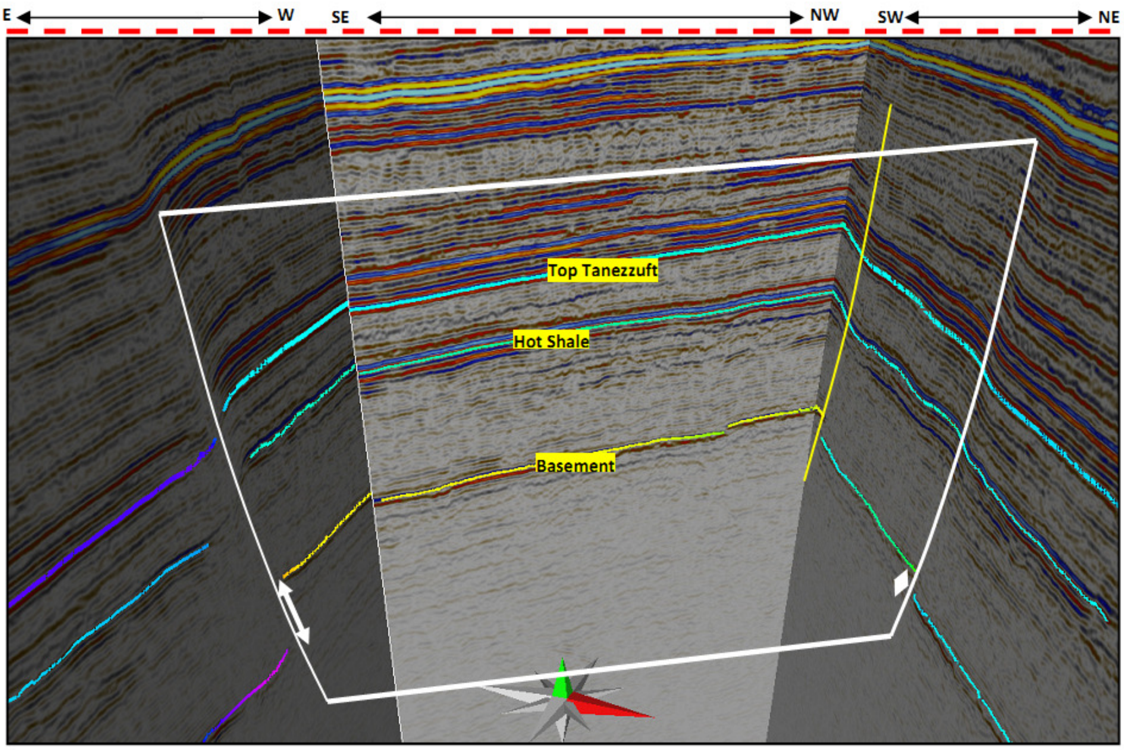


Figure-5.7: 3D View of data looking to SW. Basement induced faults characterized by larger vertical displacement in the southern part than the northern part (interpreted as Tearing Fault).

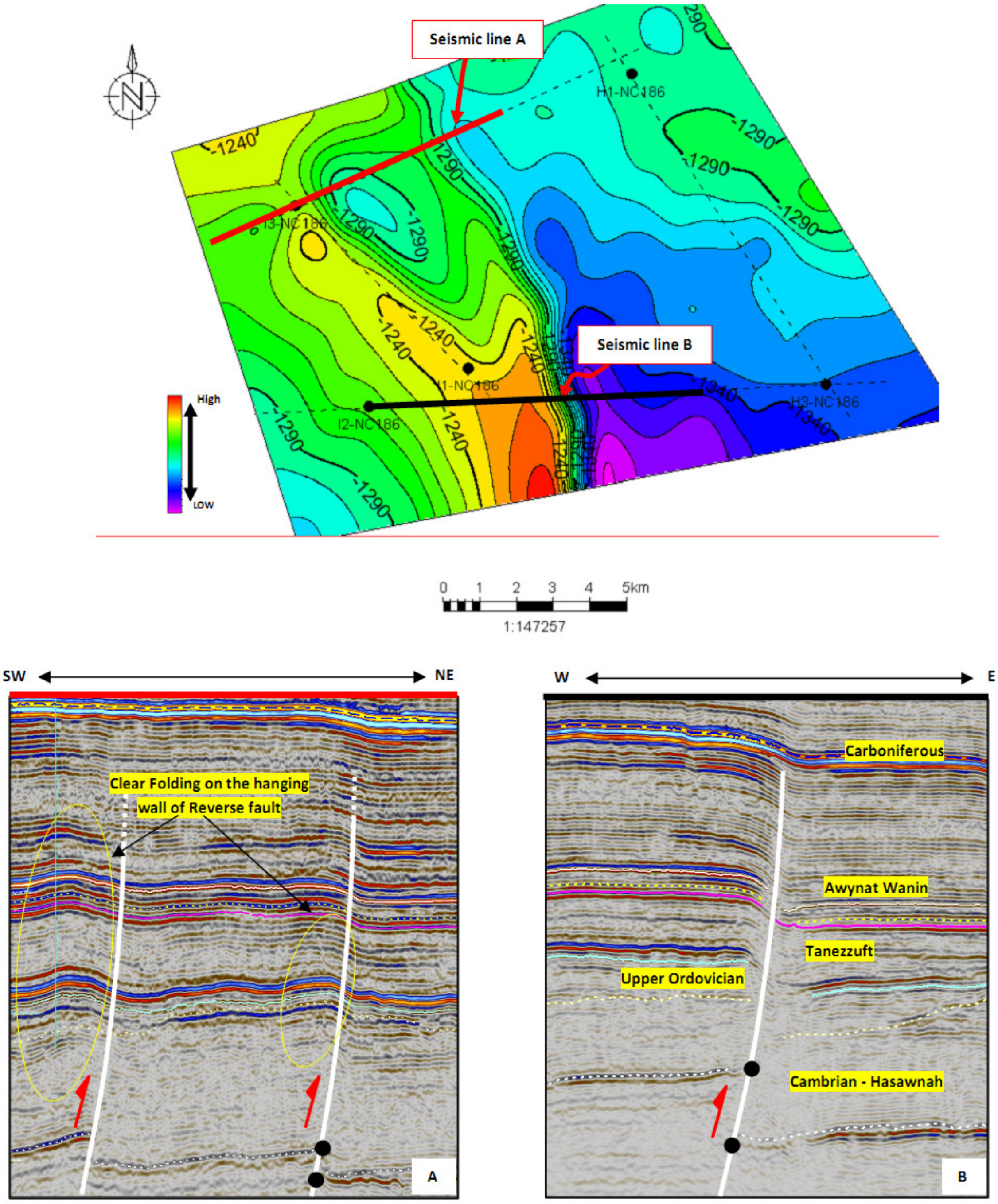


Figure-5.8: Time top structural maps of the basement shows the main faults in the area of study trending NNW-SSE at the southern part of the area and deviated to the NW-SE direction at the northern part. Vertical displacement is indicated by countering where at the southern part larger than at the northern part of the study area (see seismic lines A & B). The most effected part with faulting and folding is the western part of the area (paleolow area). Folds are confined within reverse faults and trending NW-SE direction.

During the Early Paleozoic, last stage of *Pan African Orogeny*, major shearing and compressional tectonics occurred through the collision between West African and East Saharan cratons. Basements faults in the study area are believed to be developed during this stage. However, large scale highs and lows developed within Murzuq Basin trending NW-SE. These features were subjected to reactivation in a transpressional and transtensional modes throughout the younger geological times. Indication of an extensional regime by "growth fault" was recorded from seismic data over the Cambrian deposits where the upthrown side is thinner than the downthrown sides (Figure-5.9). This extensional phase might have been followed by compression pulses during the late Cambrian-Ordovician time.

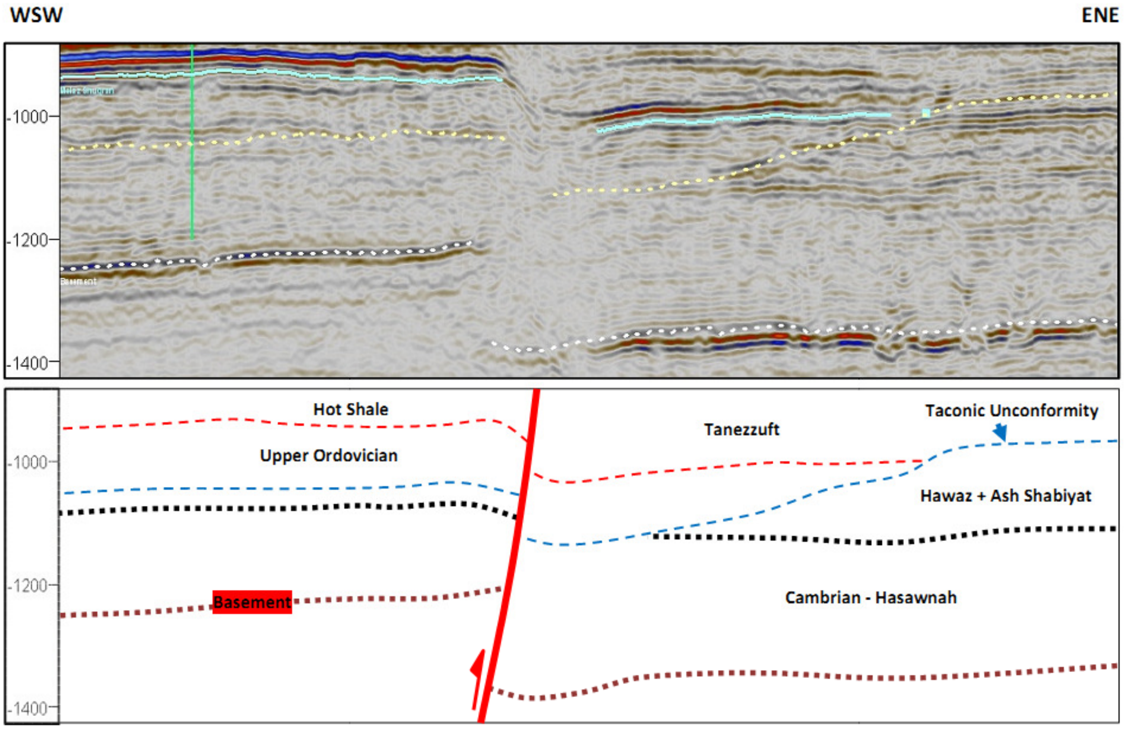


Figure-5.9: Shows the main reverse basement fault in the area of study (crossing I2-H3 seismic line) with strike direction NNW-SSW and dipping WSW. This line indicates huge vertical displacement within the Cambrian succession where it is thickening at the downthrown side of the fault indicate Syndepositional faulting during Cambrian. This is one of the strongest indications that these reverse faults are only the final configuration and passed through different types of displacements through time.

During Late Cambrian, the growth faults in the study area were rejuvenated in a transpressional manner that led to reversing the growth faults by differential vertical displacements (inversion signature). Late Cambrian compressional features were reported from both surface and subsurface of Murzuq basin (Figures-5.10 & 5.11).

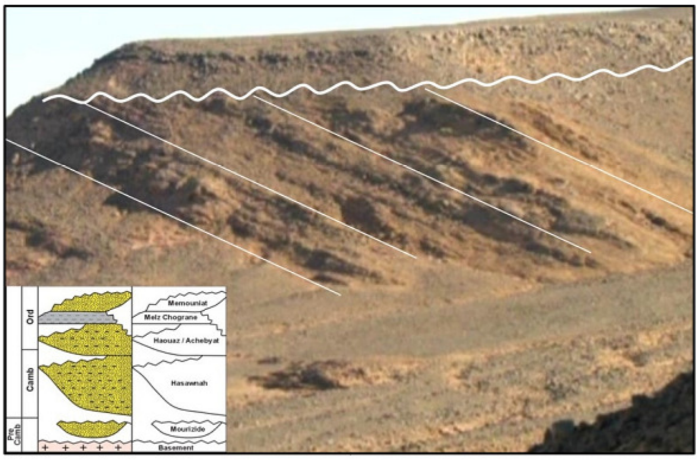


Figure-5.10: Angular unconformity separating Cambrian and Ordovician successions in Jabal Dur Al Qussah at the Eastern margins of Murzuq Basin indicate of significant compression (Klitzsch, 2000).

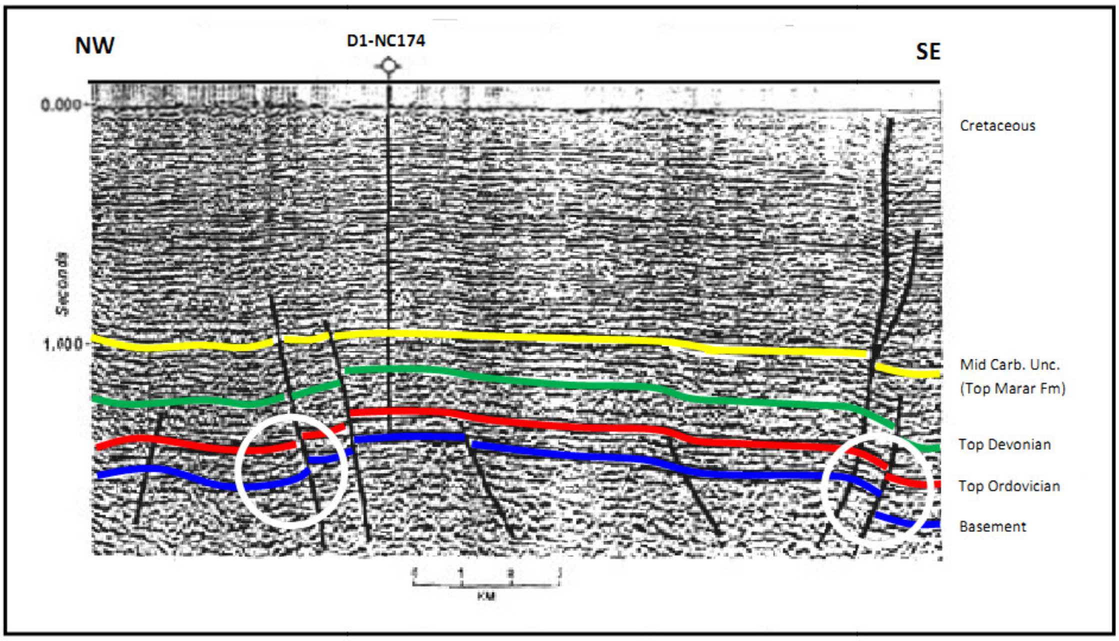


Figure-5.11: Seismic line trending NW-SE crossing the well D1-NC174, south of the study area shows clear thickening of Cambrian deposits at the downthrown side of a reverse faults (see white cycles). After Davidson et. al., (2000)

Tectonic instability during the Ordovician was subtle and decreasing relatively to the Cambrian and leading to general crustal extension. On the other hand, large glacial valleys eroded down into the older Ordovician successions aligning with the major trends of the Basement Faults towards the NW-SE. The major rejuvenation event of the basement faults in the study area recorded over the Silurian-Devonian successions. The Middle Silurian to Middle Devonian was a significant compressional structural episode in the area (known as "*Caledonian*" in some literatures). Major uplifting and erosion occurred with transpressional strike slip movements that initiated "*En echelon folds & Positive follower structures*". These structural features observed in the study area as well as in the nearby concessions along the old basement faults. Basement faults are terminated at the Carboniferous horizons and only topographic effect persisted to the Mesozoic successions (Figure-5.12).

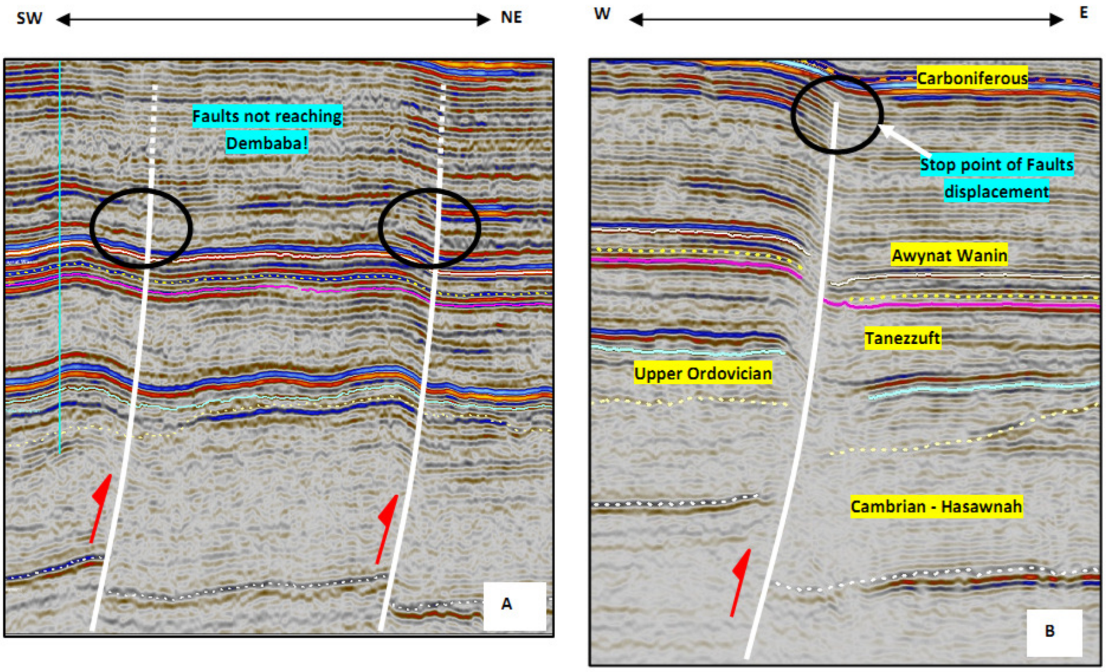


Figure-5.12: Basement faults show decrease of vertical displacement upwards. Faults are not persisting to the Mesozoic and stop at the carboniferous. Folds are generated in the northern part of the study area (Reverse drag folds). The largest vertical displacement is at the southern part of the area of study (see seismic section B) where it reaches up to 300 meters and compared to 150 meters at the northern part. (For seismic lines locations, see figure-5.8).

5.2.1.2.3. Distribution of basement faults in Murzuq Basin

Faults mapped, in the center of Murzuq Basin, based on age by Davidson *et. al.*, (2000) are as following:

1. The basin has been subjected to fault tectonics since Cambro-Ordovician times, and has been active during all the subsequent periods.
2. The faulting that occurred during Cambro-Ordovician and Silurian times was of higher density, decreasing upwards through younger geological periods. Generally, the displacements in all periods are of the same order of magnitude (Davidson, 2000), (Figure-5.13).

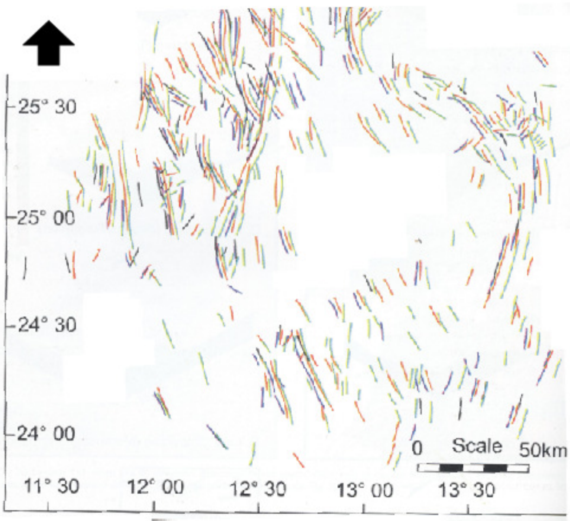


Figure-5.13: Mapping of the Faults in the central part of Murzuq Basin (dashed red area) by Davidson *et. al.,* (2000). The color coding indicates; Green: Cambro-Ordovician, Red: Silurian-Early Devonian, Blue: Late Devonian-Carboniferous. Red and green have higher frequency than other faults.

In Murzuq Basin there are many basement faults mapped by Echikh and Sola (2000) using surface and subsurface datasets. Some of these faults extended from the basement to reach the surface, such as the *Tumarolin Fault* (Figure-5.14). These basement faults are one of the major key contributors and controllers of the reservoir migration and trapping in the basin. Basement faults generally induce strike-slip tectonics in upper sedimentary cover as also observed in the study area in the form of en echelon folds and positive flower structures. These en echelon folds and flower structures indicate multi-phases of rejuvenation of the basement faults by strike slip tectonics. Change from dextral strike-slip faults in the east (e.g. Tumarolin Fault) to sinistral strike-slip in the west (e.g. Bir Tazit Fault) was reported by Echikh and Sola (2000).

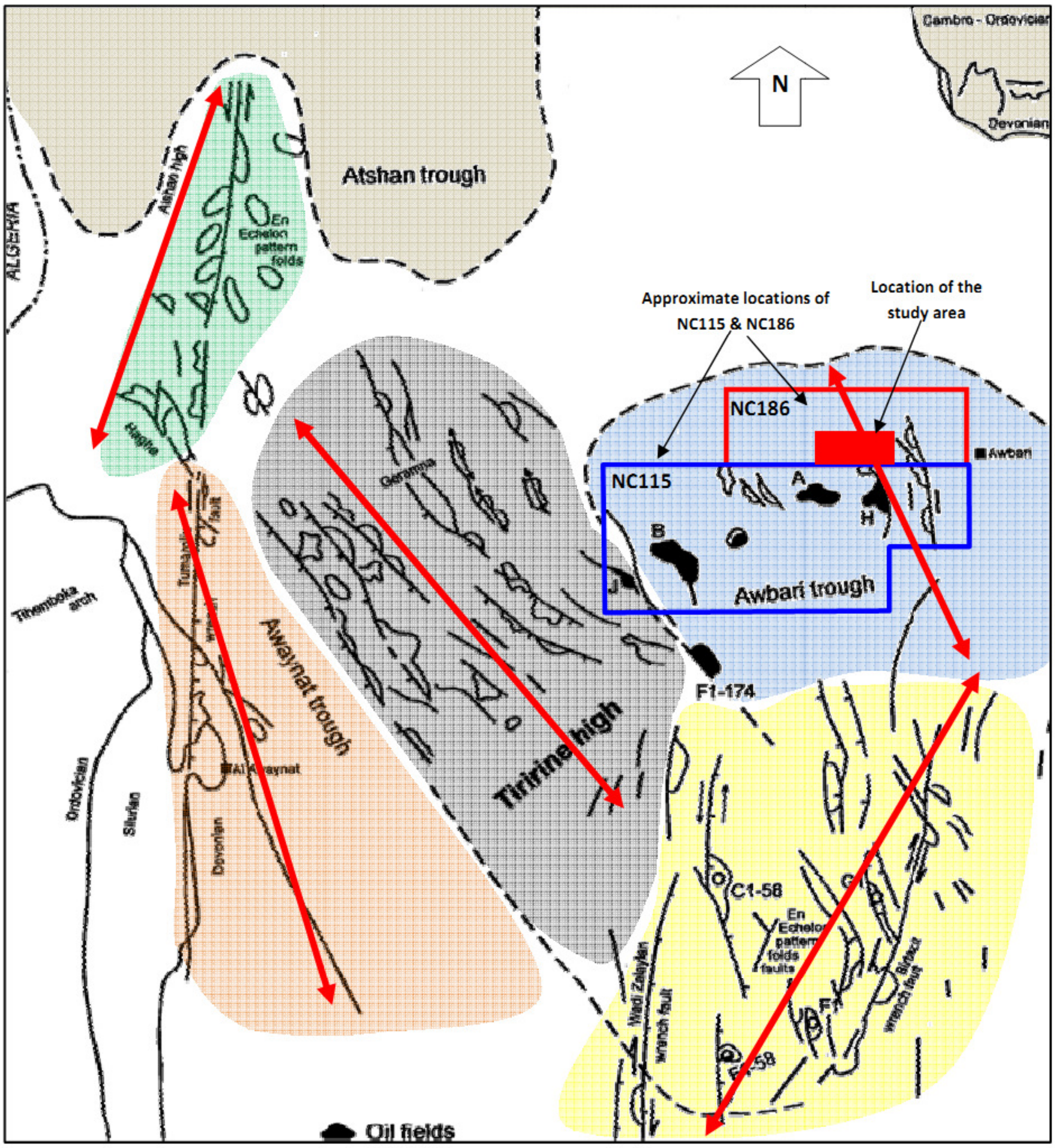
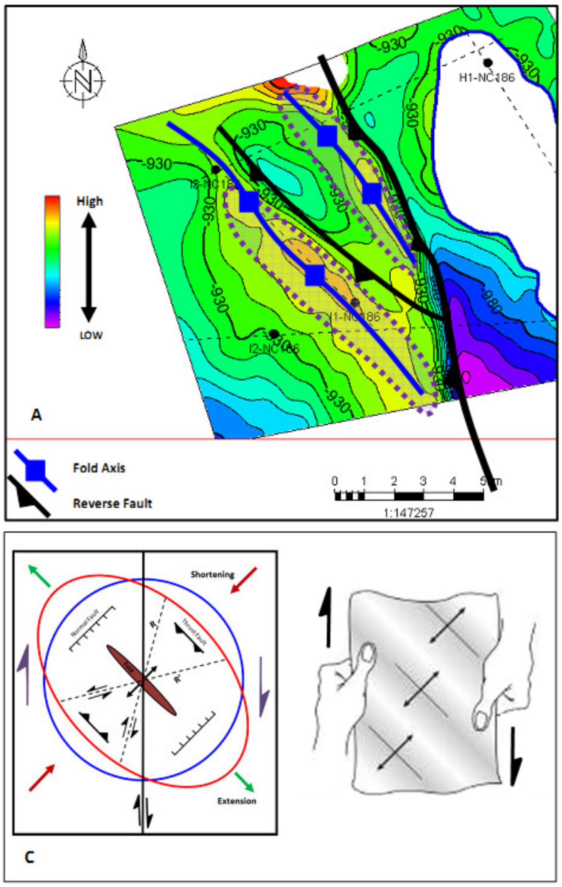


Figure-5.14: Structural configuration of the NW part of Murzuq Basin. The regional change in fault trends from NW to SE parts of the Tiririne high indicated by red arrows. This change was accompanied by strike slip movements of different style and magnitude from the NW to the SE. The area of study is located to the north of the Concession NC174 and NC115. After Echikh and Sola (2000).

5.2.1.3. En Echelon Folds

Pattern of en echelon types of folds were observed from the generated time structural maps of the early and middle Paleozoic horizons in the study area within the I-Field striking NW-SE and terminated at the plane of the major basement faults (Figure-5.15). These features represent strong indication of *dextral transpressional* movements related to the basement faults.

Folds, also known as reverse drag folds, encountered in the study area are concentrated within the Cambrian, Ordovician, Silurian and Devonian successions that indicate pre-Carboniferous tectonic event (Middle Devonian Compression). Based on the fold pattern and their termination to the major faults in the area a strain ellipse constructed to illustrate the structural setting of the area (Figure-5.16).



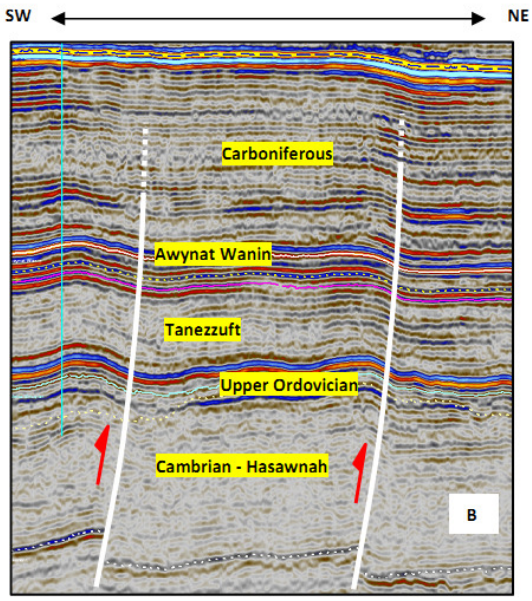
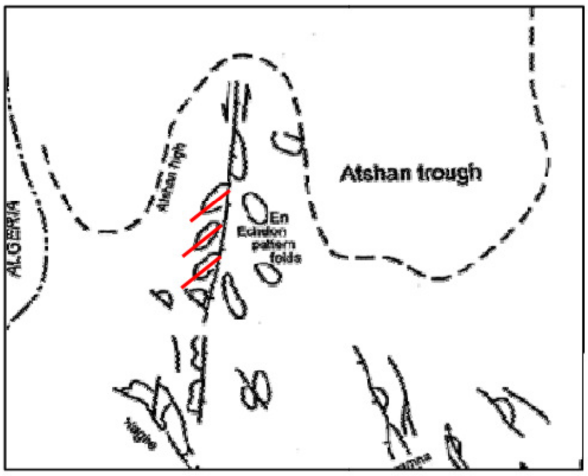


Figure-5.15: Time structural map of the Upper Ordovician shows the major reverse faults and the en echelon fold trends towards the NW-SE. (B) Seismic line at northern part of the study area shows folding effect to the pre-Carboniferous successions. (C) Strain ellipse and type of movement initiated the reverse faulting and en echelon folding in the study area.

En echelon folds observed in Murzuq Basin at many places, such as in Atshan Area to the west of the basin. This is an opposite example of the study area with sinistral strike slip fault and NE-SW en echelon folds (Figure-5.16). However, these structures were developed by transpressional strike slip within the Silurian - Devonian stage.



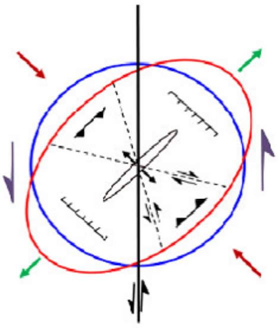


Figure-5.16: En echelon folding generated by left lateral transpressional strike slip faulting at the western part of Murzuq Basin striking NE-SW. After Echikh and Sola (2000).

5.2.1.4. Positive Flower Structures

The term "flower structure" reflects the resemblance of the structure to the petals of a flower in cross section (Figure-5.17). Positive flower structure is defined as structure that resulted from compressional strike-slip faulting (simple shear) along the fault plane. In the positive flower structures *en echelon fold* is developed due to differential lateral displacement accompanied with compressional stress.

Positive flower structures were recognized at the northern part of the study area from the seismic line I3-H1 (Figure-5.18 & 5.19). High resolution seismic interpretation shows positive flower structures intensively over the Pre-Devonian successions. This indicated transpressional events during the Early and Middle Paleozoic time (Cambrian to Mid Devonian).

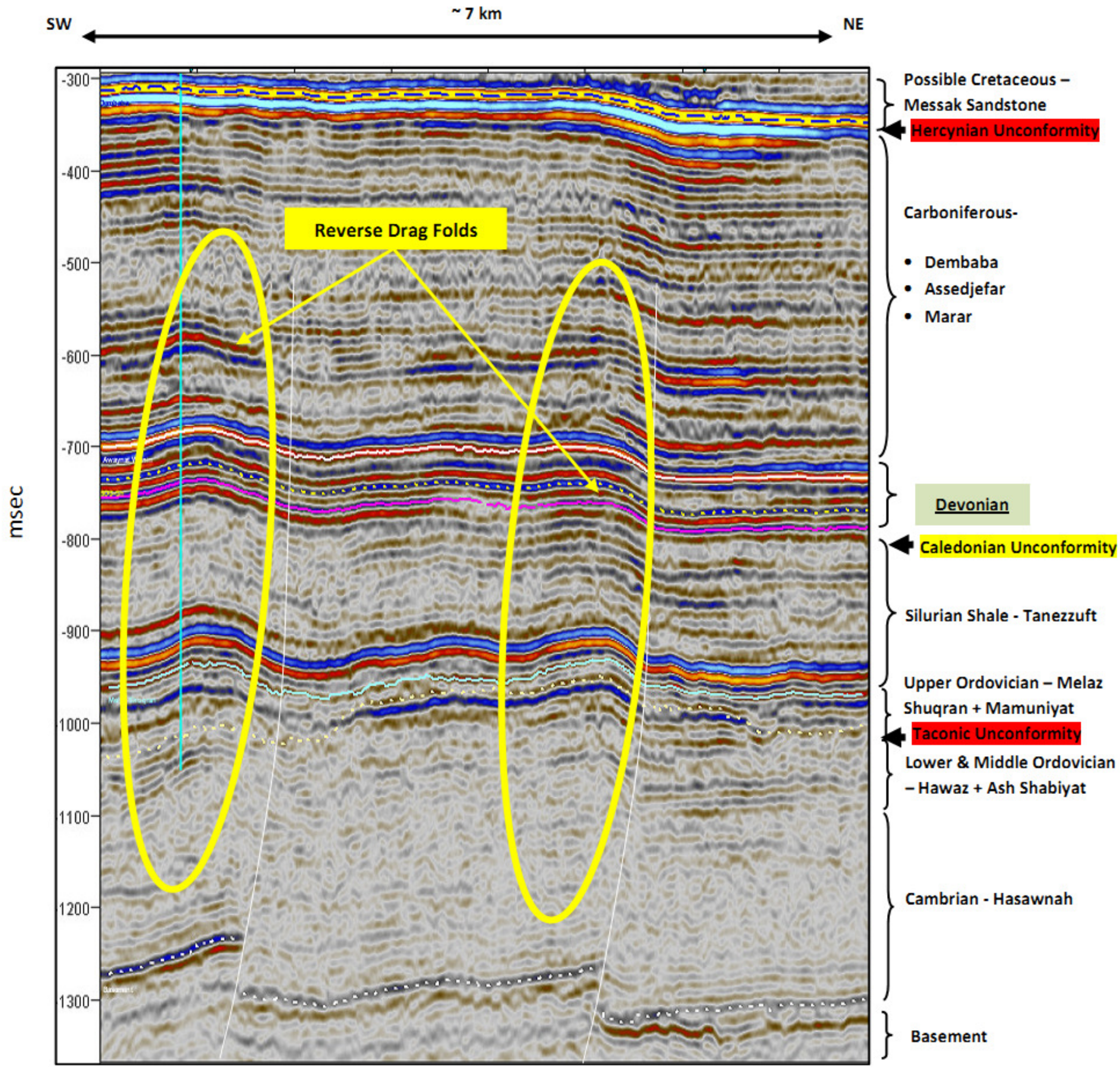


Figure-5.17: Surface seismic line of the northern part of the study area shows clear reverse drag folds. This seismic line clarifies the folds and positive flower structures encountered in the study area (see Figure-5.18 for detailed interpretation).

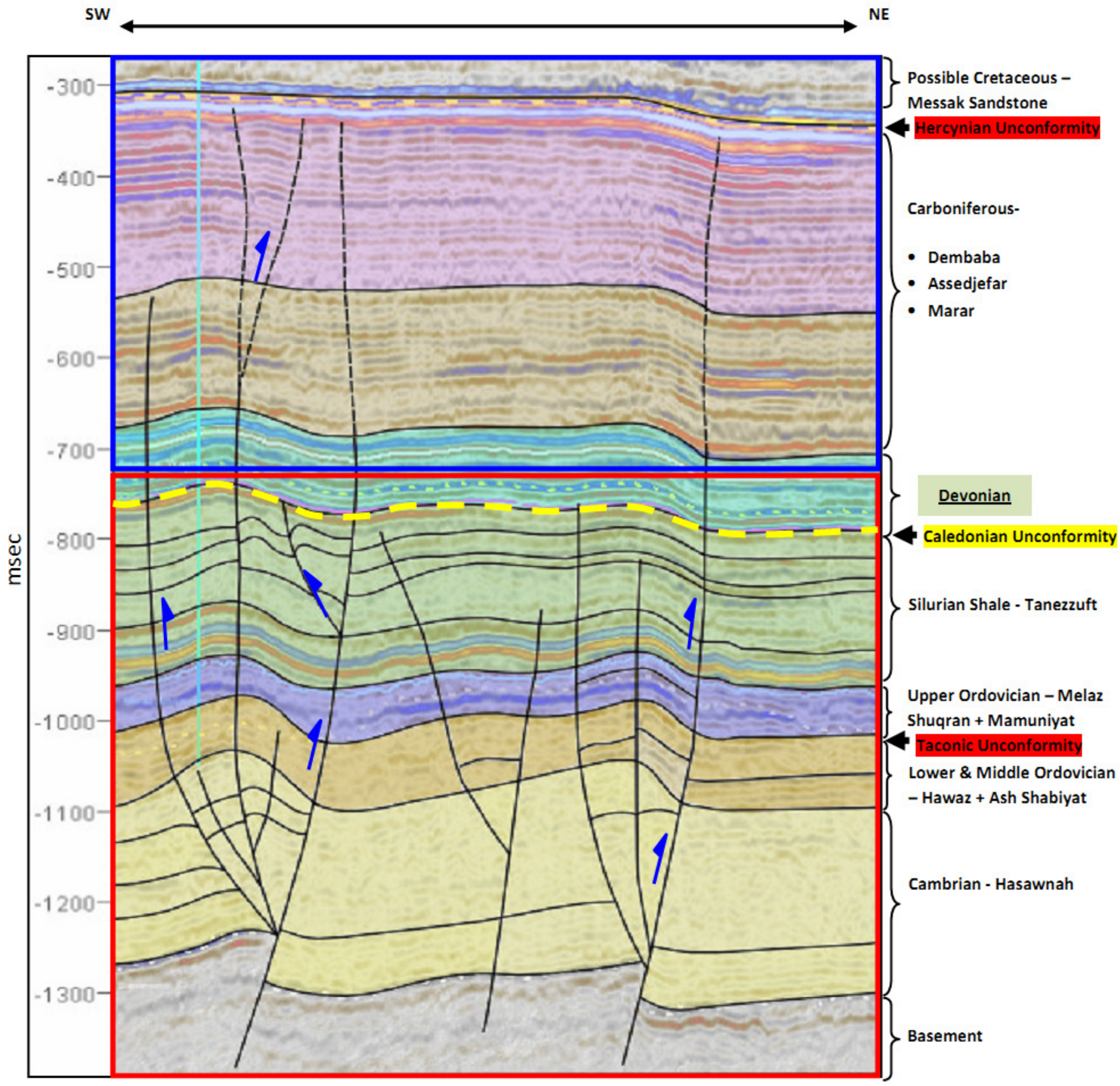


Figure-5.18: Example of positive flower structure in the northern part of the study area where en echelon folds observed (See Figure-5.15). Uniform stratigraphic distribution with decrease of faults intensity above the Caledonian Unconformity indicates of Pre-Devonian simple shear tectonics. Folding and positive flower structures are strong indications of transpressional tectonics developed in Pre-Devonian time.

Positive follower structures are well recognized in Murzuq Basin using seismic data (Craig et. al., 2006). Seismic data indicated the development of transpressional strike slip within the Silurian - Devonian stages (Figure-5.19).

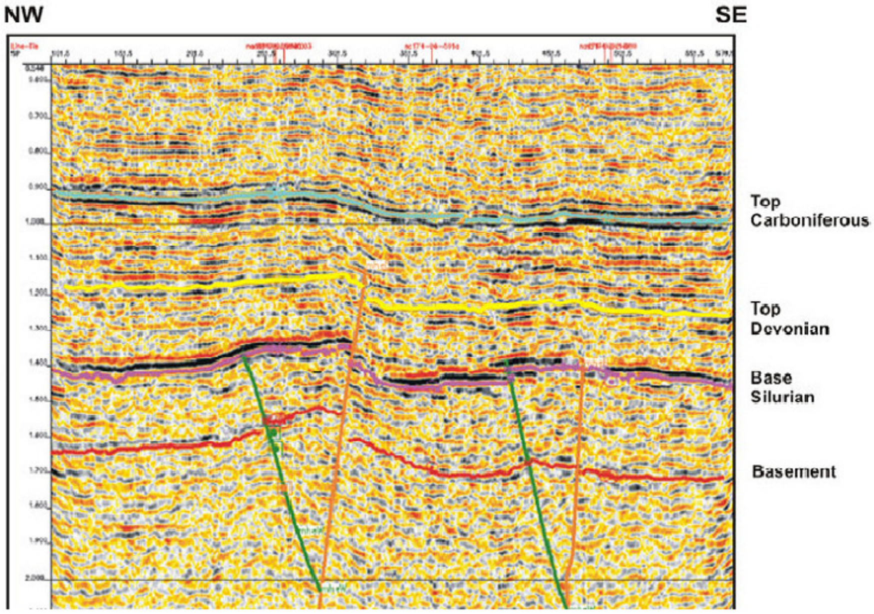


Figure-5.19: Positive flower structure in Murzuq Basin indicates Silurian-Devonian growth faulting to the SE. After Craig et. al., (2006).

5.2.2. Small Scale Structural Elements

5.2.2.1. Micro-Faults Analysis (FMI scale – Borehole size)

FMI tool is used in the oil industry as high resolution geological tool where images and dip computation for any geological features can be acquired. Faults are one of the structural features those can be recognized within the borehole coverage. Therefore, faults observed within borehole size named as Micro-Faults to be distinguished from these observed on seismic data. These features can be correlated to the seismic data and linked to the regional structure context. Based on observations form FMI, here, the faults came across the Ordovician successions are Normal faults and can be distinguished genetically as *Syndepositional* or *Postdepositional* Micro-Faults.

5.2.2.1.1. Syndepositional Micro-Faults

Syndepositional Micro-Faults are defined as faults those have thicker deposits on one of the faults plane side than the other (Figure-5.20A). This phenomenon occurs due to simultaneous faulting and deposition which is common with gravity faults (known also as normal or growth faults). These micro-faults were frequently observed within Melaz Shuqran Formation especially in the wells I1 and I2.

5.2.2.1.2. Postdepositional Micro-Faults

Postdepositional Micro-Faults are defined as faults those shows sharp layer boundaries on the FMI images which indicate tectonics after sediments lithification. These features were mainly observed within upper units of Hawaz Formation in the well H3-NC186 as well as over Ash Shabiyat and Melaz Shuqran Formations in the wells I1, I2 and I3 Wells (Figure-5.20B).

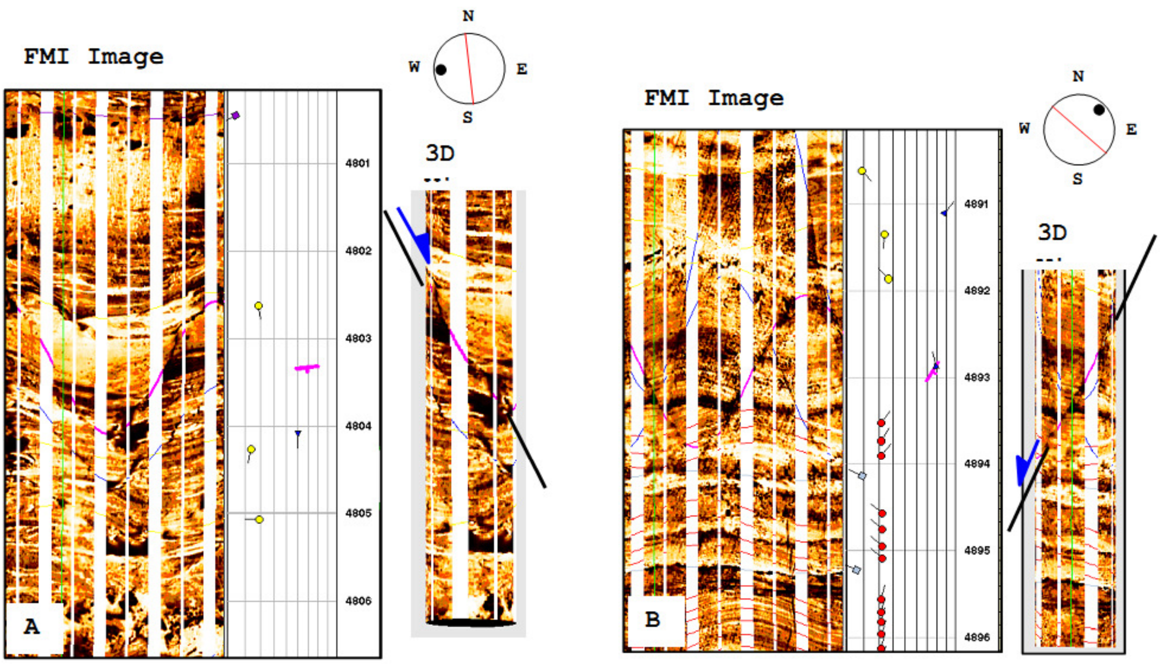


Figure-5.20: (A) An example of Syndepositional Micro-Fault (growth Fault) dipping 70, South as observed on the FMI image with thickness increase over the Melaz Shuqran Formation in Well I1-NC186.(B) An example of Post-depositional Micro-Fault (Normal Fault) dipping 75, ESE within Hawaz Formation in Well H3-NC186.

5.2.2.1.3. Statistical Analysis of Micro-Faults

The Statistical analysis of the Micro-Faults (Normal faults) picked from FMI images represented in strike rosette are illustrated in Figure-5.21. The faults strike direction show changes from Ash Shabiyat to Melaz Shuqran Formations and encountered within the I Wells. In wells I1 and I2, Ash Shabiyat Formation shows NE-SE strike direction while Melaz Shuqran Formation shows NW-SE strike direction. This reversing in faults strike direction indicates change in local structural events from Early to Late Ordovician (structural instability). Hawaz Formation shows faulting in H3 well with scattered strike direction.

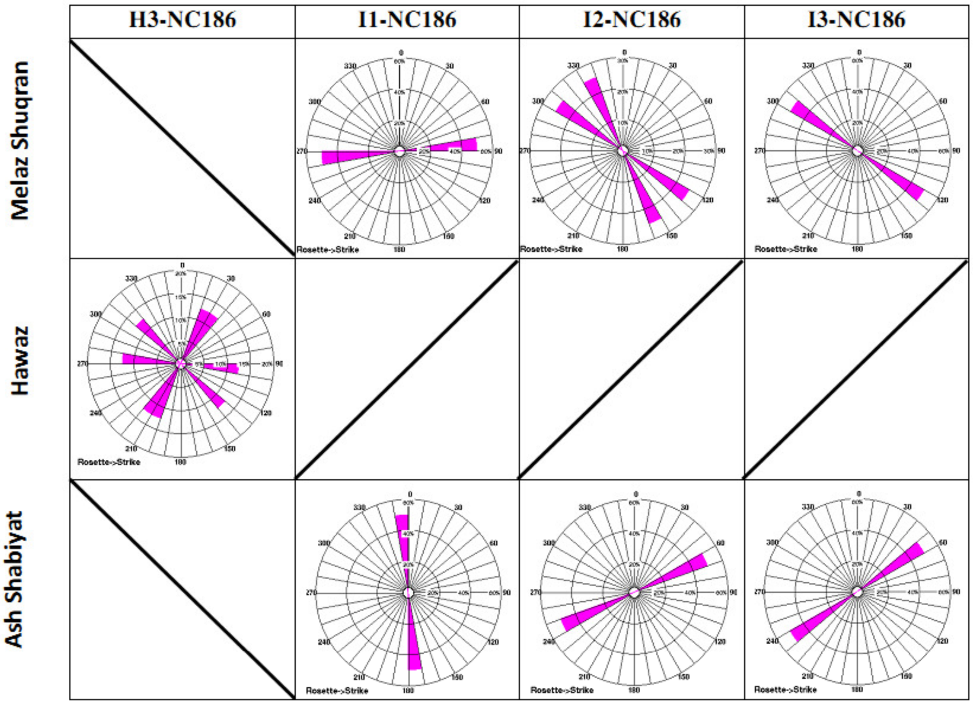
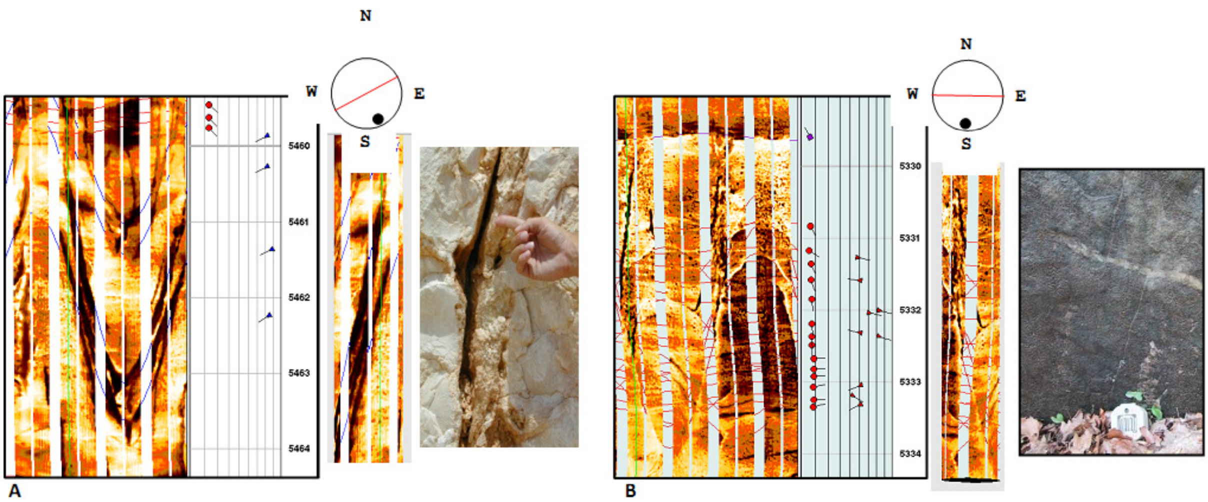


Figure-5.21: Shows the statistical analysis of the Micro-Faults observed from the FMI images in the area of study. Faults are trending either NW-SE or NE-SW which consistent with the ellipse model.

5.2.2.2. Fractures Characterization

FMI is basically a resistivity measurement that can distinguish between the conductive and resistive fractures. Accordingly for fractures characterization using FMI images, fractures are classified into two types, namely Closed Fractures (appear as resistive) and Open Fractures (appear as conductive) based on their appearance on the images (Figur-5.22).



Figurre-5.22: (A) Example of conductive type of fracture over the Ash Shabiyat Formation, well I1-NC186. (B) Example of resistive type of fractures over the Ash Shabiyat Formation, well I3-NC186. Both examples are correlated with outcrops (not for the same formation or area) for illustration

In the area of study, fractures observed within the five wells allowed the following observations and conclusions:

1. Most of the fractures observed within Ash Shabiyat and Hawaz Formations to indicate that the early to middle Ordovician time was a stressed period.
2. The fracture detected using FMI can be related to the fault pattern in the study area. The strain ellipse shows that most of the fractures in the area of study are considered as Riedel and anti Riedel (R and R') Shear fractures (Figure-5.23).
3. The Riedel shears trend mainly NNE-SSW, while the anti Riedel shear fractures trend WNW-ESE.

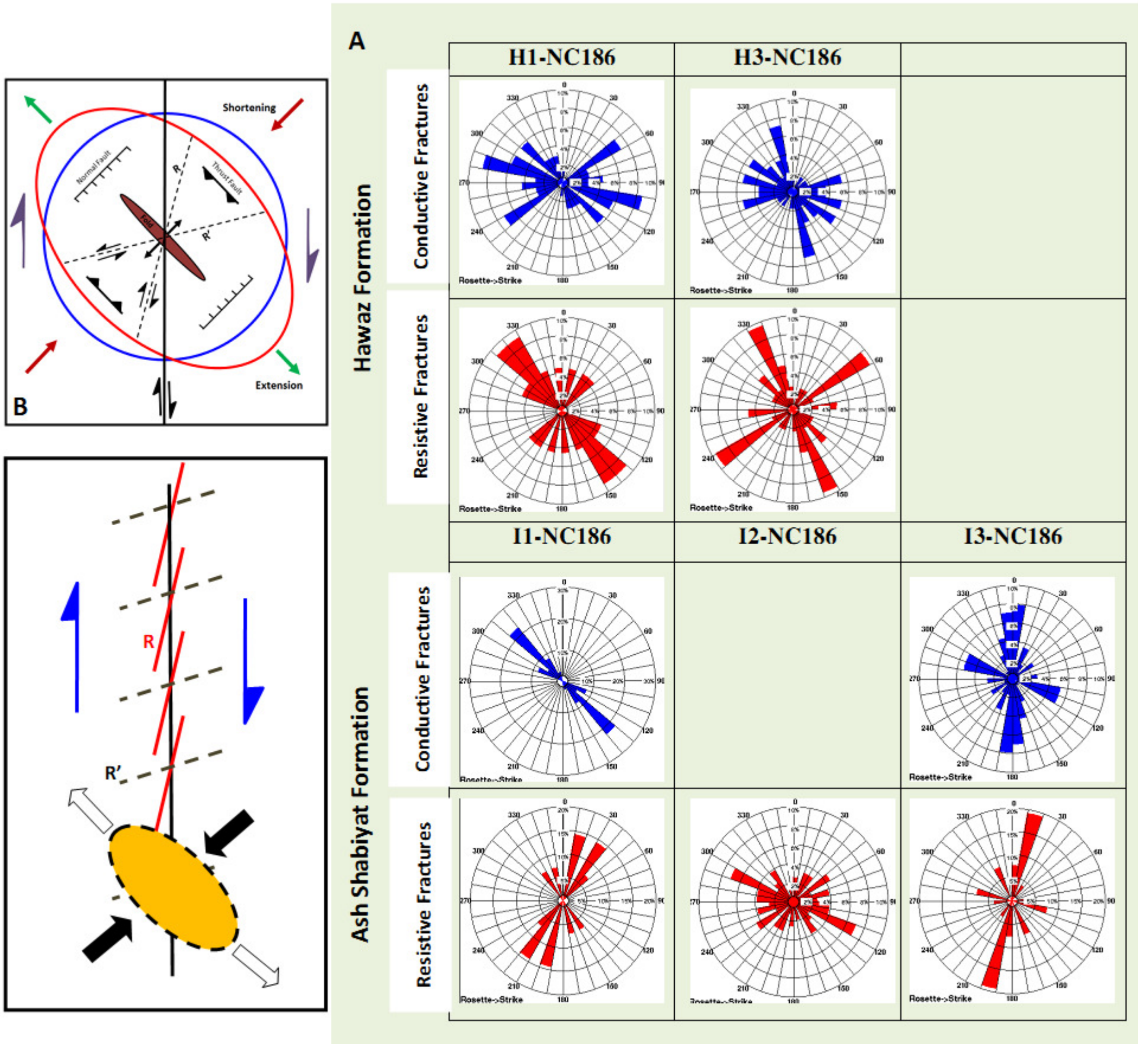


Figure-5.23: Statistical Analysis of both conductive and resistive fractures over Ash Shabiyat and Hawaz Formations. Dextral transpressional generated these fractures are interpreted as Riedel and anti Riedel (R & R') shear fractures. (A) Statistic of the fractures, (B) strain ellipse of the study area and (C) model of generation of R and R' fractures.

Summary of the main structural features and its orientation as observed in the study area *(Basement Faults, Folds, Micro-Faults, F and Fractures)* is summarized in Figure-5.24.

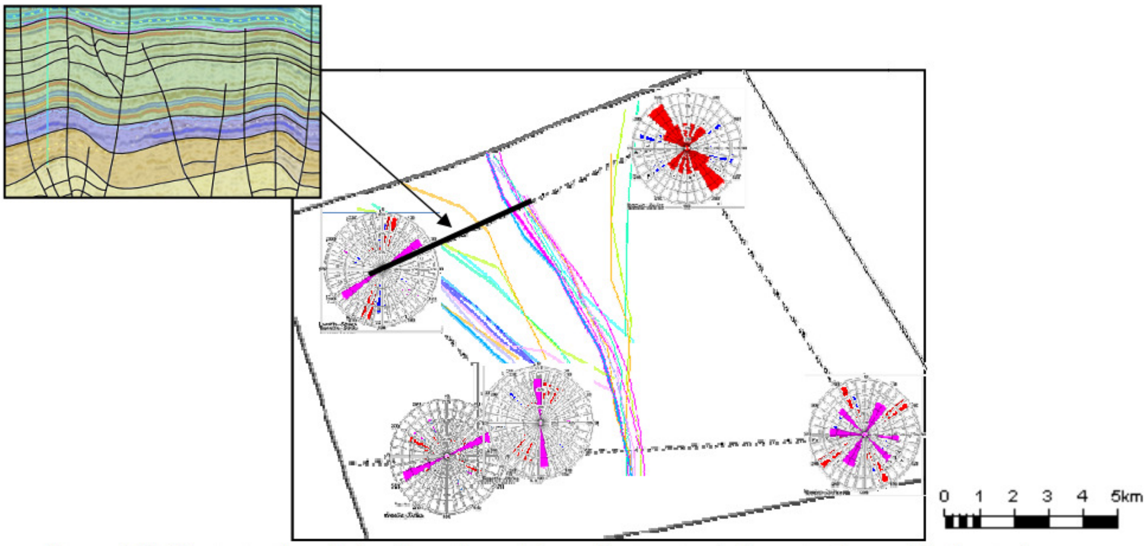


Figure-5.24: Ilustrates the relative durections of the main structural elements observed in the study area.

Major basement reverse faults in the study area trend in NNW-SSE direction where the folds were observed at the northern part of the area trending NW-SE. The micro-faults observed from FMI images almost strike NE-SW and are extensional normal faults within the Ordovician. The fractures were intensively developed within Ash Shabiyat and Hawaz Formations with a general NW-SE and NE-SW strike direction. These observation indicates a multi-tectonic phases comprsssion to extension events combined with strike slip movements. The molde in Figure-5.25 illustrates such elements.

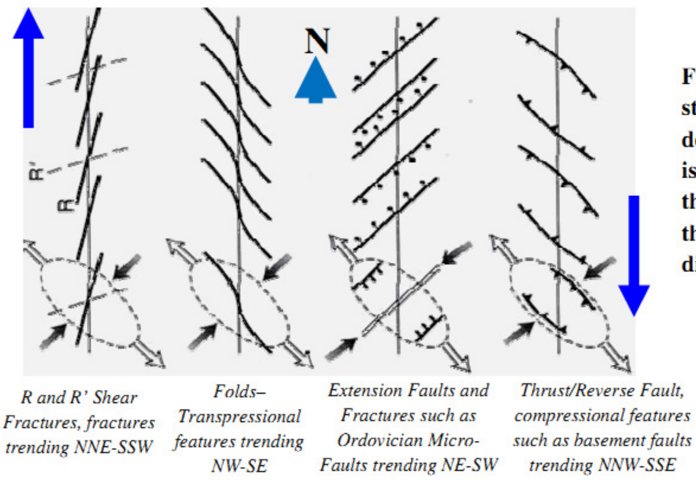


Figure-5.25: shows modeled simple shear strain ellipse, structural elements can develop in different directions. This model is an analog to the structural elements in the area of study in terms of features and their directions. Blue arrows indicate the direction of main stress.

CHAPTER SIX

TECTONIC EVOLUTION & CONCEPTUAL STRUCTURAL MODEL (H & I FIELDS)

This section is a regional synthesis of all the previous observations (i.e. stratigraphic and structural) and interpretation made in the study area. It is only focus on the tectonic evolution of I and H Fields at the south central part of the Concession NC186 and attempt to link it with the regional tectonic evolution (especially the northern part) of the basin.

The tectonic evolution of the study area is complex, especially during the early Paleozoic, in terms of both structure and stratigraphy. Nine episodes or phases are proposed and briefly explained with conceptual modeling for each phase individually as follow:

6.1 Pre-Cambrian to Late Cambrian (Phase-1: Compression & Extension of Pan African).

6.2 Early to Middle Ordovician (Phase-2: Extension + Tectonic Instability).

6.3 Late Ordovician Erosion (Phase-3: Climate Change-Glacial Episode).

6.4 Early Silurian (Phase-4: Extension & Major Marine Transgression).

6.5 Mid Silurian - Mid Devonian (Phase-5: Caledonian Uplifting & Erosion).

6.6 Carboniferous (Phase-6: Hercynian uplifting and regional erosion of Permian).

6.7 Permo-Triassic (Phase-7 Extension to Compression).

6.8 Cretaceous (Phase-8 Compression and erosion).

6.9 Present Day Stress Analysis (Phase-9).

6.1. Pre-Cambrian to Late Cambrian (Phase-1: Compression & Extension of Pan African)

By the end of the Pre-Cambrian, the configuration of the major structural elements in Murzuq Basin took place in the form of highs and lows separated by basement Faults. Intensive shearing and compression occurred due to multiple mega collisions between the terranes and cratons along the Trans-Saharan Megabelt. The first configuration of Murzuq Basin was started during this time as one of the largest intracratonic basins in North Africa. Many basement faults in the basin were recognized and identified as being generated during Pan African Orogeny strike mainly NNW-SSE and NW-SE which controlled later depositional trend of early Paleozoic successions.

Variations of the Cambrian stratigraphic successions at the faults plane indicated syndepositional activation of basement faults. The sense of movement is considered as extension due to thickness increase at the hanging walls and deposition of fluvial sandstone sequences. At the end of the Cambrian, compression (transpressional) dominated the study area as indicated from seismic data. Positive flower structures observed crossing the Cambrian successions propagating from the Basement-Cambrian contact which might be related to Late Cambrian compression (Figures-6.1 & 6.2). The directions of the compressional forces were dominant NE-SW.

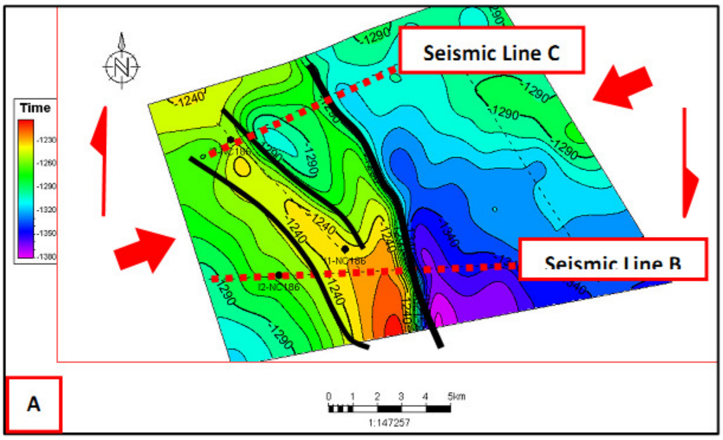
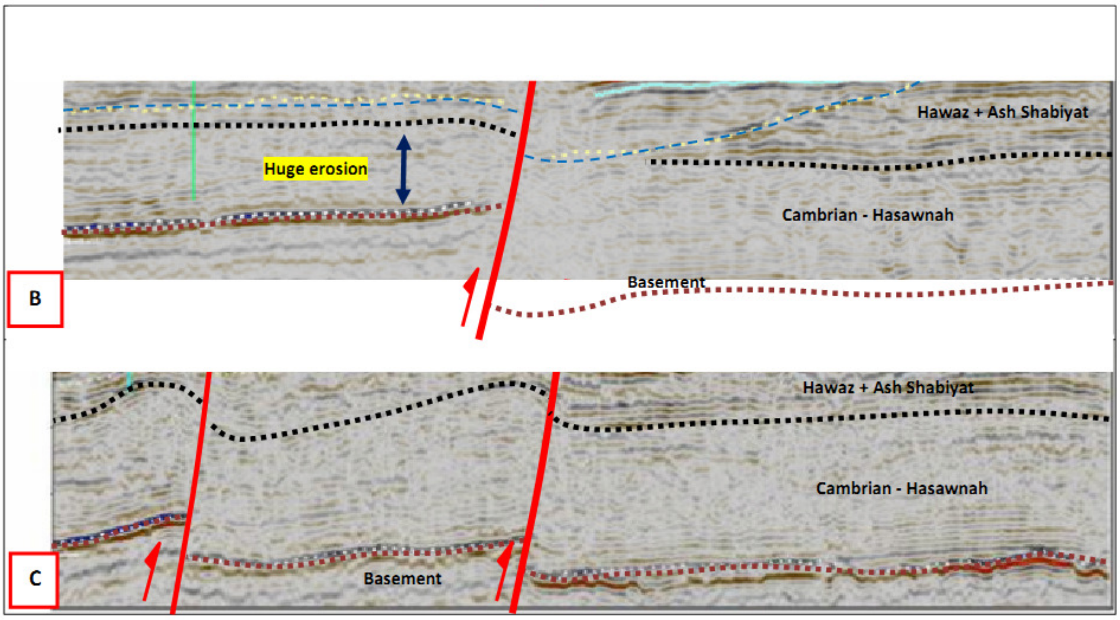
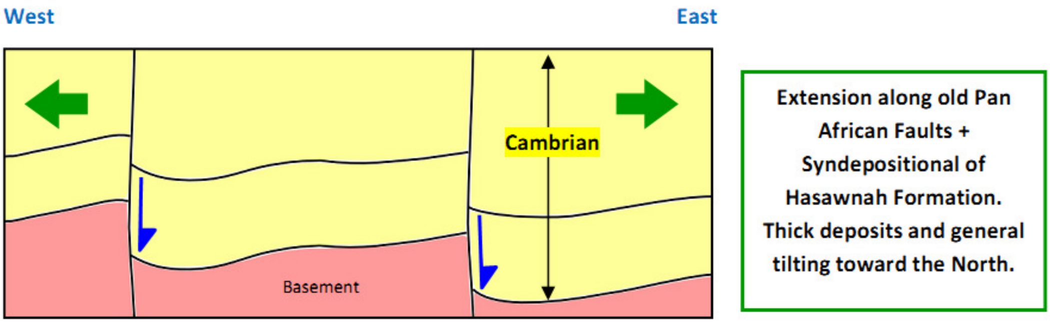


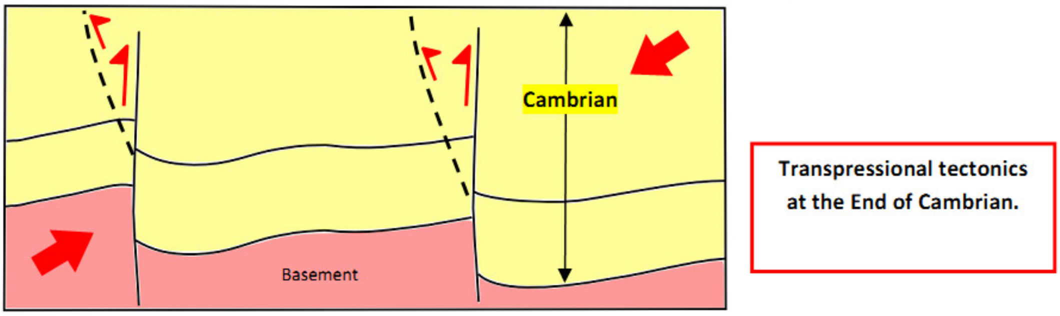
Figure-6.1: (A) Present day time structural map of top Basement shows the major reverse faults in the area trending NNW-SSW and NW-SE. (B) Seismic line at the southern part of the area shows thick Cambrian deposited at the reverse fault which indicates an episode of previous extension (growth faults). (C) Seismic line at the northern part of the area shows present day reverse faults crossing the basemen and Cambrian rock. These faults are interpreted as positive flower structures. Both sides of the faults are of similar thickness which exhibit erosion variations from north to south.



a. Cambrian Extension and thick deposits of Hasawnah Formation



b. Late Cambrian Compression (Positive Flower Structures! – Uplifting and Erosion).



c. Seismic interpretation of the Cambrian succession.

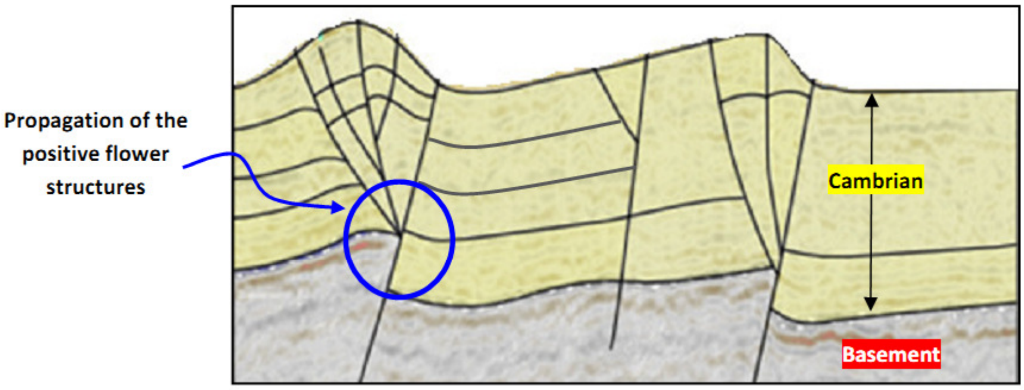


Figure-6.2: Shows the possible tectonic phase during Cambrian in the study area form extension to transpression. Positive flower structure propagating from the Basement-Cambrian contact which indicates compressional event during Late Cambrian.

6.2. Early-Middle Ordovician (Phase-2: Extension + Tectonic Instability)

After the deposition of the Cambrian sandstone and at the beginning of the Ordovician times uplifting and tilting with subsequent unconformity eroded most of the Cambrian deposits at the southern part of the study area in the upthrown sides (hanging wall) of the basement faults (Figure-6.1B). Tectonically, Early to Middle Ordovician was not active relative to the other Early Paleozoic ages as indicated from the lateral stratigraphic continuity a of Hawaz and Ash Shabiyat Formations.

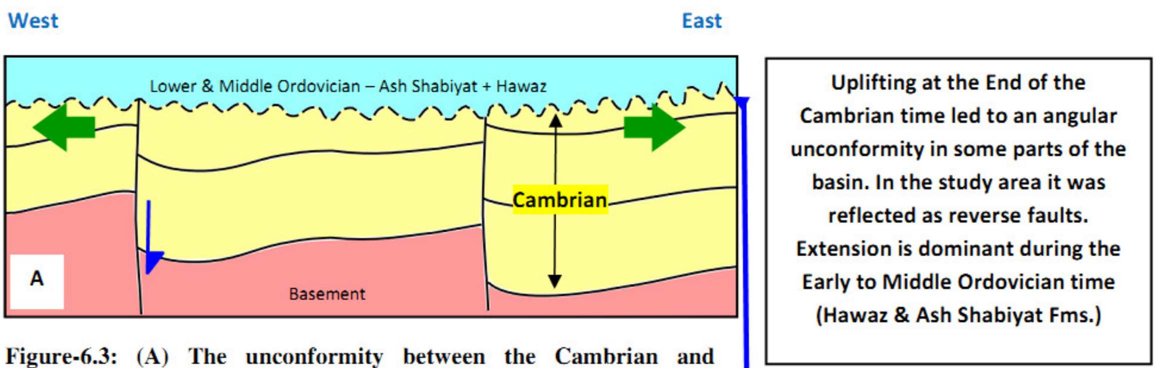
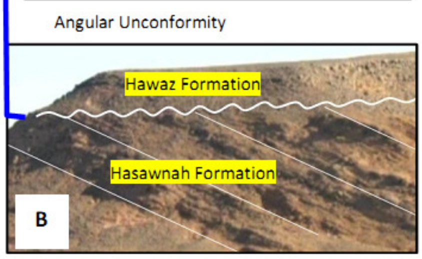
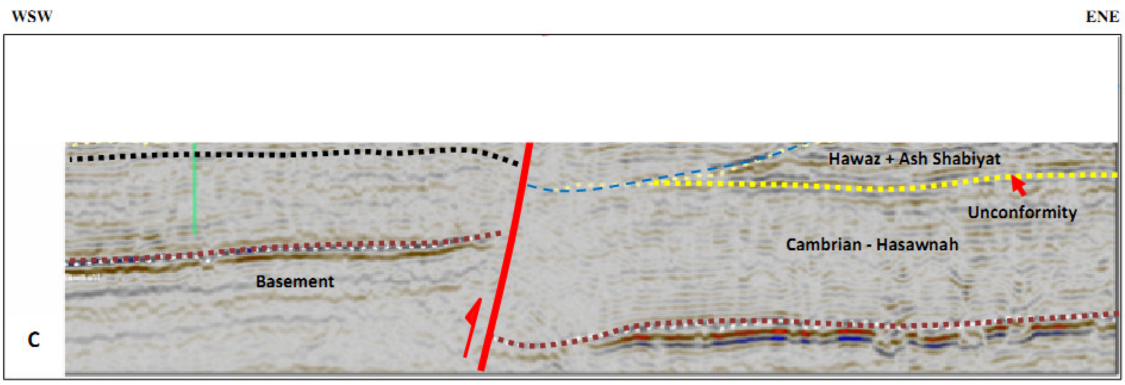


Figure-6.3: (A) The unconformity between the Cambrian and Ordovician successions in the area of study. In this model it is demonstrated that the upthrown side of the reverse faults were subject of erosion. (B) An example of angular unconformity between the Hasawnah and Hawaz Formations in Jabal Dur Al Qussah. (C) Shows the unconformity between the Cambrian and Ordovician successions in the area of study.





6.3. Late Ordovician Erosion (Phase-3: Climate Change-Glacial Episode)

During the late Ordovician a short lived glacial episode (between 0.5 to 1 Ma) was recorded in the whole of North Africa (Figure-6.4). The contact between Middle to Upper Ordovician has a particular impact on the geological history of the area where the depositional environment of Middle Ordovician was shallow marine and the Upper Ordovician as glacial. At the contact between these two episodes, of Middle and Upper Ordovician successions, a regional unconformity developed crossing the whole of North Africa and known as polygenic "Taconic Unconformity" and can be correlated for hundreds of kilometers. This unconformity generated topographic paleohighs and paleolows and becames candidate of the Upper Ordovician deposits.

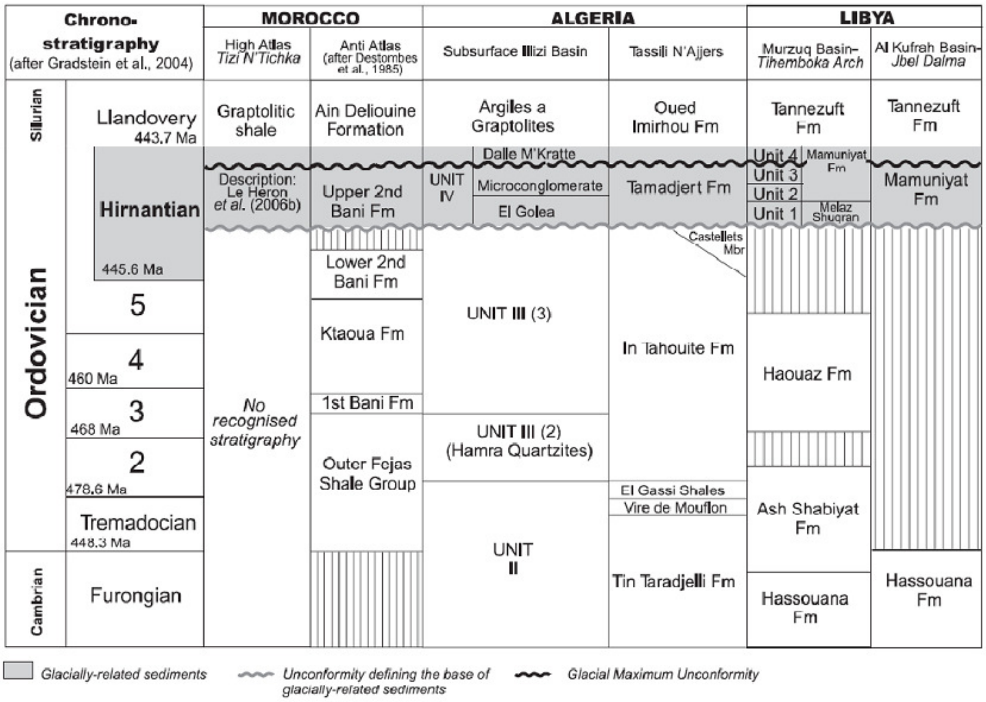


Figure-6.4: Stratigraphy of Late Ordovician glacially related deposits and their correlation across northern Morocco, southern Morocco, Algeria (subsurface), Algeria (Tassili N'Ajjers outcrop) and western Libya (Murzuq Basin) and eastern Libya (Al Kufrah Basin). The correlation emphasizes the Glacial Maximum Unconformity (Source: Le Heron and Craig, 2008).

Large glacial valleys eroded widely and deeply (more than 7km wide and 300 meter deep) into the older Paleozoic formations reaching Hasawnah Formation in some areas. From the stratigraphic correlation between the three wells I1, I2 and I3 it is concluded that; the deeper depositional setting at the Late Ordovician time generally was towards the south. These observations indicate subtle extension during the glacial episode (Figures-6.5 & 6.6).

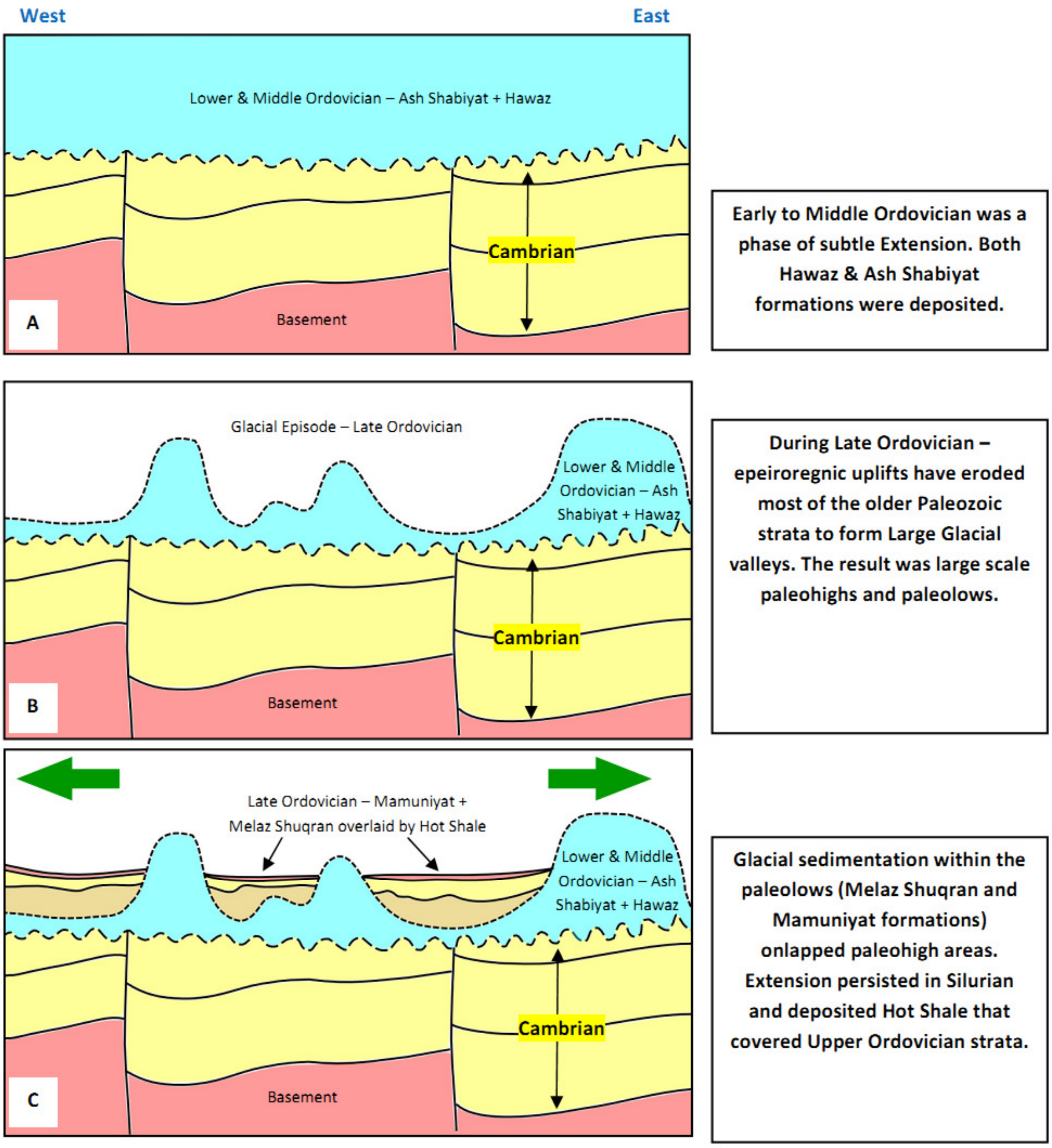


Figure-6.5: Modeled cartoons of the tectonic evolution in the study area within the Ordovician (A, B and C).

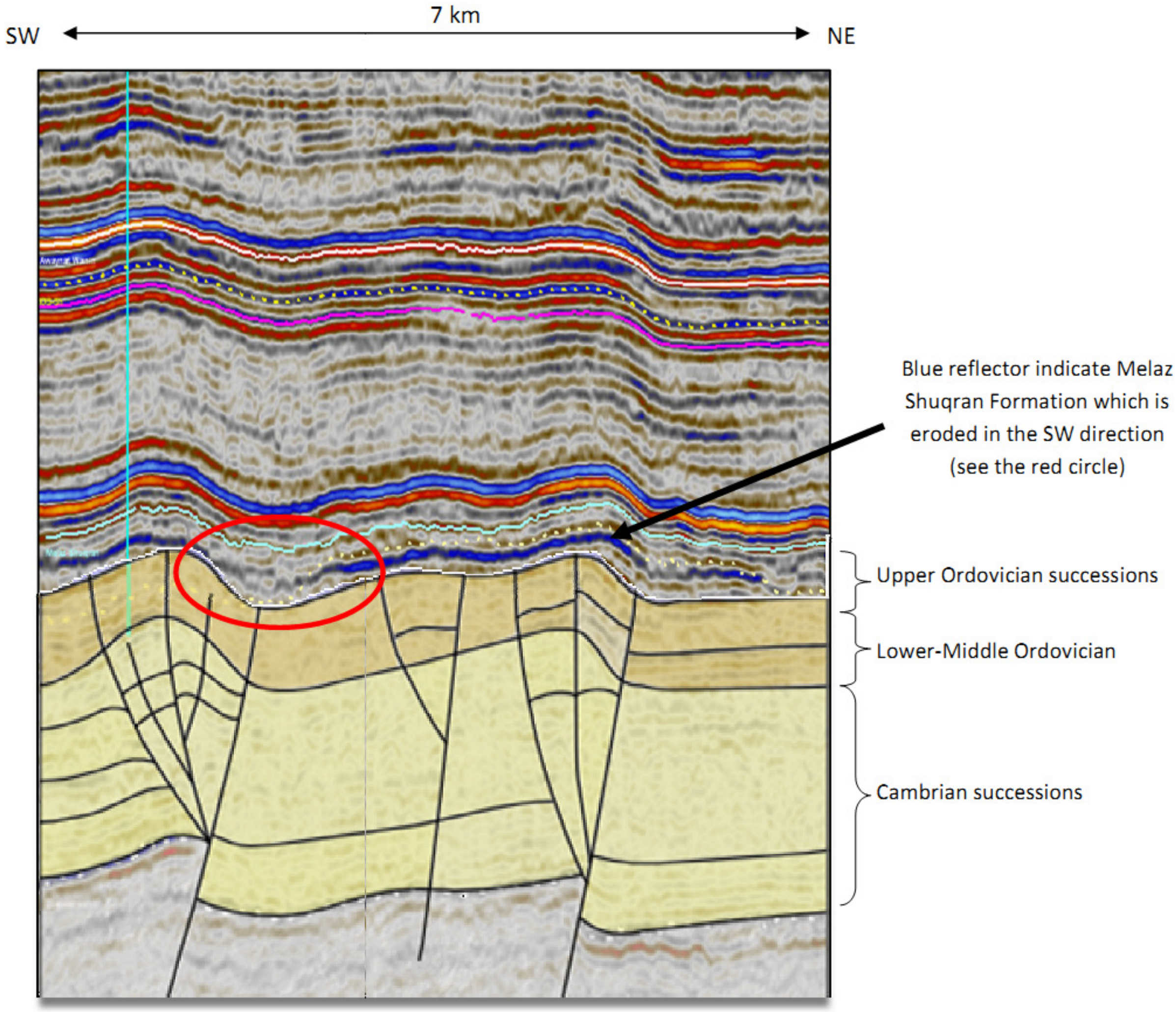


Figure-6.6: illustration of the Upper Ordovician successions based on seismic data. The clear eroded zones are located at the trough sides of the pre deposits.

6.4. Early Silurian (Phase-4: Extension & Major Marine Transgression)

During the early times of the Silurian and due to ice melting, regional unconformity was recorded and defined by transgressive event. Early Silurian was characterized by regional subsidence and extension of the north Gondwanan passive margin reflecting the development of the proto-Tethyan ocean between Gondwana, Armorica and Avalonia (Craig et. al., 2006). In the area of study, this extension is reflected by major transegression and deposition of thick sequences of Tanezzuft Shale covering all the older paletopography of Ordovician successions (Figure-6.7). The absence of any new deviating in faults with this significant subsidence approves that the subsidence generated faults along the old existed basement faults.

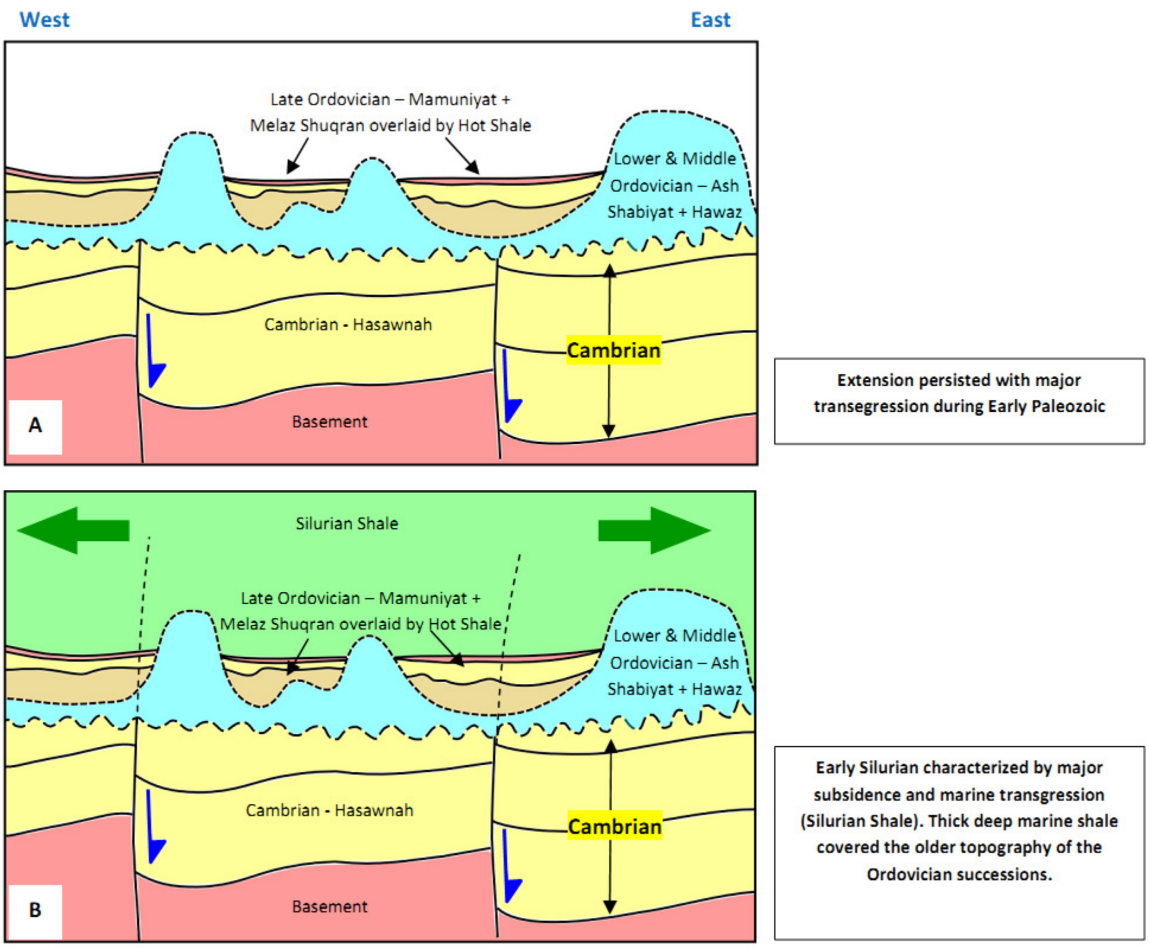


Figure-6.7: Modeled cartoons of the tectonic evolution in the study area within Early Silurian (A and B).

6.5. Mid Silurian - Mid Devonian (Phase-5: Caledonian Uplifting & Erosion)

The second major tectonic event in Murzuq Basin, after the Pan African Orogeny, was recorded in the Middle Silurian to Middle Devonian (known also as Caledonian Orogeny). It's highest peak was in the Middle Devonian where uplifting and intensive erosion took place such as the total erosion of Akakus Formation. During this tectonic phase intensive rejuvenation of the old basement faults in the area of study occurred under transpressional mode as indicated by positive flower structures, tear faults, and en echelon folds. From seismic data interpretation it is visible that, all positive flower structures are created by basement faults terminated at the Silurian-Devonian contact which is in accordance with a mid Devonian compression (Figure-6.8).

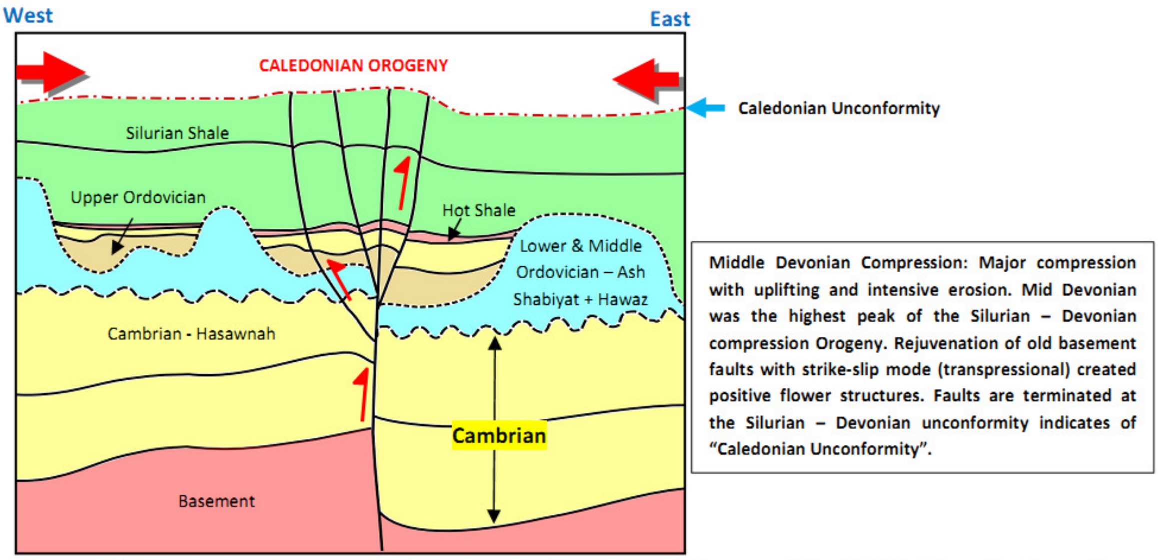


Figure-6.8: Modeled cartoons of the tectonic evolution in the study area of the Middle Devonian Inversion. Compression is the dominant structural movement with uplifting and intensive erosion during this phase.

6.6 Carboniferous (Phase-6: Hercynian uplifting and regional erosion of Permian)

During Late Carboniferous - Early Permian, a regional tectonic orogeny (uplift and erosion) occurred in North Africa (Hercynian Orogeny). The Late Paleozoic is characterized by the thickest sedimentary accumulations in the study area. The tectonics activities during late Paleozoic eroded the entire Permian successions in the study area. From seismic data, it is noticed that this tectonic event has no major vertical component compared to the lateral impact.

Mapping the top of the Carboniferous (Dembaba Formation) shows change in faults direction towards the NE-SW comparing to the early Paleozoic (Figure-6.9). This change indicates change in the direction of compression forces from early to late Paleozoic from NE-SW to the NW-SE respectively. Pop ups or folds were observed to indicate large scale drapping on the older Paleozoic structures. The general compressional stress direction in the area was in NW-SE direction during the Hercynian Orogeny. This stress has affected the whole Murzuq Basin and formed the Gagaf Arch trending ENE-WSW. The time top structural map of the Dambaba Formation (Upper Carboniferous) in the study area confirms ENE-WSW structural trend analog to the structural elements trend of the Hercynian in the northern part of the basin.

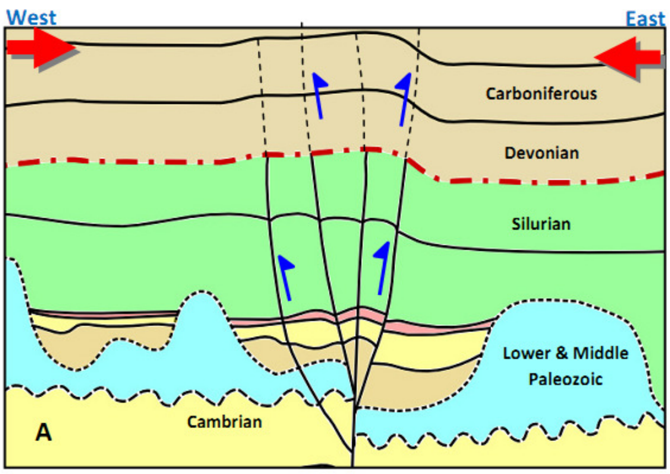
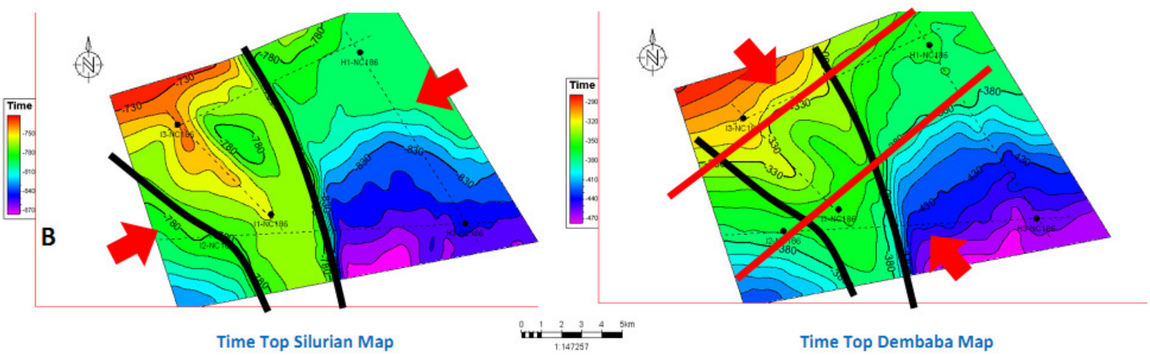


Figure-6.9: (A) Modeled cartoon of the study area shows possible extending of the faults into the Hercynian Unconformity. (B) Shows the time top structural map of Dembaba Formation indicating the major structural elements. New late Paleozoic direction in ENE-WSW indicates new structural trends (Hercynian trend – Red lines); early Paleozoic trend (Black lines). Red arrows indicate the major trend of the Hercynian Orogeny in the area.



6.7. Permo-Triassic (Phase-7 Extension to Compression)

Due to rifting of Pangea supercontinent, regional extension and transtension tectonics occurred during the period between the end of Permian and beginning of Triassic and persisted till Early Cretaceous. The available seismic data revealed that; the Mesozoic succession in eastern part is thicker than the western part and thicker towards the south (Figure-6.11). Generally, the thickening of the Mesozoic sediments is towards the SE that indicates Mesozoic formed highs to the NNW. This tilting from NW to the SE might be related to the extensional phase that was dominant during Triassic and Jurassic in the whole basin. Onlapping of the Triassic successions over the Carboniferous indicates angular unconformity that is related directly to the Hercynian Orogeny (Figure-6.10).

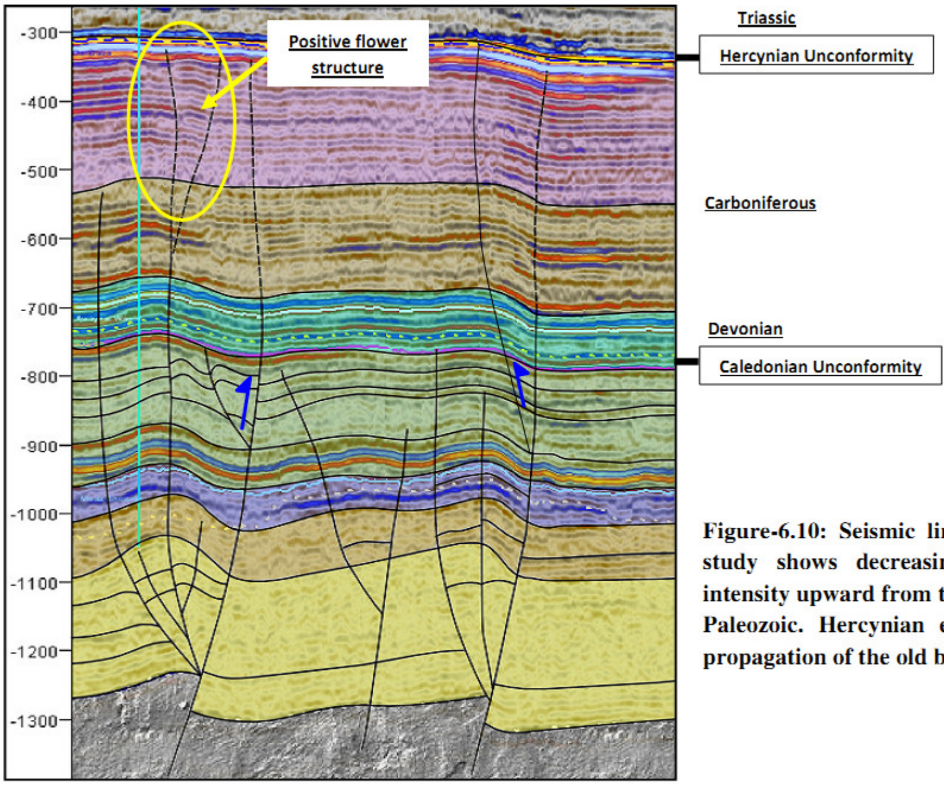


Figure-6.10: Seismic line in the area of study shows decreasing of the faults intensity upward from the Middle to Late Paleozoic. Hercynian event shows only propagation of the old basement faults.

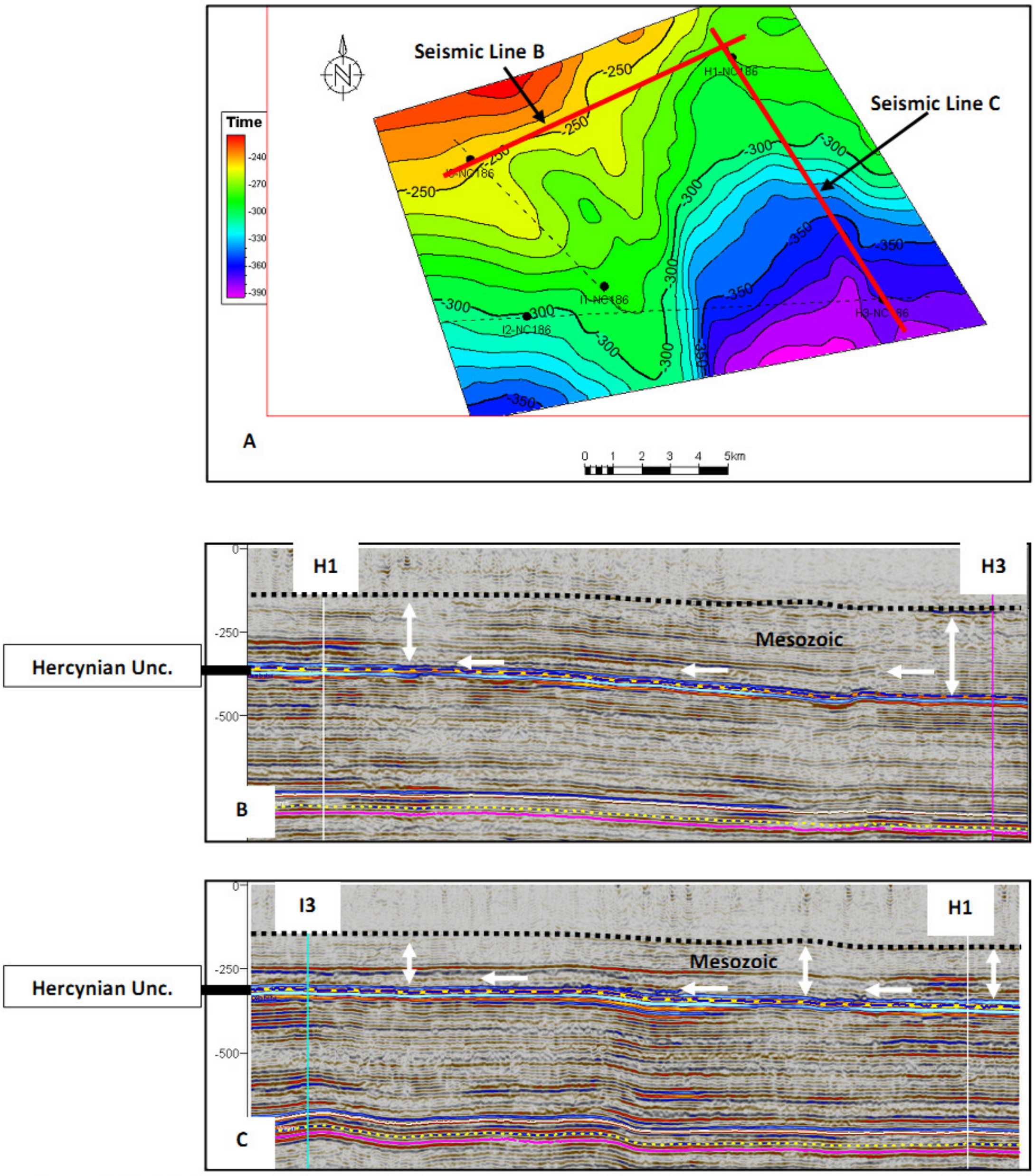
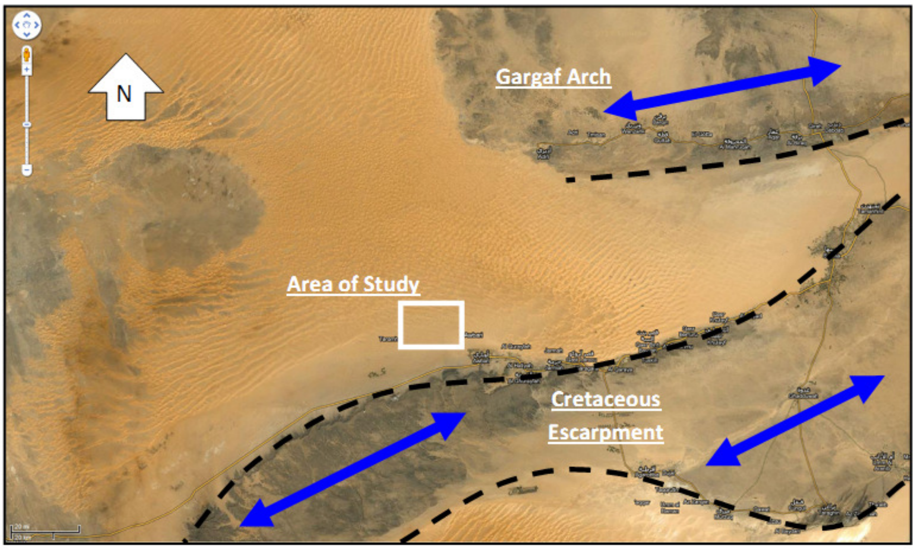


Figure-5.11: (A) Time top structural map of the Mesozoic successions shows high areas in the NW and Lows in the SE direction. (B) seismic line H1-H3 crossing the eastern part of the study area and shows thickening of the Mesozoic successions over the Hercynian Unconformity towards SE. (C) seismic line I3-H1 crossing the northern part of the study area and shows onlapping of the Mesozoic successions in the Hercynian Unconformity.

6.8. Cretaceous (Phase-8 Compression and erosion)

The study area is located between and confined by two large structural elements trending ENE-WSW (i.e. Gargaf Arch and Messak Escarpment) these structural elements controlled the tectonic evolution of the area from Mesozoic to present day. Regional uplifting and erosion occurred in the study area during late Cretaceous coincides with the Alpine Orogeny. Tilting towards the SE could be related to rejuvenation along the basement faults and compressional tectonics developed the "Messak Escarpment" to the South of the study area (Figure-6.12). This structural element is trending parallel to Gargaf Arch (Middle Devonian) towards the ENE-WSW. The upper sequences of the Mesozoic successions in the study area are characterized by thickening in the hanging wall sides of the major faults trending ENE-WSW.



Source of Images: http://maps.google.com

Figure-6.12: Satellite map of the area shows the main surface highs in the nearby area of the study. The area is bounded from the North and South with post Middle Devonian structural highs (i.e. Middle Devonian Gargaf Arch to the north and Messak Escarpment of Cretaceous to the south). Both elements are mainly trending ENE-WSW and NE-SW which might be controlled the Post Middle Devonian tectonic evolution.

Inversion like features might be related to Cretaceous (Early Extension and Late Compression) striking ENE-WSW direction (Figure-6.13). This is mainly of early Cretaceous extensional and compressional tectonics which axis was extending in NNW-SSE direction.

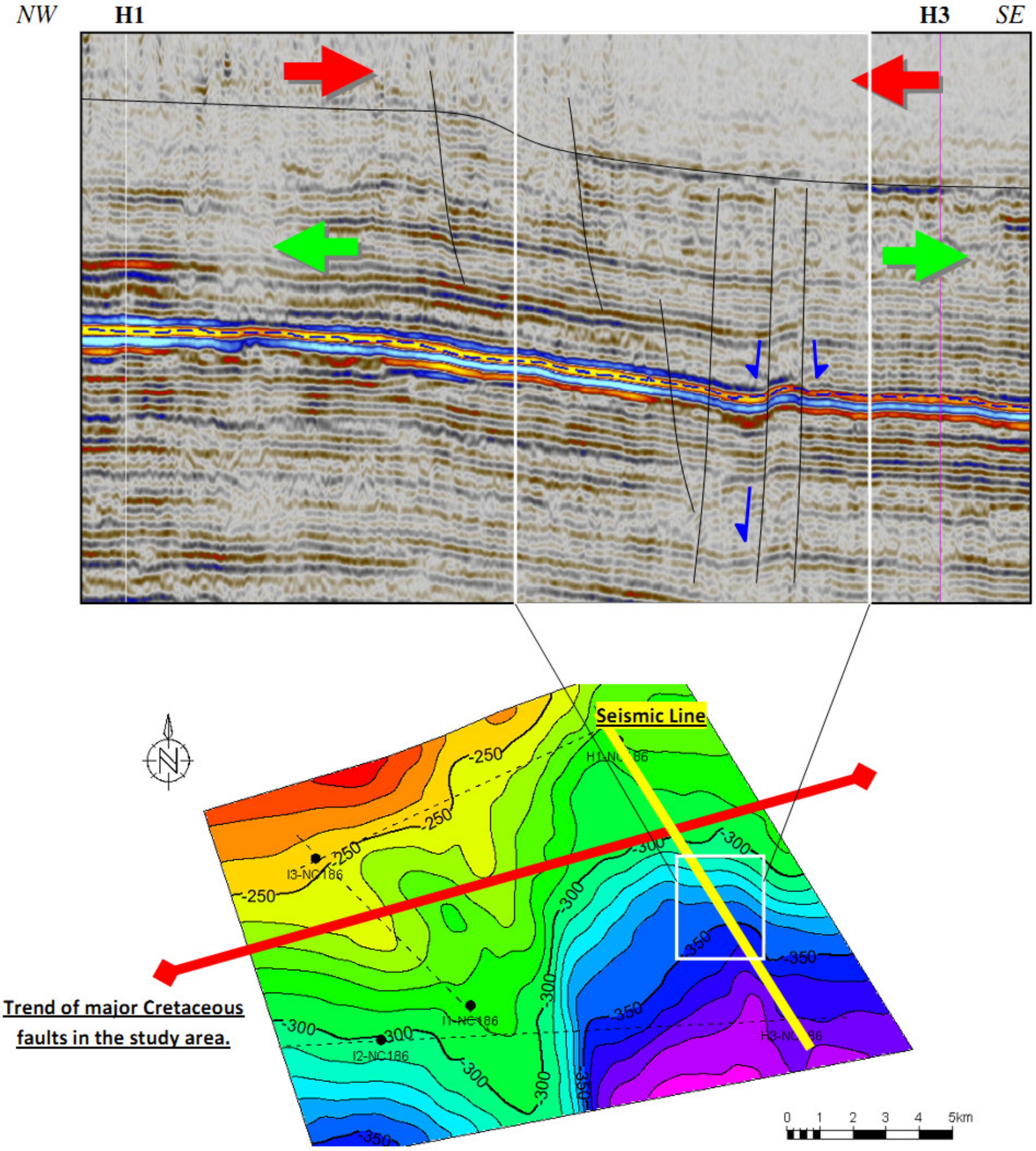


Figure-6.13: Surface seismic line trending NW-SE direction shows reverse fault of two movements from extension to compression (possible inversion!). Majority of faults strike ENE-WSW to coincides with the nearby Messak Escarpment direction.

6.9. Present Day Stress Analysis (Phase-9)

The present day stress analysis over the area of study carried out using borehole stability to recognize the present day stress direction in horizontal direction. Stress state is lithostatic when all points in the crust are subjected in all directions to equal stresses ($\sigma 1 = \sigma 2 = \sigma 3$). But by drilling of well, the vertical stress component value is considered zero and only the other two main horizontal stresses are present. Knowing the directions of these two horizontal stresses and the regional tectonic setting of the area present day stress can be analyzed. However, wells drilled in areas subjected to unbalanced stress systems often exhibit two types of borehole failures, shear and tensile (Figure-6.14).

The rocks can bear both compressive and shear stresses but the fluid filling the borehole can bear only compressive stress. A concentration of stresses can take place around the borehole in the form of so called hoop stress (tangential stress) and radial stress. When the mud weight is too low, then the maximum hoop stress becomes much higher than the radial stress and a shear failure of the rocks exposed to the borehole takes place. This failure takes the form of a borehole elongation as seen on the orthogonal calipers of pad type imaging tools and as sub-vertical dark regions on the images that are 180 degrees apart. Features developed at this stage known as "*borehole breakouts*" (Figure-5.13). When the mud weight is too high, the radial stress increases and the hoop stress decreases and the rock around the borehole comes under tension and fails in tension with creation of "*drilling induced fractures*" (Figure-6.14).

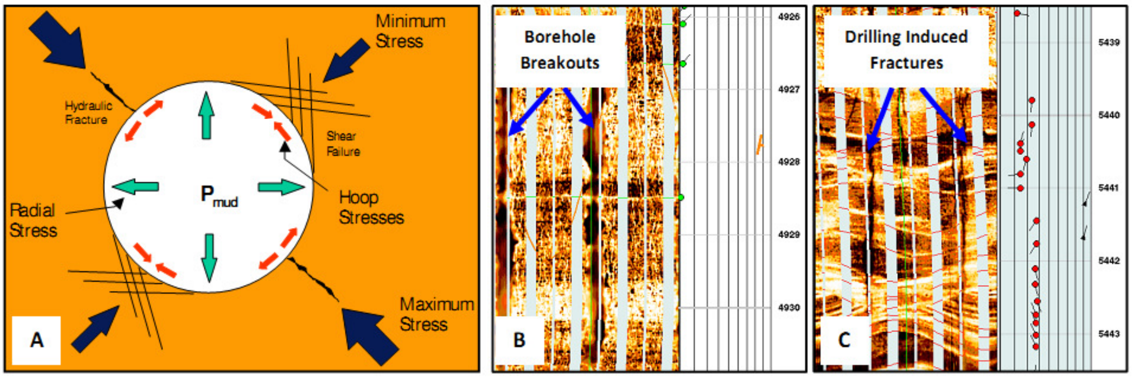


Figure-6.14: (A) Theory of stress distribution in the borehole and the 180 degrees of minimum and maximum horizontal stresses. Drilling induced fractures developed parallel to the maximum horizontal stress while borehole breakouts developed parallel to the minimum horizontal stress direction. (B) Example of borehole breakouts in Hawaz Fm., well H3-NC186. (C) Drilling induced fractures in Ash Shabiyat Formation, well I3-NC186. Both B and C features show 180 degrees between each others.

Generally, in vertical wells such as in the area of the study, the orientation of borehole elongation is aligned with the trend of minimum horizontal stress. Similarly, the strike of drilling induced fractures is aligned with the trend of maximum horizontal stress (Figure-6.15). Two different techniques used for analyzing the present day stress either by picking the borehole breakouts and drilling induced (i.e. statistical analysis) or using calipers for ovalization interpretation. The statistical analysis in the five wells show maximum horizontal stress trending WNW-ESE and minimum horizontal stress trending NNE-SSW direction (Figure-6.15). The CALIBAN* analysis using calipers confirm also the minimum horizontal stress in the area trending NNE-SSW (Figure-6.16).

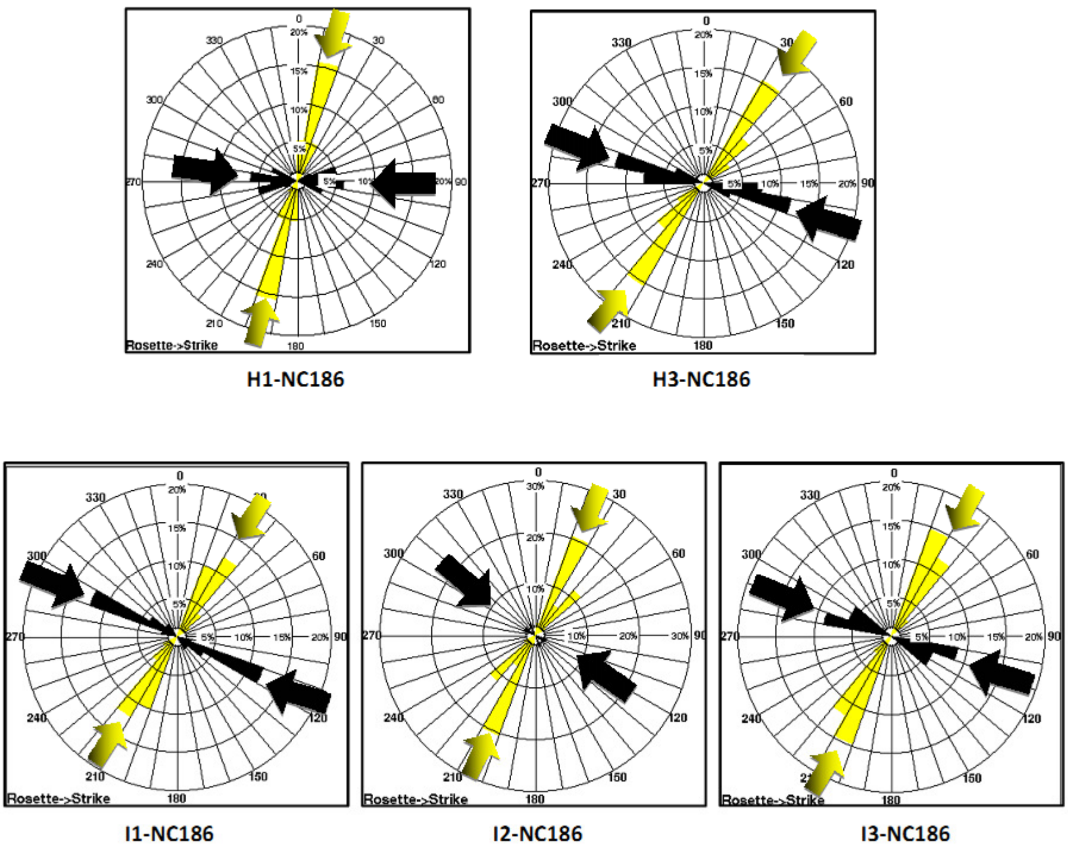


Figure-6.15: Statistical Analysis of the Drilling Induced Fractures (maximum horizon stress) and the Borehole Breakouts (minimum horizon stress) in the studied wells. The present day horizontal maximum stress is toward the ESE -WNW while the minimum horizontal stress is toward the NNE-SSE direction. Black is the drilling induced and Yellow is the borehole breakouts.

7. Summary & Discussion:

The detailed study and work performed for structural analysis in the H and I Fields, Concession NC186 can be summarized and discussed in the following points:

- The Paleozoic time, especially the Ordovician, was subjected to various large scale structural and stratigraphic events through the older and younger geological record. It is concluded from the study that the most intensively affected successions were the Cambrian to Silurian.

- The stratigraphic column of the study area, from seismic and open hole data, ranges from Pre-Cambrian (Basement) to the Cretaceous and covered by quaternary sands. The Ordovician successions (Ash Shabiyat, Hawaz, Melaz Shuqran and Mamuniyat formations) were all studied using both seismic and FMI dataset. All of the contacts separating the formations in the study area are unconformable in nature.

- The main structural elements in the study area are: paleohighs and paleolows, reverse basement faults, positive flower structures, en echelon folds (reverse drag folds), micro-faults and shear fractures. These features encountered on different stratigraphic levels indicating different structural events and episodes.

- Reverse basement induced faults spread from basement to Carboniferous trending in NNW-SSE and NW-SE directions. These reverse faults are related in origin to the Pan African Orogeny.

- Differential vertical displacement is considered and reaches around 300 meters, at the basement and Cambrian level, but decreases towards the Carboniferous. This differential displacement indicated tear pattern along the basement faults where the amount of displacement in the south is larger than the northern one. The value of the vertical displacement along the basement faults was much reduced after the Mid-Devonian Orogeny.

- Positive flower structures and en echelon folds with tear pattern indicate that the area was subjected to transpressional strike slip regime during early to middle Paleozoic. The highest intensity of these tectonics was recorded during the Middle Devonian compression. Both positive structure and en echelon folds were observed at the northern part of the study area trending NW-SE where less vertical displacement of the basement faults occurred.

- Conceptual tectonic model was built for the study area and concluded the following:

1. In Cambrian: during early Cambrian; steep reverse faults were rejuvenated by extensional modes along the old exiting Pan African faults and Hasawnah Formation was deposited. Thickness variation observed from seismic data indicated either differential erosion along the fault planes or growth faulting. During late Cambrian; compressional regime was dominant with uplifting and erosion as observed on the upthrown side of the faults. Both extension and compression tectonic elements axis were trending toward NW-SE direction.

2. In Ordovician: the early Ordovician time was characterized by general extensional regime towards the NW-SE (tension towards NE-SW) which controlled the sediments depositional trend towards NW as indicated by the paleocurrent analysis of Hawaz Formation. This formation is located as a complete succession at the Paleohighs of the area within H-Field. These paleohighs area are not intersected with any major faults. During the late Ordovician; glacial episode has occurred and created large valleys that eroded the older Paleozoic deposits in the NW-SE direction (same trend of the basement faults). This episode coincides with regional unconformity surface known as Taconic Unconformity. Combination of both structural and stratigraphic events that occurred during this episode was the main reason of the complexities encountered within the upper Ordovician. Interpretation of the lateral and vertical variation of the Ordovician succession concludes that:
    - Hawaz Formation is almost eroded in the paleolows areas with differential intensities from north to south, where it is completely eroded at the southern part of the area.
    - Upper Ordovician deposits are thicker in the southern direction of I-Field.
    - Upper Ordovician deposits show a thin sequence of “Sand dominated deposits” at the northern part of the area and “Mud-dominated deposited” at the southern part which indicates relatively deep depositional setting to the south.

- Silurian Hot Shale unit was only observed in I-Field paleolows. The full Silurian succession is generally thicker in the paleolows, particularly in the northern part of the study area.
- Upper Ordovician and Tanezzuft shale deposits were onlapped against the Hawaz paleohighs.

3. In Silurian: early Silurian time was characterized by regional extension and major marine transgression. Consequently, thick shale sequence was deposited that covered the whole Ordovician topographic variations.

4. In Devonian: major compressional tectonic regimes were occurred in the study area due to intensive uplifting and erosion (known as Caledonian Orogeny). All of the Akakus formation units were eroded during this orogeny as indicated by the seismic data in the study area. In addition, the direction of the compressional forces was mainly NE-SW. Positive flower structures were observed within the Silurian succession that indicate, post Silurian transpressional tectonics.

5. Comparing the local tectonics of the Concession NC186 from basement to the Devonian with the regional context it is concluded that; (A) The Early Paleozoic, Cambrian to Silurian, is recognized as the most intensive active tectonics within Murzuq Basin (Figures-7.1 & 7.2).

6. In Carboniferous-Permian: from Mid Devonian to Permian; new tectonic episode (i.e. Hercynian Orogeny) has occurred. This orogeny generated the main structural elements in Murzuq Basin which are trending toward NE-SW and ENE-WSW directions such as Gargaf Arch. From the seismic data, no obvious large scale vertical displacement was observed, while all Permian sequences were eroded. Top structural map of Dembaba Formation indicated ENE-WSW structural trend perpendicular to the Caledonian and early Paleozoic trends.

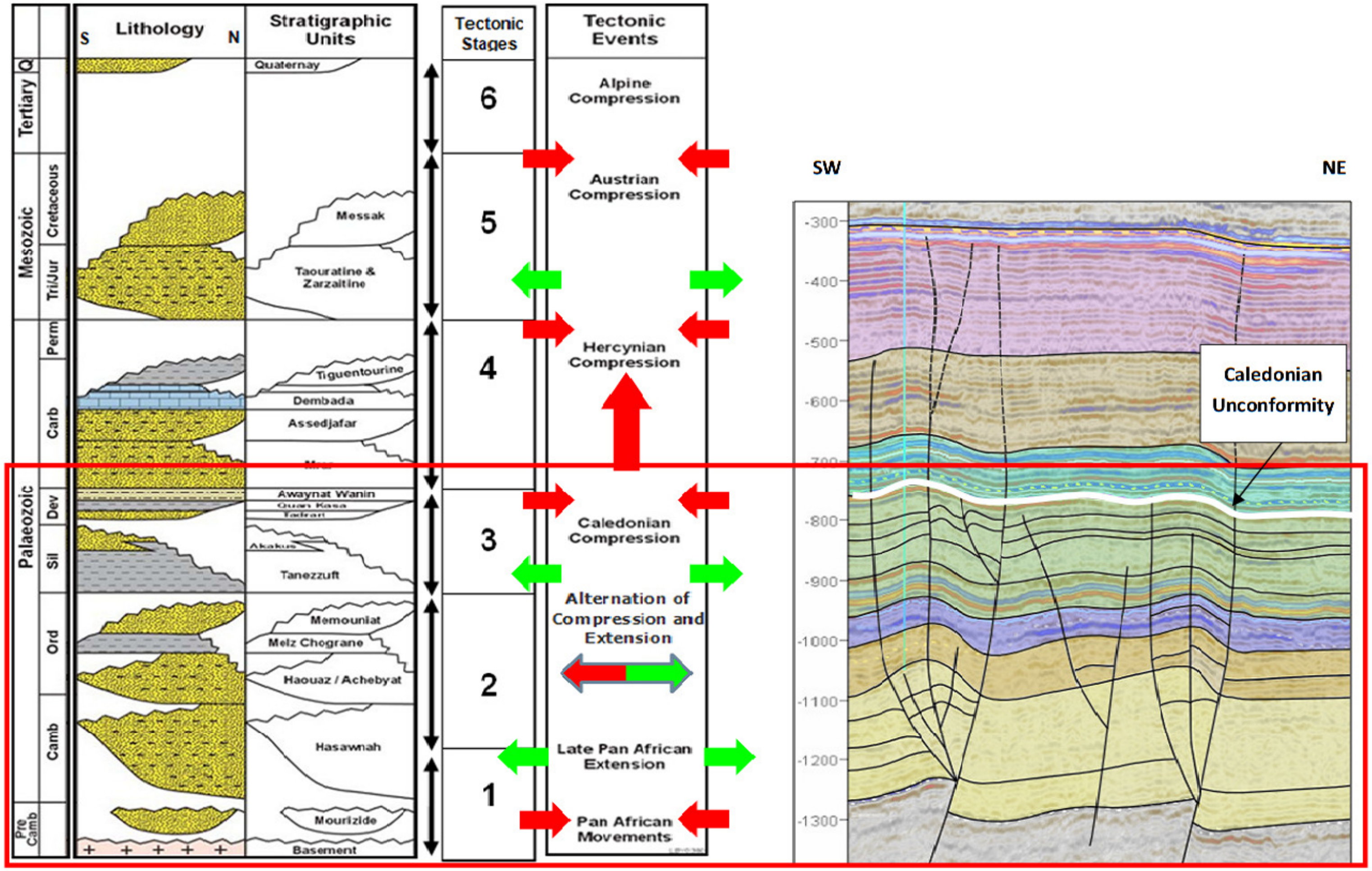


Figure- 7.1: Correlation between the regional tectonic phases of Murzuq Basin (to the left) and the local tectonics of the study area (to the right). It is obvious that the tectonic intensity producing significant vertical displacement and positive flower structures terminates at the Caledonian Unconformity level.

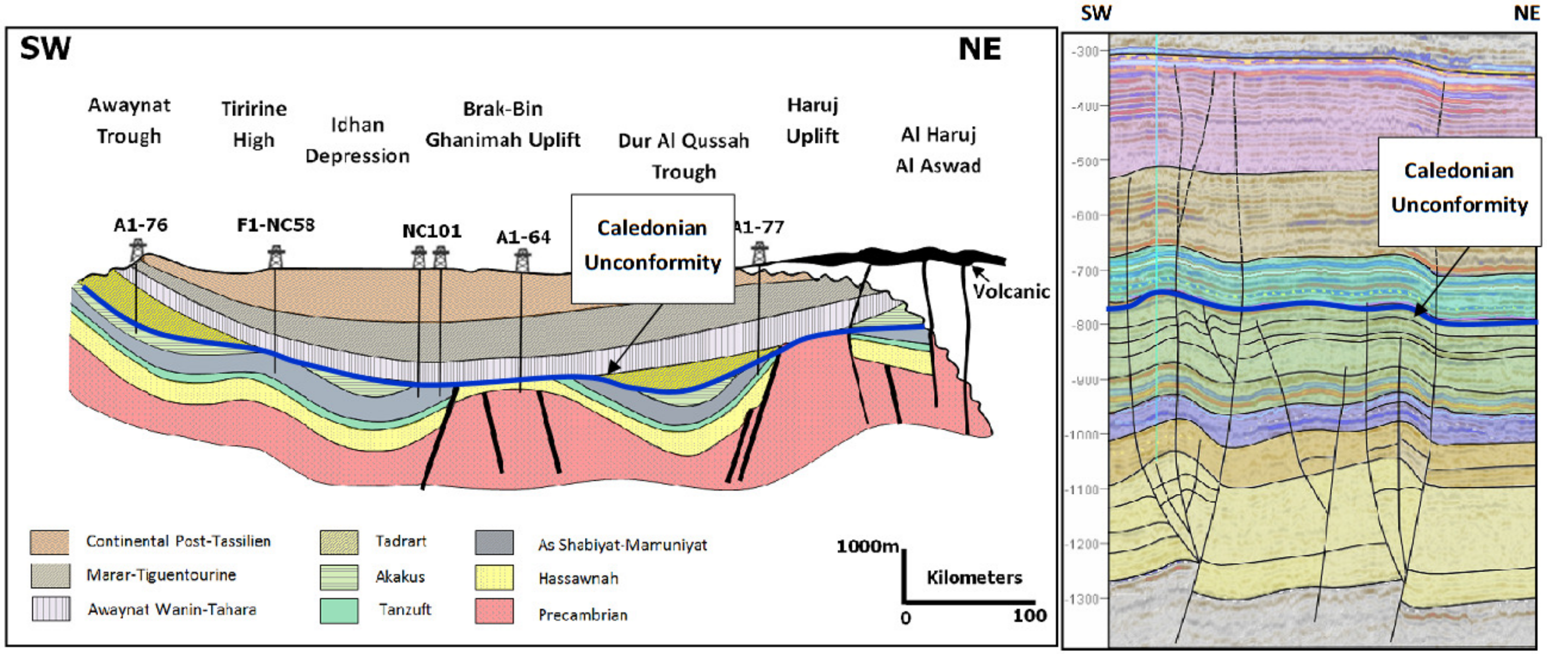


Figure-7.2: Correlation between the regional cross section of Murzuq Basin and local tectonic phases in the study area (to the right). Illustrating the termination of the significant vertical displacement and positive flower structure at the Caledonian unconformity level.

7. In Mesozoic: the post Hercynian tectonic regimes are mainly trending and controlled by ENE-WSW structural elements, such as Gargaf Arch, with overprinting of the oldest Paleozoic structures. This has indicated a change in the direction of the compression and extension axis to NW-SE. Multiple compression and extension phases were also dominant during the Mesozoic as observed in study area.

8. In Cretaceous: compressional regime was clearly dominant in the study area and features like inversion striking ENE-WSW were observed. During this time and due to compressional regime, Messak Escarpment was developed. This escarpment indicates Cretaceous uplift event (i.e. Alpine Orogeny!) trending towards the ENE-WSW in the southern part of the study area.

9. Present Day In-Situ Stress: utilizing the imaging logs acquired in the two fields, concluded that; the present day maximum horizontal stress direction is toward ESE -WNW direction and minimum horizontal stress direction is toward NNE-SSE.

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9. APPENDICES

APPENDIX-A: FMI Tool (Specifications, Acquisition & Processing):

(reference www.connect.slb.com)

The FMI* Fullbore Formation MicroImager provides microresistivity formation images in water-base mud:

- 80% borehole coverage in 8-in. hole size,
- 0.2-in. (5-mm) image resolution in vertical and azimuthal directions,
- Fully processed images and dip data in real time.
- Top combinable with other wireline tools such.
- Generates an electrical image of the borehole from 192 microresistivity measurements.

FMI Specifications	
Applications	Structural geology, stratigraphy, reservoir analysis, heterogeneity, fine-scale features, real-time answers
Vertical resolution	0.2 in. with 50-micron features visible
Azimuthal resolution	0.2 in. with 50-micron features visible
Measuring electrodes	192
Pads and flaps	8
Coverage	80% in 8-in. borehole (fullbore image mode)
Max pressure	20,000 psi
Max temperature	350°F [175°C]
Borehole diameter	
Min	5⅞ in.
Max	21 in.
Max hole deviation	90°
Logging speed	
Fullbore image mode	1,800 ft/hr with real-time processed image
Four-pad mode	3,600 ft/hr with real-time processed image
Dipmeter mode	5,400 ft/hr with real-time dip processing
Inclinometer mode	10,000 ft/hr
Max mud resistivity	50 ohm-m
FMI tool	
Max diameter	5 in.
Makeup length	24.4 ft
Makeup length with flex joint	26.4 ft
Weight in air	433.7 lbm
Compressional strength (TLC* operations)	12,000 lbf (safety factor of 2)
Max pad pressure	44 lbf
Combinability	Top combinable with openhole wireline tools

Measurement physics

The figure to the right illustrates the FMI measurement principle. An applied voltage causes an alternating current (AC) to flow from each electrode button in the lower pad section through the formation to the electrode on the upper cartridge housing. As the current emerges from a button on the pad or flap, its path is initially focused on a small volume of the formation directly facing the button. The current path expands rapidly to cover a large volume of formation between the lower and upper electrodes. The current consists of two components:

- High-resolution component, modulated by the resistivity variations in the formation directly facing the button
- Low-resolution component, modulated by the resistivity of the zone between the lower and upper electrodes.

The microresistivity image of the borehole wall is created from the current measured by the array of buttons. The high-resolution component dominates the image because its value varies from button to button. The lower resolution component appears only as a gradually changing background. Microresistivity changes are elated to lithological and petrophysical variations in the rock, which are conveyed mainly by the high-resolution current component, are interpreted on the image in terms of rock texture, stratigraphic and structural features, and fractures.

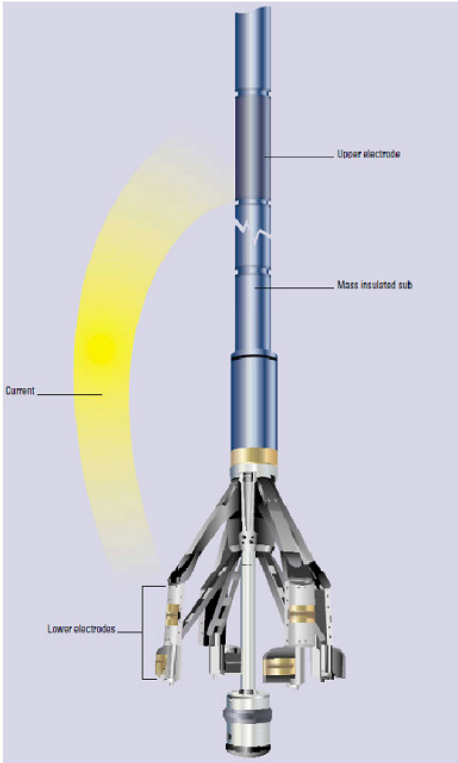

Figure-9.1: FMI Tool String.

Signal Processing:

The data was processed at the Schlumberger Tripoli data services centre and at the client instruction computed dip results and images have been produced over a specified interval using standard processing parameters. The main objective has been to provide a continuous log of formation structure in the form of interpreted dip results and near-wellbore images.

Microresistivity variations recorded by the tool are converted into colour images after speed correction, depth alignment, electrode equalisation and **'static'** normalisation using a histogram equalisation technique. Further contrast enhancement was achieved using a sliding 2 ft normalisation window to produce the **'dynamic'** images. The data is processed to generate computed images using the following GeoFrame* workflow:

1. Depth Matching

As openhole logs and images are acquired at different sampling rates, logging speeds and time (in the case of multiple runs), so each log may be affected by variable amounts due to irregular tool movement. Consequently, each set of logs may be off-depth relative to other logs or sets of logs by a variable amount of shift. To correct for this, all logs and images are depth matched to a reference log before any actual analysis of the image and log data starts.

2. GPIT Checks

Dip computation and speed correction requires inclinometry data provided by the GPIT tool. This data is checked using the GPIT_Survey module of GeoFrame. The corresponding plots for the various log passes have been included.

3. Speed Correction

Where the wireline cable depth at surface and data acquisition depth downhole differ then it is essential to make a correction. The method used for the FMI data is accelerometer-based and estimates the speed and the depth of the tool by using simultaneously the cable depth and the integration of the z-axis accelerometer data.

4. Image Generation

BorNor is the GeoFrame module that performs image enhancement prior to graphical display. It uses histogram equalisation to optimise the use of a given number of colours in a given interval based on a histogram distribution of the resistivity values.

Static Normalization is a single computation where the colour classes are based on a measurement distribution histogram defined over the whole logged interval. Changes in colour represent gross variation in the measurement and correspond to major changes in porosity and pore fluid type.

Dynamic Normalization is the result of multiple computations, repeated at regularly spaced positions over user specified depth interval using a window of relatively short interval (2 ft in this well). Changes in colour represent small-scale features, corresponding to small changes in porosity, texture and mineralogy. Dynamic normalisation of the FMI data enhances the sedimentary structure on the images to assist manual dip picking.

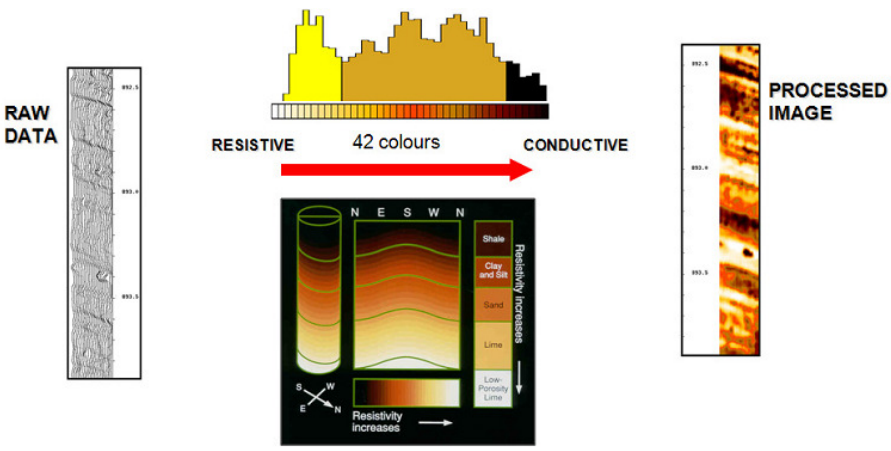

Figure-9.2: Image generation histogram.

APPENDIX-B: Features Identified and stratigraphic columns of the studied wells:

Geological features were first identified from the images and classified on the basis of their morphology and genesis. The orientations of these features were then computed interactively from the images. A sinusoid of known orientation was matched with the features on the image to determine the orientation of the latter. The computed orientations were represented by their magnitude and azimuth values. Brief descriptions of the features identified over the studied interval are as follows:

Legend for Features Identified from FMI Images

Features represented only by dip azimuth

- Bed Boundary
- Cross Bedding
- Contortion-Slump
- Erosional Surface
- Stylolites
- Reactivation Surface
- Unconformity
- Conductive Fractures
- Resistive Fractures
- Drilling Induced Fractures

Features represented by Strike and dip azimuth directions

- Micro-Fault
- Borehole Breakouts

Facies Catalog

- Planar Cross-Bedded Sandstone
- Bidirectional Cross-Bedded Sandstone
- Bedded Sandstone
- Structureless Sandstone
- Slumped Sandstone
- Bioturbated Sandstone
- Intensively Bioturbated Sandstone
- Erosional Surface
- Massive Siltstone
- Bioturbated Siltstone
- Contorted Siltstone
- Bedded Shale
- Laminated Shale
- Contorted Shale
- Not covered by FMI images.

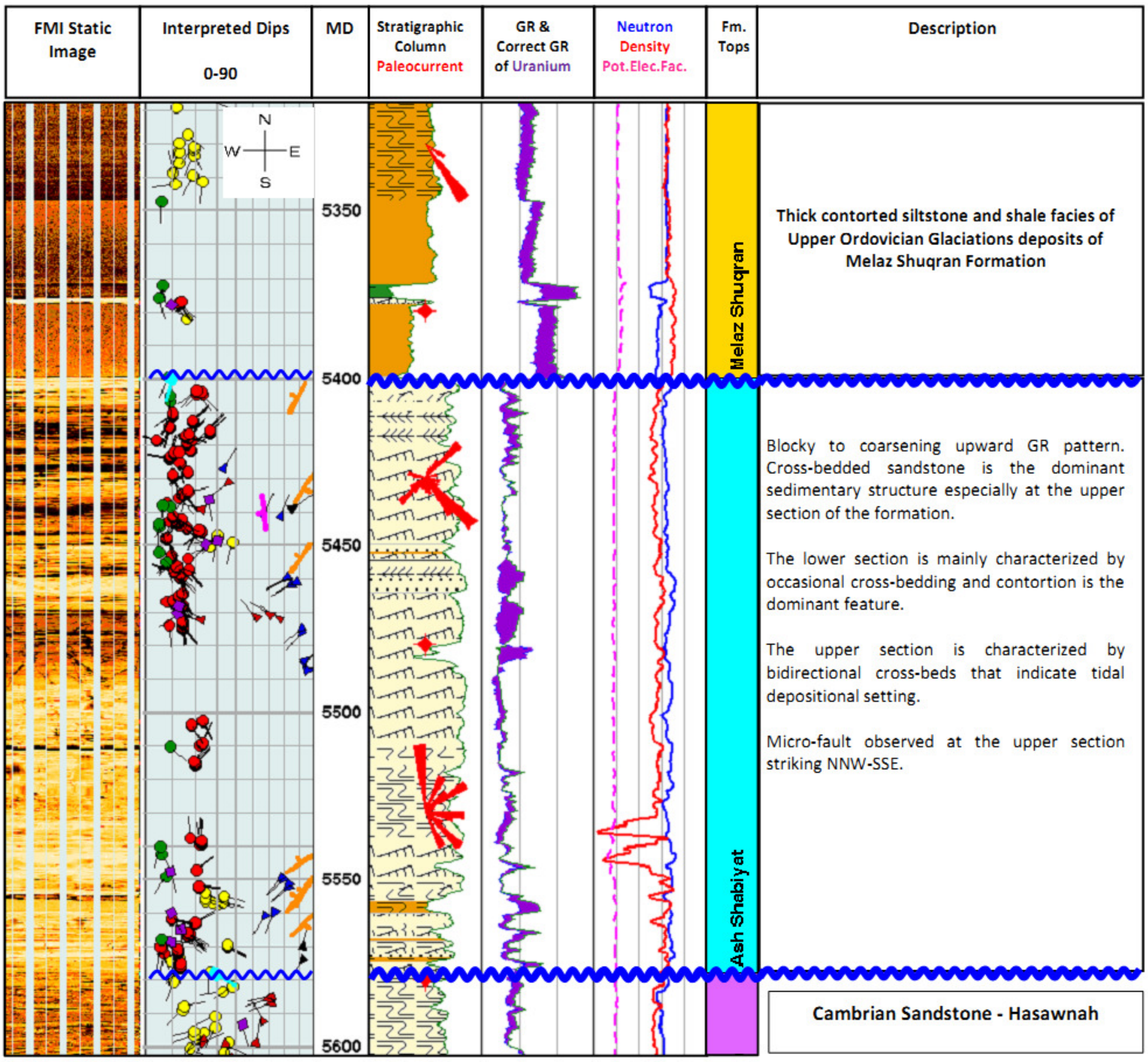

Figure-9.3: Composite display of Ash Shabiyat Formation in Well 11-NC186. Both upper and lower contacts of the formations are unconformity.

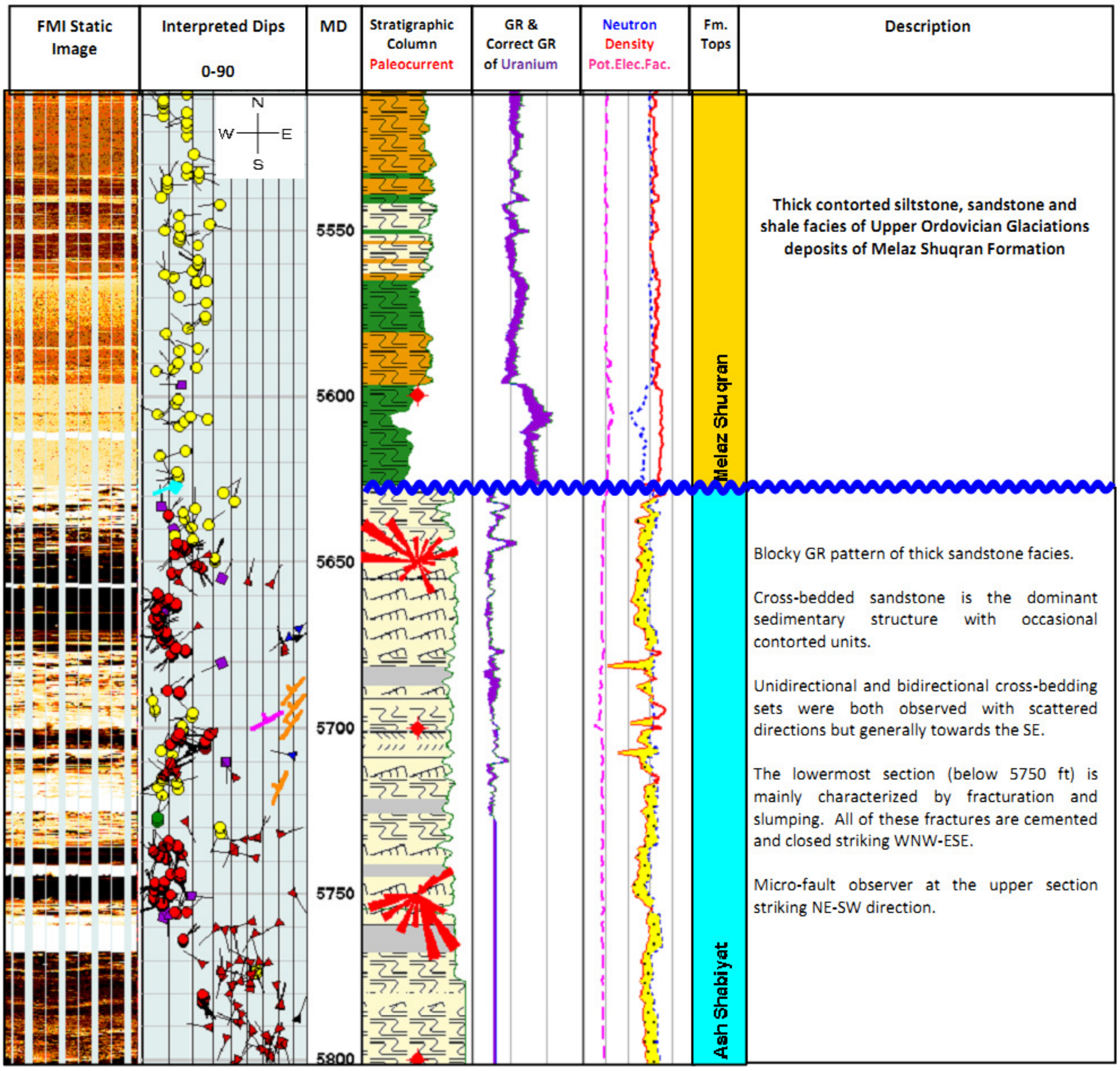

Figure-9.4: Composite display of Ash Shabiyat Formation in the Well I2-NC186. The formation is overlaid with thick contorted facies of Melaz Shuqran Formation and separated by an unconformity contact.

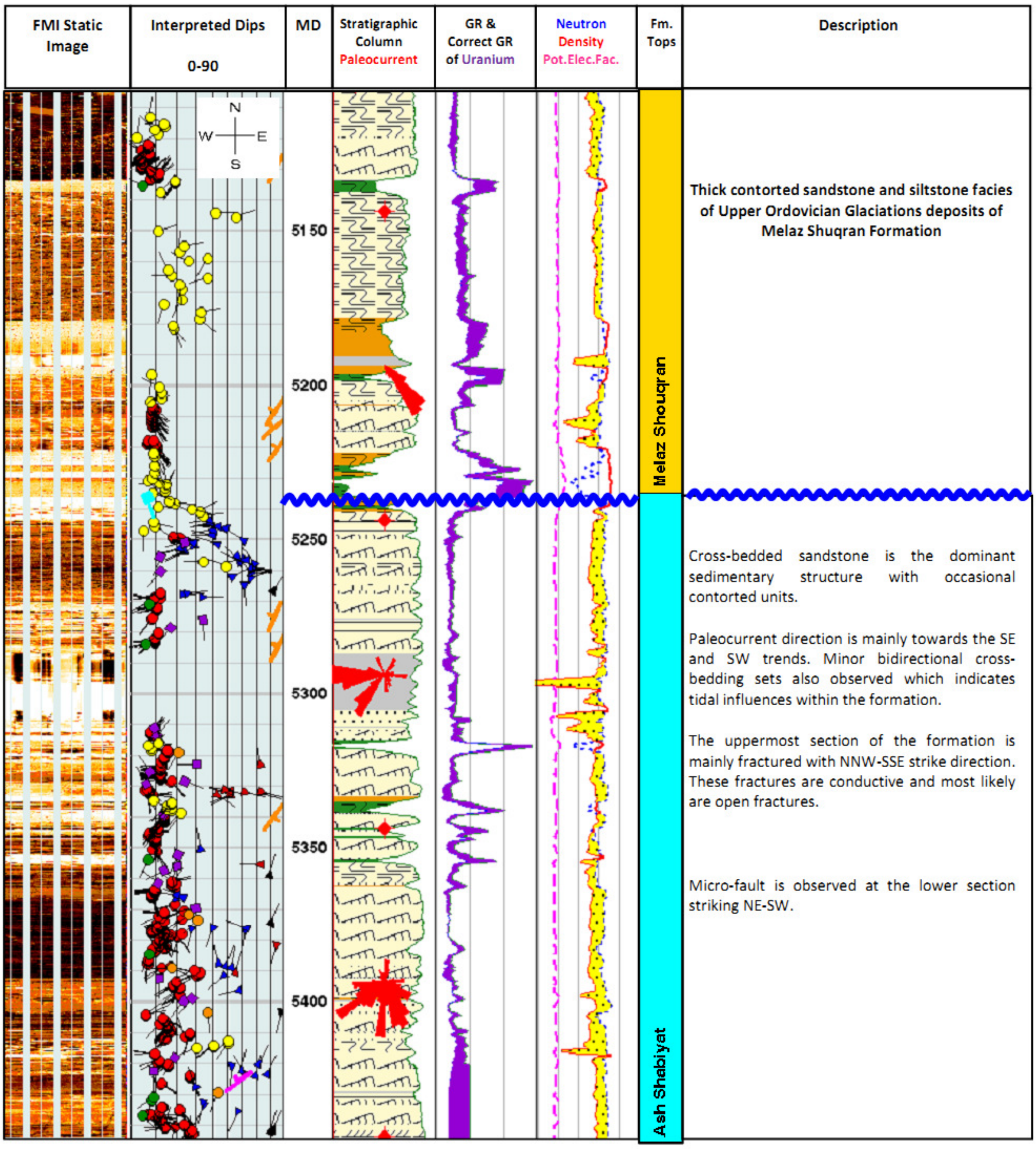

Figure-9.5: Composite display of the Ash Shabiyat Formation in the Well I3-NC186. The formation is overlaid with thick contorted facies of Melaz Shuqran Formation and separated by unconformity contact.

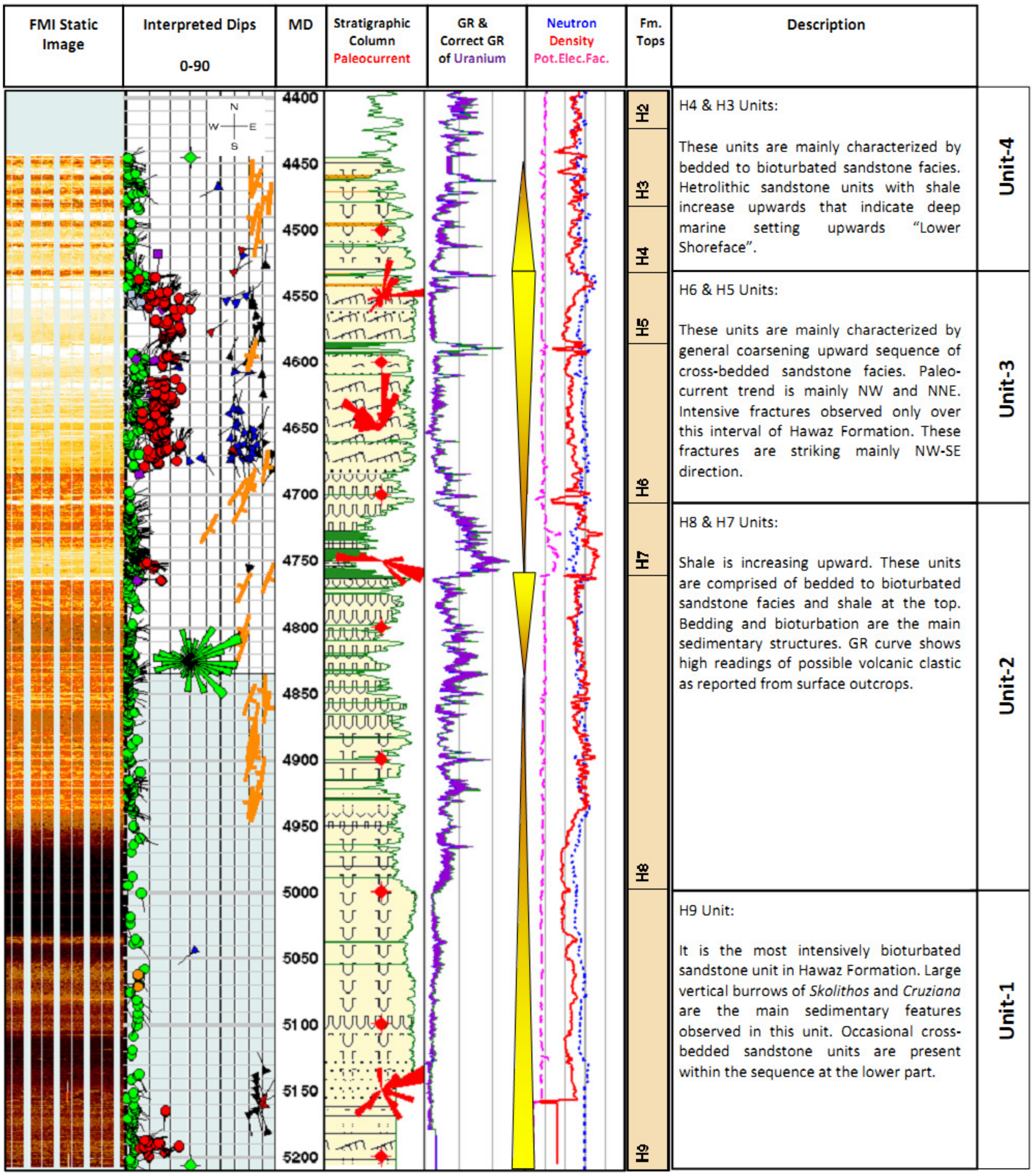

Figure-9.6: The Stratigraphic column of the Hawaz Formation in the well H1-NC186.

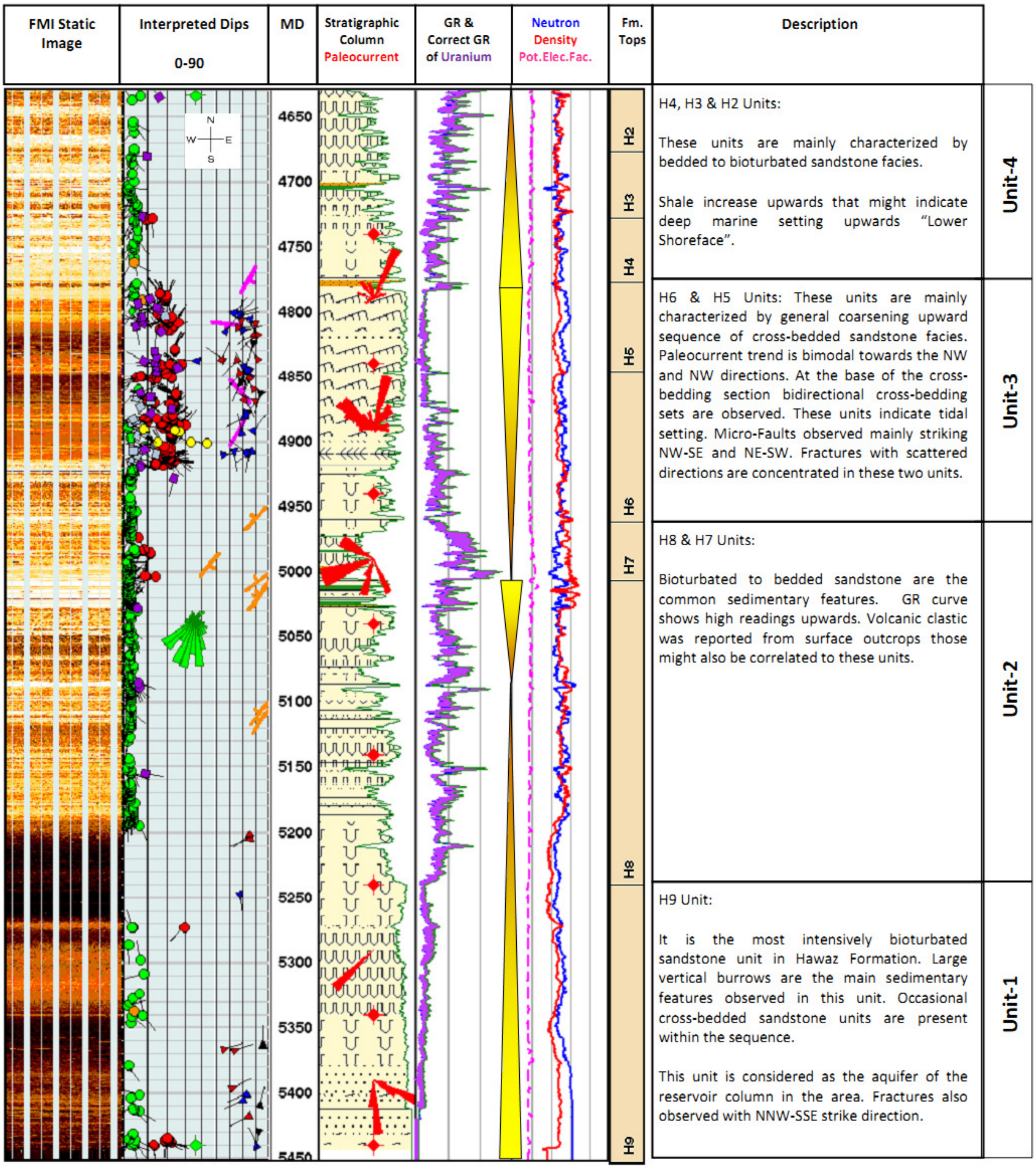

Figure-9.7: The Stratigraphic column of the Hawaz Formation in the well H3-NC186.

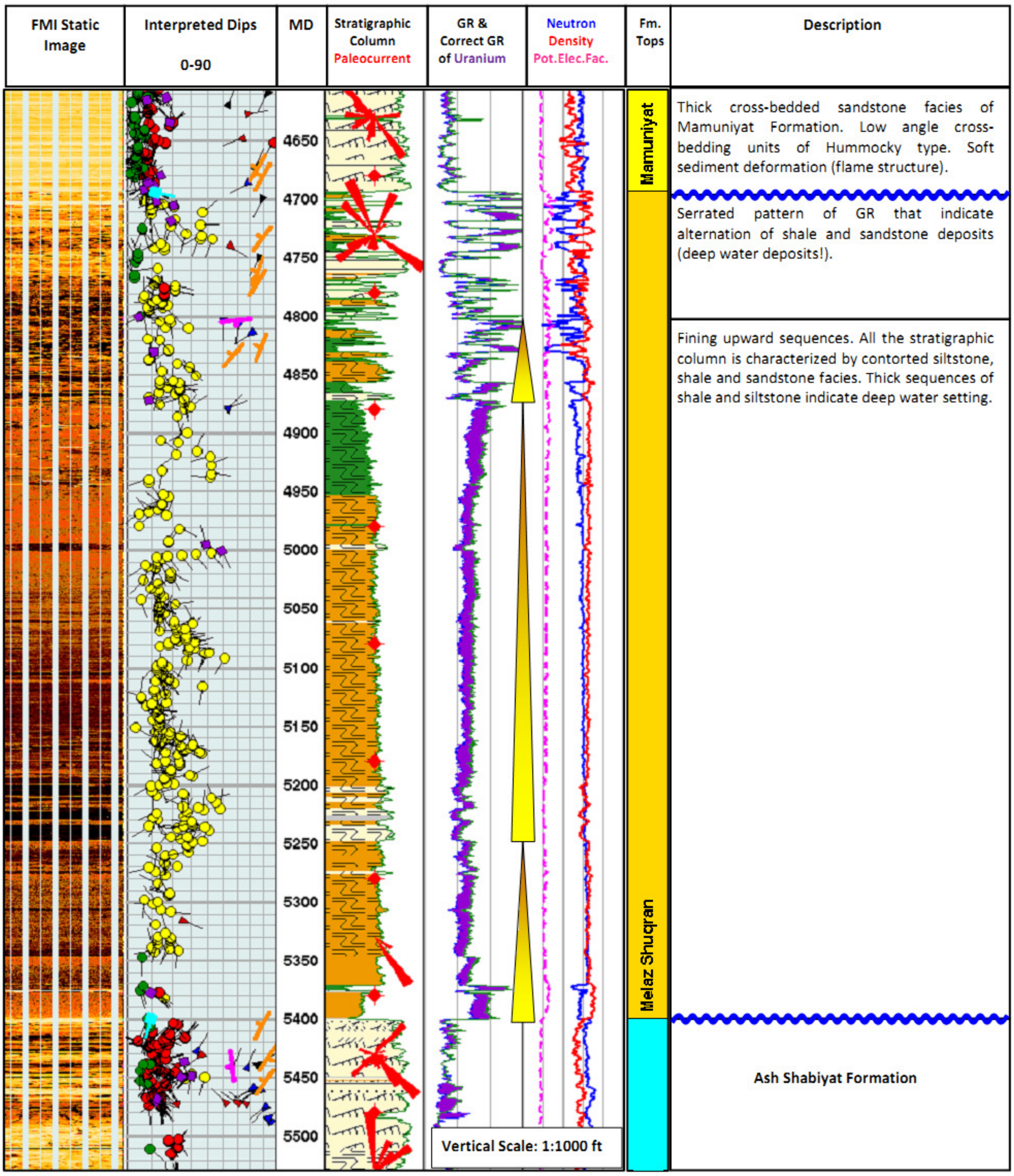

Figure-9.8: The stratigraphic column of Melaz Shuqran and Mamuniyat Formations in well I1-NC186.

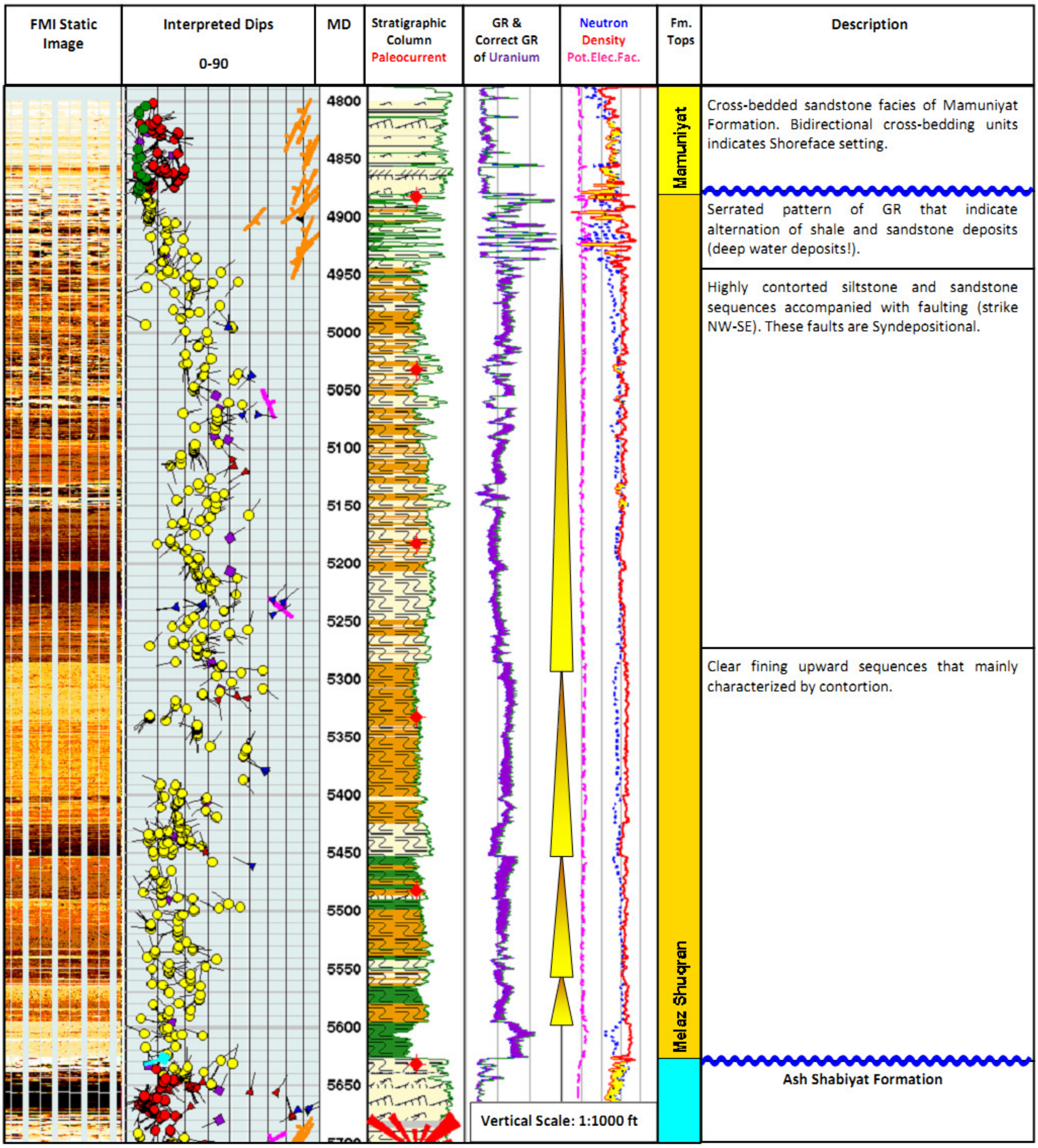

Figure-9.9: The stratigraphic column of Melaz Shuqran and Mamuniyat Formations in well I2-NC186.

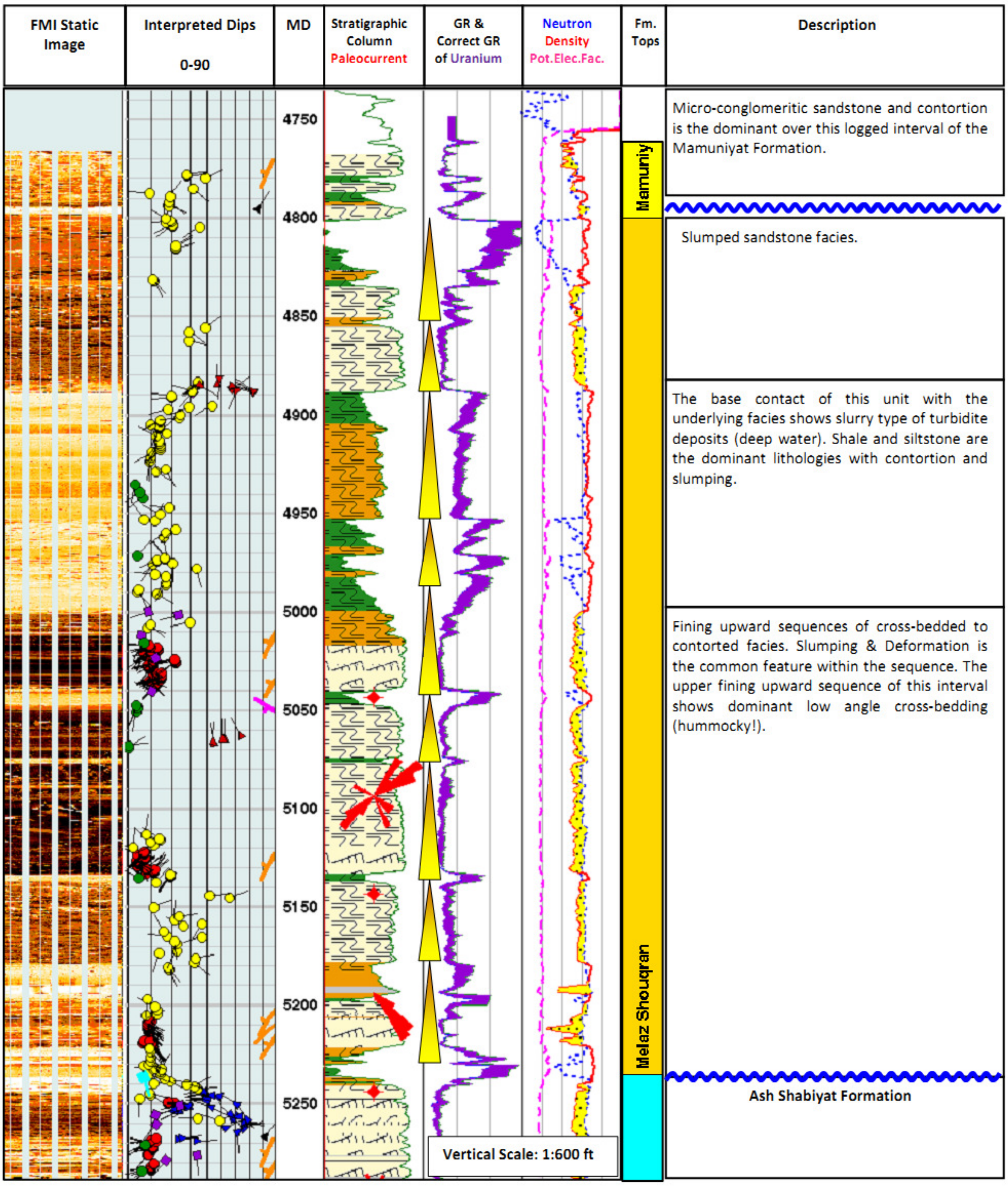

Figure-9.10: The stratigraphic column of Melaz Shuqran and Mamuniyat Formations in well I3-NC186.