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Tectonic effects of Abu-Jir Fault Zone on Euphrates and Fatha formations between Heet and Haditha western Iraq.

A Thesis

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بِسْمِ اللَّهِ الرَّحْمنِ الرَّحِيمِ

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The researcher

DEDICATION

I would like to dedicate this work to:

The best of human beings and the model of Islam. Our Prophet Muhammad, may God bless him and grant him peace.

To whom I miss every moment............................my father, may God have mercy on you.

The meaning of love and tenderness and the secret of existence, whose supplication was the secret of my success and tenderness, was a balm for my wounds....my beloved mother.

To those who supported me and made sure to continue my academic career and had support in my life and the sweetness of my eyes from which I derive hope and depend on it......... my dear husband.

To the one who gave me his knowledge and guided me to the path of knowledge....... my supervisor.

My companions on the road and my support in times of adversity........ my brother and sisters.

Those with whom I spent the best years of my life..................... my friends and colleagues.

Those who illuminate the darkness of ignorance with the light of knowledge……. my teachers.

ABSTRACT

The current study comprised four outcrops: Heet, Sahliyah, Al-Baghdadi and Haditha, that comparison with, the Melh Tharthar-1well. We used a detailed field study to evaluate the tectonic effects of the Abu-Jir Fault Zone on the study area. We concluded through lithostratigraphic studies of the surface outcrops and the Correlation between them, that although the distances between sections are close, there is a substantial variance in lithofacies laterally and vertically. The layers of marly limestone in the Euphrates Formation are becoming thicker toward the southeast. It's a good indicator of a deeper environment than the northwest in the study area.

The very quick subsidence of the eastern side of Abu-Jir Fault Zone during Late Early Miocene and Middle Miocene due to elastic isostasy of the Mesopotamian foredeep. The structural study reveals that the study area has been subjected to two types of stress during Miocene. The first one is extension in response to the tilt of the Mesopotamia sequence is took place as a result of the collision between Arabian and Eurasian plates during or after the end of the Early Miocene. The tilt created an extension zone along the axis of flexure, west of the Abu-Jir Fault System. The second type of stress is compression as a result of the strike-slip movement that occurred along the Abu-Jir Fault Zone during the Middle Miocene. The western block of the Abu-Jir Fault Zone moves northward relative to the eastern block, as a result of the right lateral strike-slip movement. The main forces come from the south during the Late Early Miocene and Middle Miocene, its source the Afar plume, as the upwelling mantle influence from the Afar plume reached the current study area during the Miocene (20 Ma), which is definitely the one that activates the western block of the Abu-Jir Fault Zone and pushes it towards the north relative to the eastern block.

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CHAPTER ONE

INTRODUCTION

1-1 Preface

Tectonics is a branch of structural geology, which refers to a group of physical processes related to geological features on a regional-scale (Pluijm & Marshack, 2004). Neo-tectonics, a relatively new branch of structural geology-tectonics, which studies the youngest geological structures and physical processes that have occurred or are still occurring in a given region after its final orogeny or after its last important tectonic reconstitution. Neo-tectonic movements can be interpreted and explained by regions containing recent geological formations, which lie either at the boundaries of active plates or in Neogene and Quaternary basins inside the plates (Pavlides, 1989).

Structural geology is a branch of geoscience that is concerned with studying the characteristics of deformation structures and inferring the direction and magnitude of forces involved in driving deformation. It is a field-based system that aims to broadly understand surface geology, so it requires the development of an acute sense of observation (Rey, 2005).

The Abu-Jir Fault Zone is one of the Nabitah fault systems, which formed around 680 Ma during the Late Precambrian Nabitah orogeny. It may be seen in the central Iraqi basement, where N-S trending discontinuities are pulled and deformed along the Najd faults that NW-SE trending, along the Euphrates River (Jassim & Goff, 2006). It's a complex fault zone where limited trans-current movement occurred along the zone during the Late Tertiary, and the Abu-Jir finally became a right-lateral strike-slip fault (Fouad, 2004). The Abu-Jir Fault Zone forms an expressive linear structure across Iraqi territory that may be seen on satellite pictures for around 600 kilometers. This zone is composed of several NW-SE trending faults that extend from Anah Graben across Heet, Awasil, Abu-Jir, Shithatha, and along the western bank of the Euphrates River across Kerbala, Najaf, and Samawa to reach the Al-Batin lineament in west Basrah and northwest Kuwait (Al-Bassam, 2007).

1-2 Location and Tectonism of the study area

The study area is located in the western part of Iraq, along the western bank of the Euphrates River (Figure1-1), from the Heet city at (N33°. 37'02.7", E42°50' 27.4") to the Haditha city at (N34° 05'32.2", E42°21' 52"). In terms of tectonics, the study area covers the northern part of the Abu-Jir Fault Zone, which coincides with the boundary between the Stable and Unstable Shelves of the Arabian Platform (Figure1-2) according to (Fouad ,2007).

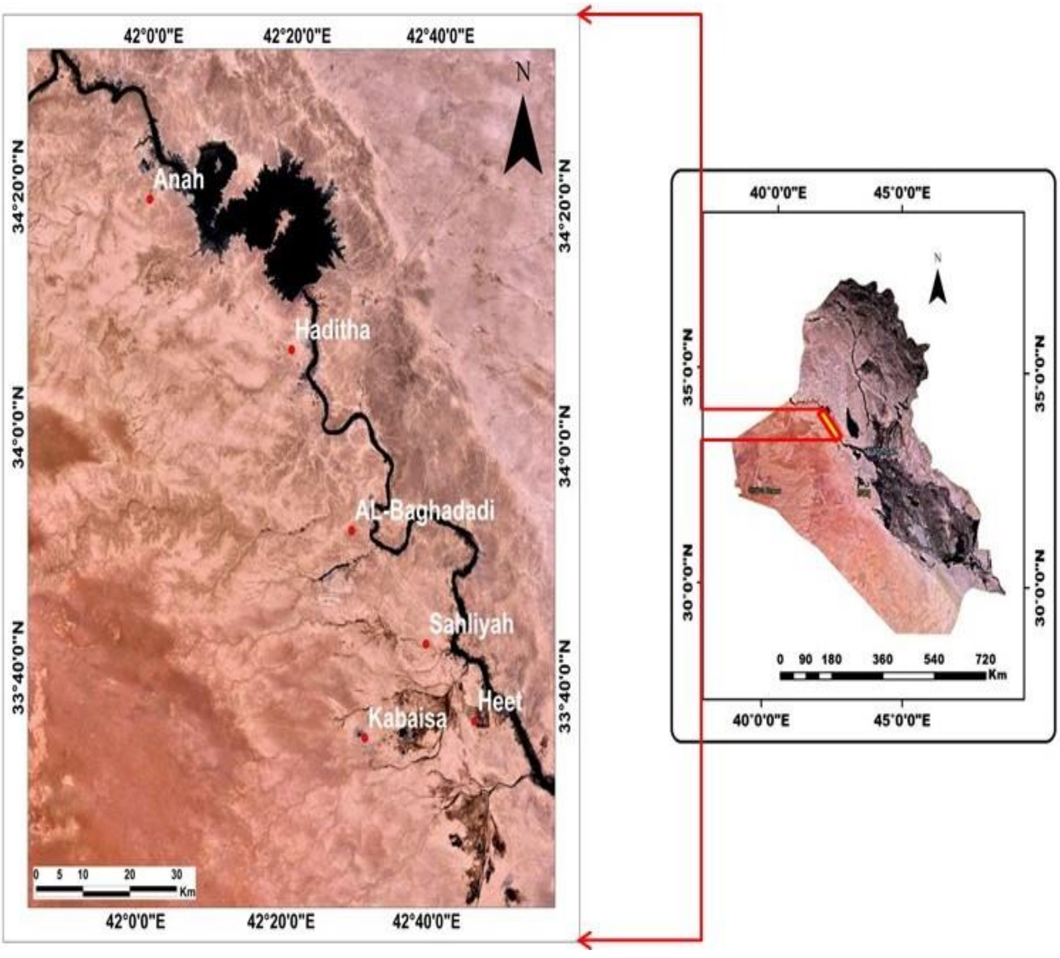

Figure 1-1: Location map of the study area (Landsat satellite image 2013).

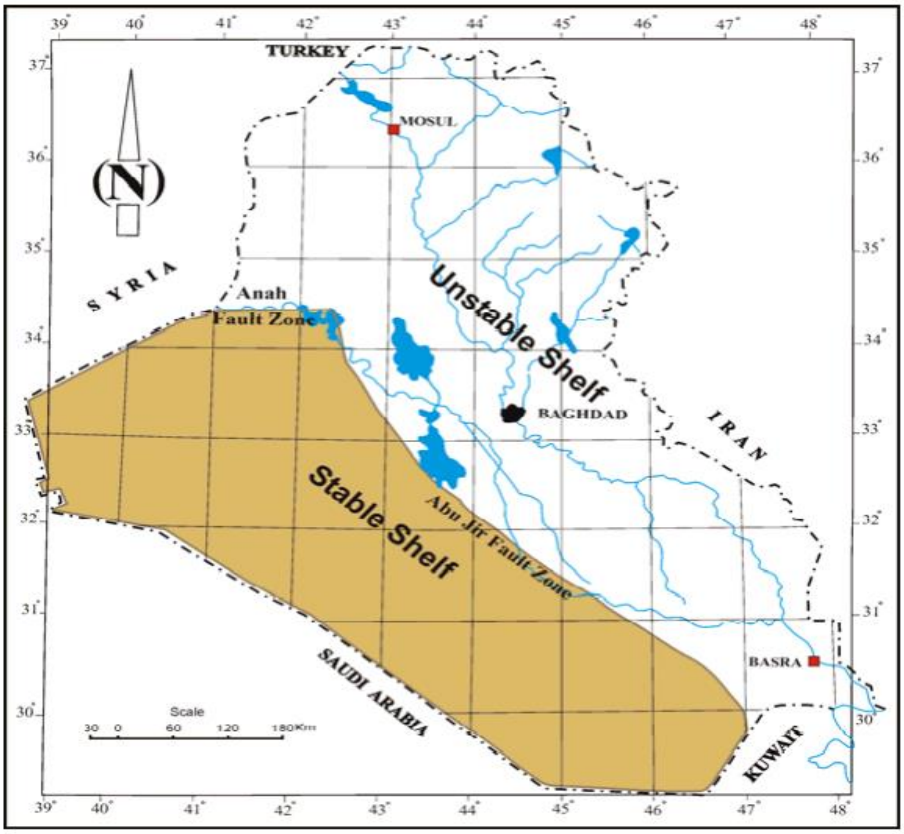

Figure 1-2: The boundary between the Stable and the Unstable Shelves of the Arabian Platform (Fouad, 2007).

1-3 Aims of study

1. The litho-stratigraphic relationships of the formations in the outcrop sections in the study area.
2. Types of structures and their relationship to the main faults.
3. The behavior of the Abu-Jir Fault Zone between Heet and Haditha cities and determine the direction of the forces that led to its development.

1-4 The previous studies

Many studies have been conducted on the area from several aspects, as it marks the borderline between Stable and Unstable Shelves in Iraqi lands, so it is of great interest. But there is no detailed study of the surface structures present in the study area, which prompted us to take up this research. The important previous studies are:

- Buday & Jassim (1987) show that the Euphrates and Abu-Jir fault zones form the boundary from southern Iraq northward to the vicinity of Heet city, in the west. Then they continued the boundary across the Euphrates River, following Al-Tharthar valley northward to meet the Hamrin-Makhul Subzone, where it disappears just south of the Sinjar area.

- Fouad (1997) accused the major distortion in the Brecciated Unit of the uppermost part of the Euphrates Formation to seismic disturbances, generated by earthquakes.

- Marouf (1999) studied the Abu-Jir Fault Zone from Ain el Tamur west of Razzazah lake to Anah town. Through the interpretation of seismic-time sections, it is suggested that Abu- Jir Fault is one of the basins bounding faults and it was present at least since early Mesozoic, probably working as simple normal or growth fault. The subsidence increases across Abu-Jir from west to east.

- Fouad (2004) studied the structures along the Abu-Jir Fault Zone from the Heet city southward to the Abu-Jir village. Through the analyses of the time seismic sections, it was concluded several releasing and restraining bends were developed along the zone. On profiles, these bends appear as a negative flower and positive flower structures, whereas on surface as sag ponds (the largest them, from north to south, Awasil, Al-Jabha, Al-Mudowar and Abu-Jir depressions), and pressure ridges (Heet Pressure Ridge) respectively.

- Fouad (2007) showed Abu-Jir Fault Zone forms the eastern border of the Western Desert and eventually the border of the stable portion of the platform. The zone is composed of several NW-SE trending faults. Anah-Abu Jir Fault Zones are intracontinental rift basins in the northern Arabian Platform formed during the extensional phase (Campanian-Maastrichtian).

- Al-Ghreri (2007) conducted a biostratigraphic succession study of the formations in the Euphrates Valley between the regions of Heet and Al-Qaim, it was observed that there is a great discrepancy between the outcrop sections, despite the convergence of the distance between them, within the same sedimentary basin. This may be due to a tectonic cause that occurs on a local scale in the study area.

- Sissakian et al., (2014) concluded that the deformations the uppermost part of the Euphrates Formation (Brecciated Unit), are syn-deformational structures as a result of seismic shocks during deposition which prove "Seismites" type, indicating tectonic disturbance during the Early Miocene. The restriction of brecciation and deformation along the northern part of tectonically active Euphrates and Abu-Jir fault zones, particularly near the growing Anah anticline.

- Al-Aslami (2015) showed through the hydrocarbon analysis of the oil seep samples in Heet area that the hydrocarbon does not come from the Fatha Formation, but comes from sources Jurassic as well as Triassic. These seeps are linked to the fracture system, particularly those that are part of the Abu-Jir Fault Zone.

- Alhadithi (2017) studied four depressions (sag ponds) well-developed along with a line trending northwest–southeast, Abu-Jir, Al-Mudowar, Al-Jabha and Awasil that locate south of Heet city. Seismic reflection sections appear Abu-Jir Fault Zone extended beneath the four sag ponds. Abu-Jir Fault Zone consists of some main faults that are curved back and forth to some degree forming the sag ponds and pressure ridge, which are formed by divergent and convergent steps of major faults respectively.

- Al-Khafaji et al. (2020) performed organic geochemical study on four oil seep samples collected from the Abu-Jir Fault and proved that the source of these seeps is Middle Jurassic Sargelu source rock and then migrated to the surface of the earth through Abu-Jir major faults.

1-5 Geological Settings

The Arabian Plate became a separate plate with the development of the Red Sea and the Gulf of Aden, after a long time of regional rifting deformation (Szymanski et al., 2016). The Red Sea is generated in response to the separation of the African and Arabian plates and reflects an example of an orthogonal to rotational extension system (Molnar et al., 2018). The neighboring Gulf of Aden likewise records the separating of the African and Arabian plates but has developed as an oblique ocean system (Leroy et al., 2013). The Gulf of Aden opened first in Oligocene time after that the Red Sea in the Early Miocene. The Arabian Plate has been gradually drifting northward and northeastern toward the Eurasian Plate since then. The Arabian Plate collides with the Turkish and Iranian plates, pushing up the Zagros Mountain of Iran (Jassim & Goff, 2006).

By integrating the data previously displayed, the tectonic and structural evolution of the Western Desert as a part of the Stable Platform of the Arabian Plate can be broadly illustrated (Fouad, 2007). During the Early Miocene (25-17 Ma), the final marine transgression across the eastern and northern parts of the Western Desert occurred. Different Middle Miocene sedimentary facies were deposited on both sides of the Anah-Abu Jir fault zone. Along most of the zone, the sediments display significant syn-depositional (soft-sediments) deformational patterns, showing that the Anah-Abu Jir Fault System was active at the time (Fouad, 1997 & 2000).

The deposition of the lower Miocene Euphrates Formation points to a return to the calm shelf condition. The marine condition persisted until the termination of the whole foreland basin of north Arabia as a result of the main compressive phase of the Alpine orogeny which took place in the Plio-Pleistocene. Regional folding and thrusting of the north Arabian Plate boundary occurred as a result of the compression, as did inversion of late Cretaceous ENE-WSW trending rift basins such as Palmyride (Chaimov et al., 1993), Sinjar (Daly, 1990), and Anah (Fouad, 1997). The Late Tertiary collision caused compressive stresses normal to the ENE-WSW trending troughs, but exerted transpressive movement along the NW-SE trending fault zones such as Euphrates and Abu-Jir (Figure 1-3).

Due to its orientation to the regional N-S compressive field in the Late Tertiary (Figure 1-3), the NW-SE trending Euphrates trough largely escaped structural inversion (De Ruiter et al., 1995). The same reasoning applies to Abu-Jir. The associated flower structures, pressure ridges pull-apart, and sag ponds provide extra evidence to the occurrence of right lateral movement on these fault zones. Transcurrent zones are discovered to be capable of transmitting compressive stresses and producing considerable intra-plate compressional deformation at distances up to 1300 km (or more) from the collisional margin of the foreland plate by reactivation of crustal discontinuities (Fouad, 1997).

Megasequence APII (Figure 1-4) of the study area is subdivided into three sequences of the latest Eocene-Oligocene, Early-Middle Miocene, and the Late Miocene-Recent age. The megasequence contains many formations (Jassim & Goff, 2006).

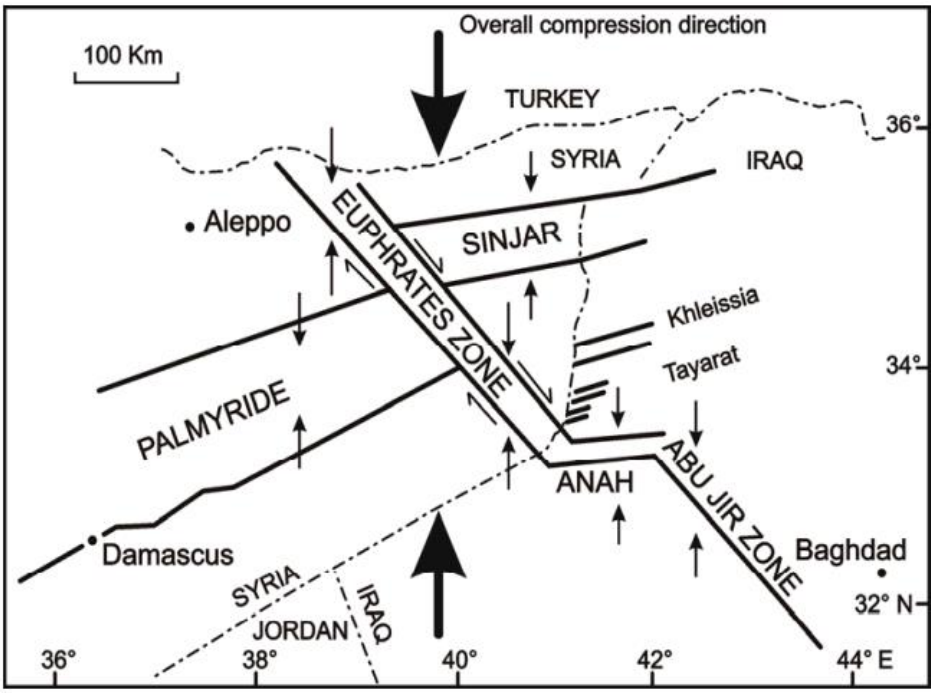

Figure 1-3: Simple sketch map shows the Late Tertiary compression, which resulted in structural basin inversion and transpressive movements on some of the North Arabian rift basins (Fouad, 1997).

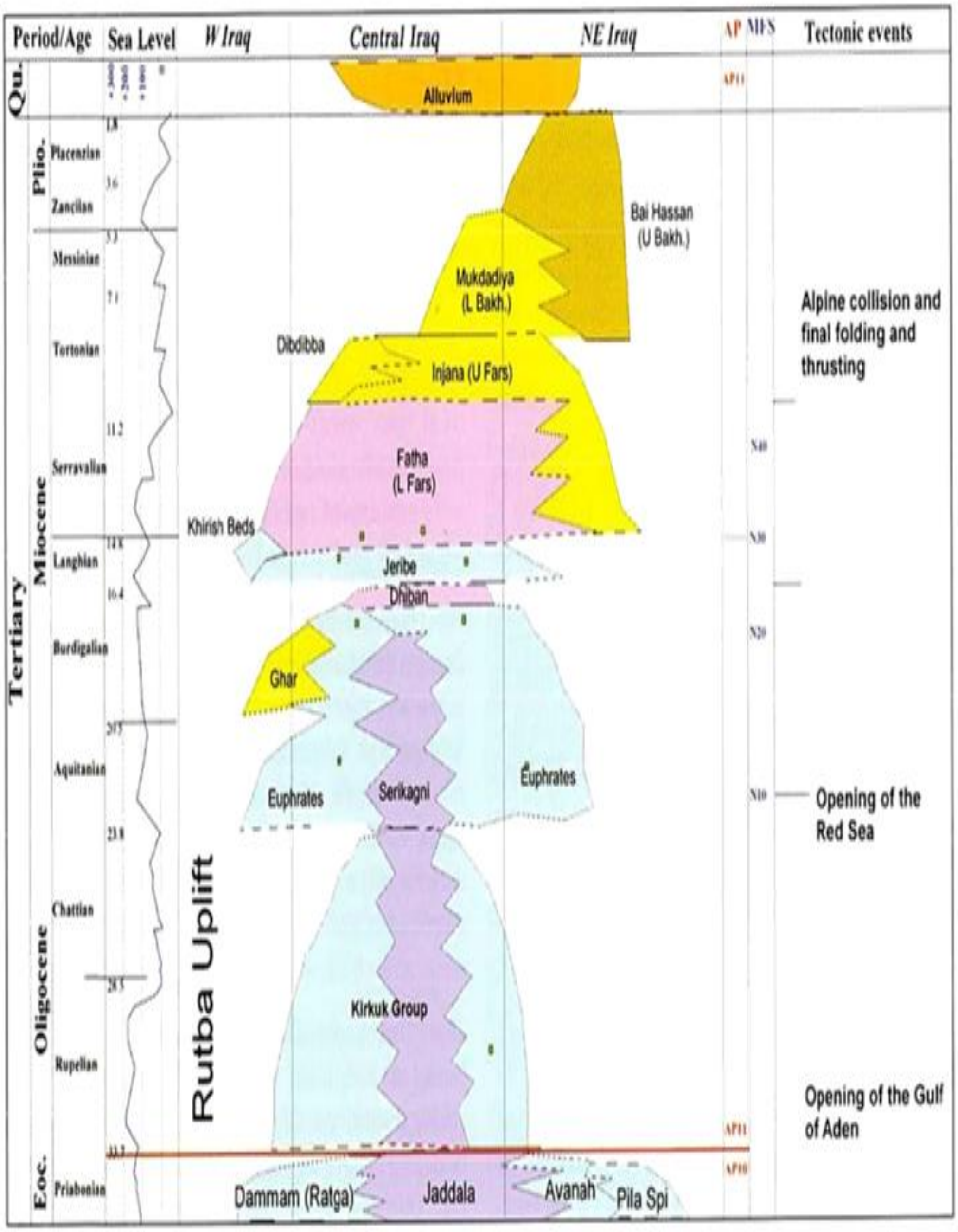

Figure 1-4: Stratigraphic correlation of formations of Megasequence AP11 (Jassim & Goff, 2006).

The Euphrates Formation (Aquitanian-Burdigalian) is the most widespread formation in outcrops and subsurface of the Iraqi Western Desert sequence, where it exposed along the Iraqi-Syrian borders at Al-Qaim and runs eastwards, adjacent to the Euphrates River along both sides, passing through Anah, Haditha, Al-Baghdadi, and Heet adjacent regions, then passing laterally to the Ghar Formation between Nasirriyah and Basrah in the south and southeast (Sissakian & Mohammed, 2007). Bellen et al. (1959) suggested the type locality in Wadi Fuhaimi close Anah on the Stable Shelf includes shelly, chalky, and well bedded recrystallised limestone; but this represents only a small part of the formation and excludes the underlying conglomerate, which has a thickness of up to 8 m. While it reaches between (60-70) m in the neighboring area. Jassim et al. (1984) proposed a type location in Wadi Chabab, nearby Anah, where the formation thickness reaches up to (110 m), indicating the best outcrop of the Euphrates Formation.

The Euphrates Formation was deposited under the shallow marine, reef, and lagoonal conditions, with local coral and intermittently occurring fore-reef conditions. The lower contact of the formation is usually unconformable with Oligocene Anah Formation in the type area. In many areas, the formation overlies different Oligocene and Eocene formations. The upper contact at the type locality is not exposed. So it seems, that the upper contact is conglomeratic marking an erosional termination or at least an emergent phase at the top of the formation (Buday, 1980).

Fatha Formation (Serravallian) is one of the most widespread formations in Iraq and is of economic importance because it represents the main cap-rocks for a number of oil reservoirs (Buday, 1980). Al-Rawi et al. (1992) chose the type locality of the Fatha Formation (Lower Fars) is in Makhul Range, with a thickness of 445 m. It includes cyclic deposits consisting of greenish-gray clay and marl in addition to limestone, anhydrite, and gypsum. The Fatha Formation was deposited in a rapidly subsiding sag basin which periodically became evaporitic with the formation of sabkhas and salinas. It consists of cycles of mudstone, limestone, and gypsum in the Heet area (Jassim & Goff, 2006).

The lower contact with Euphrates Formation is unconformable. The upper boundary, with the Injana (Upper Fars) is gradient and asynchronous (Bellen et al., 1959). Bitumen layers containing aragonite and celestite may also be found in the Fatha Formation's basal marl near Heet city, and they are thought to be of the same origin. These deposits are found near the Abu-Jir Fault Zone, which is also known for its prolific asphalt seepages (at Ain Jabha, Ain Abu Jir, Ain Atalt, and Ain Heet) (Jassim & Goff, 2006).

CHAPTER TWO

MATERIALS AND METHODS

2-1 Preface

This chapter deals with the explanation of the method used in the field work and how to collect information from the study area, the tools used, and the methods used in office work, in order to Reaching the aim of the study.

2-2 Preparatory stage

After tracking the study area by google earth software and knowing its topography, the preparatory stage began, where a reconnaissance trip to the area was determined to determine the locations of the surface outcrops that will be studied and data collected from them.

This stage also included the preparation of geological equipment that can be used to collect data from the area during field work, where I was equipped with a geological hammer that can be used as a tool to scale when taking some pictures of the geological structures and layers as well as for collecting samples, a compass-clinometer that is used to record the attitude of the layers and geological structures as well as to determine the direction of the north, handheld GPS device to location of the outcrops that will be studied, a tape measure to calculate the thickness of the layers of geological formations, a camera to depict the important geological features, and a topographic map of the area at a scale of 1:100000, on which the locations of cities and valleys are installed, and it also included a collection of published research on the study area and the subject of the research.

2-3 Materials

Several materials are used to achieve the main objective of this study. They consist of Tectonic and geological maps with a scale of 1:1,000,000. The Landsat satellite images are downloaded from the websites (google earth pro and sas-planet). Many types of equipment are used during field trips to the study area, for example, compass-clinometer, a geological hammer, tape measure, diluted hydrochloric acid, handheld GPS, hand lens, relevant topographical map, and camera.

Many softwares are applied such as ArcGIS software v. 10.4.1 to fit the maps that are derived from satellite images, and to layout a geological map of the study area, Adobe Illustrator software v. 2019 to draw stratigraphic sections, Adobe Photoshop software v. 2020 to process some field photos, the Paint 3D software to add symbols on photos, and Stereonet software v.11.3.0 to draw the attitude of the structure features.

2-4 Methods

2-4-1 The field stage

Many field trips are conducted in the study area. The first is an exploratory field trip to the Heet, Khalidiyah, and Sahliyh areas where some outcrops were selected on 9/1/2021. The second trip was on 10-15/1/2021 to the same areas that were mentioned for the detailed study of the geological structural features such as joints, faults, and types of small folds, where the type of these geological structures was studied and their attitude was measured in terms of dip, strike and dip direction of inclination by compass-clinometer.. The third trip was on 16-17/2/ 2021, during which a detailed study and stratigraphic column of the outcrop in the Al-Baghdadi area was conducted. The fourth trip was on 2/3/2021, in which a stratigraphic column was made for the outcrops in the Heet and Sahliayh areas, and documented with pictures of some geomorphological features in the study area. The last trip was on 29/3/ 2021, during which a detailed study of the outcrop in the Haditha area was achieved.

A stratigraphic column was made in the field for the aforementioned outcrops, starting from the bottom of the section up to its top end, by taking a measurement of the thickness of the layers using a tape measure and determining the type of rock layers and examining them if they contain fossils by a hand lens, as well as knowing the type of geological structure that each layer contains it and documents all this information in the notebook with determining the coordinates of the outcrop by handheld GPS.

2-4-2 The office stage

2-4-2-1 Location map

A satellite image of the study area was taken on 2013 by Google Earth Pro after making sure that the image is directed in the exact north direction. Four points with known coordinates have been added to the satellite image by using the add placemark tool in the Google Earth Pro and then this image was saved on the computer. Then the ArcGIS software v. 10.4.1 was opened, and the coordinate system was chosen as the first step, and then the satellite image was added to the ArcMap software, and a georeferencing was made for it. The image has been processed to increase its resolution and clarity, then I made a final output of the map using the layout view tool, where insert the main map elements such as a frame, legend, scale bar, coordinates, and the north arrow.

2-4-2-2 Geological map

I made a geological map of the study area by cutting part of the GEOSURV Geological map of Iraq (2000), by using ArcGIS software v. 10.4.1. Where the cut part of the map has been called and returned geographically until it is recognized in the ArcGIS software. Several shapefiles were drawn for the map, including polygon, point and polyline, adding colors and geological symbols to geologic formations, and merging these shapefiles in the form of layers with each other to form the geological map. then I made a final output of the map using the layout view tool, where insert the main map elements such as a frame, legend, scale bar, coordinates, and the north arrow.

2-4-2-3 Stratigraphic column

The stratigraphic columns were designed for outcrops that have been studied in the field by Adobe Illustrator software v. 2019, depending on the data that was recorded during the field work stage. These stratigraphic columns are projected on location map (Figure 2-1) based on the handheld GPS coordinates in the field. Then a lithostratigraphic correlation is made between them.

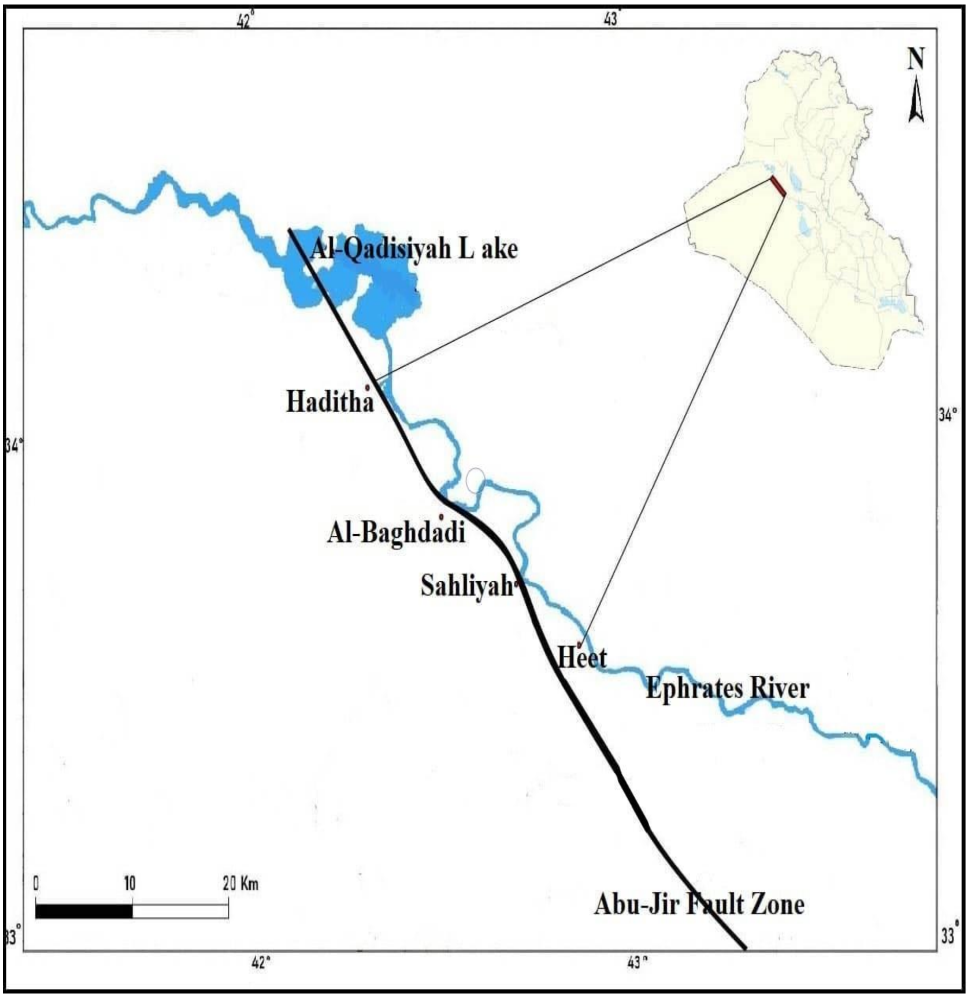

Figure 2-1: Location map of the studied outcrops.

2-4-2-4 Geological structures

Some illustrations have been added to the field photos of geological structures by the Paint 3D software. As well as drawing the attitude of the joints, by Stereonet software v. 11.3.0. By entering the values of the dip, strike and dip direction that were measured by the compass-clinometer during the field work stage.

2-4-2-5 The field photos

Some photos of geological structures and geomorphological features have been processed and their clarity increased by Adobe Photoshop software v. 2020.

CHAPTER THREE

RESULTS AND DISCUSSION

3-1 Geomorphology of the study area

The study area extends over a large area in the Western Desert that reflects many geomorphological features as a result of lithology, structure, and climate interacting (Hamza, 2007). The geomorphological features in the area were deduced from field visits, satellite imagery analysis, and previous studies.

3-1-1 Valleys

The main valleys in the study area drain into the Euphrates River. The valleys are: Al-Marj, Al-Sahiliya, Al-Baghdadi, Asad, Huaran, Banat Al-Hassan, Zghadan, Heqlan from the Heet to the Haditha, respectively. These valleys are parallel with each other mostly because of their very clear relationship with the faults system, as it appears in Landsat images and topographic maps (Hamza, 2007).

3-1-2 Plateaus

The presence of plateaus in the study area on the Euphrates Formation. The plateau on the upper part of the Euphrates Formation (Plate 3-1), which consists of limestone and dolostones, its surface is covered by soils. It extends on both sides of some valleys that make their way through these plateaus. So, it appears as patches of variable size.

Plate 3-1: Plateau on the upper part of the Euphrates Formation in the Al-Sahiliya valley.

3-1-3 Mesas, Butte and Hills

This type of landscape is very common along the current study area within Fatha Formation (Plate 3-2). A mesa is usually an isolated landform with flat-topped, steeper sides, and is smaller than the plateau within the Fatha Formation in Al-Dulab area (Plate 3-2A). It occurs along a cliff that separates plateaus from each other and is developed due to differential erosion along with the intersecting joints of the outer parts of the plateaus. Also, the butte is similar to mesa in terms of characteristics, but it is smaller. The layers of marly limestone and gypsum rock that compose a mesa or butte give them their distinctive shape, with a flat top and cliff-like sides. The top layer of a mesa and a butte is a hardened gypsum layer of rock that is resistant to erosion. The butte may turn into a small hill in an advanced stage of erosion (Plate 3-2B).

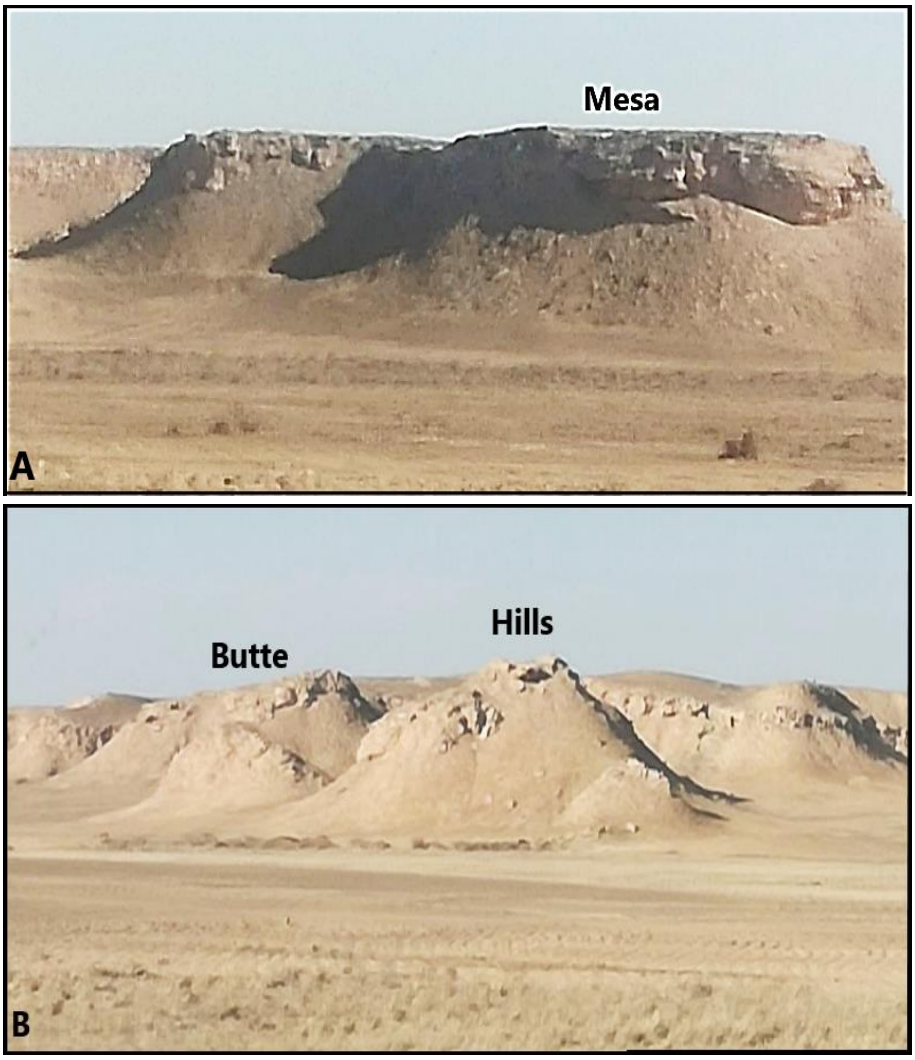

Plate 3-2: (A) Mesa and (B) Butte and Hill within Al-Fatha Formation in the Al-Dulab area northwest the Heet city**.**

3-1-4 Sabkha

Sabkhas are flat landscapes in which a wholly or partly accumulation occurs as a result of the precipitation of evaporators (and in some cases carbonate precipitation). Salt precipitation requires periodic wetting and is often controlled by subtle changes in the water level (Mountney, 2005). Sabkha is being developed in the Heet area (Plate 3-3), along the Abu-Jir Fault Zone and the source of saline water in this area is spring water.

Plate 3-3: Sabkha in the Heet area.

3-1-5 Flood Plains and River Terraces

Flood Plains are of fluvial landforms in origin, as their presence is limited to the Euphrates River and some main valleys. Flood Plains are subject to periodic floods. They form flat, cultivated plains, consisting of a plate of variable thickness from sand, silt, and clay (Plate 3-4). In the same area, river terraces of the Euphrates River are developed (Plate 3-5). Hamza (1975) reported the four stages of Euphrates River terraces in Heet area: (100, 70, 50, and 20) m above the river level. The terraces are made up of loose and cemented, pebbles of chert and carbonate, as well as rare of that of igneous, and metamorphic rocks. The pebbles are of variable shapes and range in size from gravel to cobble.

Plate 3-4: Flood Plains along Euphrates River to the south of Heet area.

Plate 3-5: Euphrates River Terraces to the south of Heet area.

3-1-6 **Sinkholes**

The sinkholes are characteristic of the present study area, as the Haditha region is one of the most karst regions in Iraq. Karst landscapes can be found all over the world, where limestones and dolomites (and, less usually, gypsum) grow out of the ground and there is enough flowing water for dissolution weathering to take over (Frisia & Borsato, 2010). 56 sinkholes of various shapes and depths have been recorded, such as the Salman Al Rosa sinkhole (Plate 3-6A), and the K3 sinkhole is the latest sinkhole that has been discovered in a Haditha city after its cover suddenly collapsed (Plate 3-6B). The reason for the proliferation of this phenomenon in the area within the Euphrates Formation is the presence of the basal conglomerate at the bottom of the formation, especially when the base is exposed at the bottom of the valleys. This is because the cement materials are dissolved by the movement of water leaking out into the valley floor, then the carbonate layers above the basel conglomerate are dissolved, as the remaining surface becomes difficult to bear the weight and then collapses (Sissakian et al., 2015).

Plate 3-6: Sinkholes within Euphrates Formation near the Haditha city. A- Salman Al Rosa sinkhole, and B- K3 sinkhole.

3-2 Stratigraphy of the study area

The age of the exposed rocks in the study area is ranging from Oligocene to Middle Miocene. The oldest rocks are referred to as Sheikh Alas Formation (Early Oligocene) exposed in Ain Al-Asad valley unconformably with Euphrates Formation (Al-Ghreri, 2007). Whereas, the upper contact of the Anah Formation (Late Oligocene), is exposed unconformably below the Euphrates Formation in the Haditha section. The present study focused on the Euphrates and Fatha formations (Figure 3-1), which belong to the Lower and Middle Miocene respectively. The present study area comprised of four outcrops; Heet, Sahliyah, Al-Baghdadi, and Haditha, and the comparison was made with Melh Tharthar-1 well.

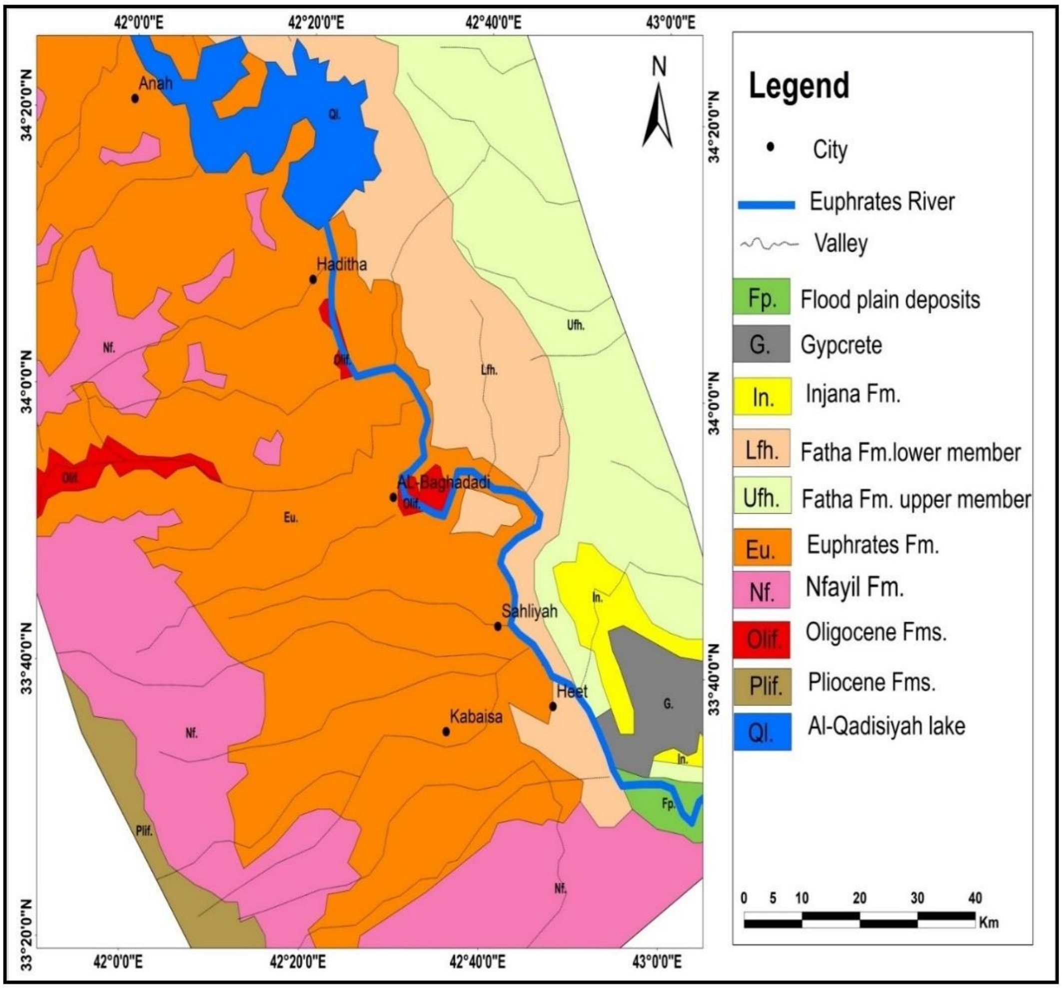

Figure 3-1: The geological map of the exposed stratigraphic units within the study area, after (GEOSURV Geological map of Iraq 2000).

The sections of the outcrops will be explained in detail, arranged from southeast to northwest in the study area, as follows:

3-2-1 Heet outcrop section

The Heet section was measured in detail at (N33°. 37'02.7", E42°50' 27.4"). The total thickness of this section is approximately 12 m, as it turns out that it has one lithological sequence, represented by the Fatha Formation, which is the age of the Middle Miocene (Serravallian), according to its position in the stratigraphic column in Iraq.

The lithostratigraphic sequence (Figure 3-2), consists of four layers from bottom to top. The bottom layer consists of yellowish to reddish silty claystone with intercalation of siltstone, which has a thickness of 2 m. The topping layer consists of layers of marly limestone, with very thin layers of secondary gypsum alternating periodically which at a thickness of 4 m. It is topped by the third layer, made of greenish to yellowish marl, with intercalation of anhydrite, weathered in places, which a thickness of 2 m. It is topped by the fourth layer, which appears at the end of the sequence, which consists of hard gypsum rocks white color which a thickness of 4 m, and contains hydrocarbon seepages (Plate 3-7). These hydrocarbon seepages come out through cracks and fractures in the gypsum layer, and after their exit into space, they will become very dense due to the escape of liquids and gases.

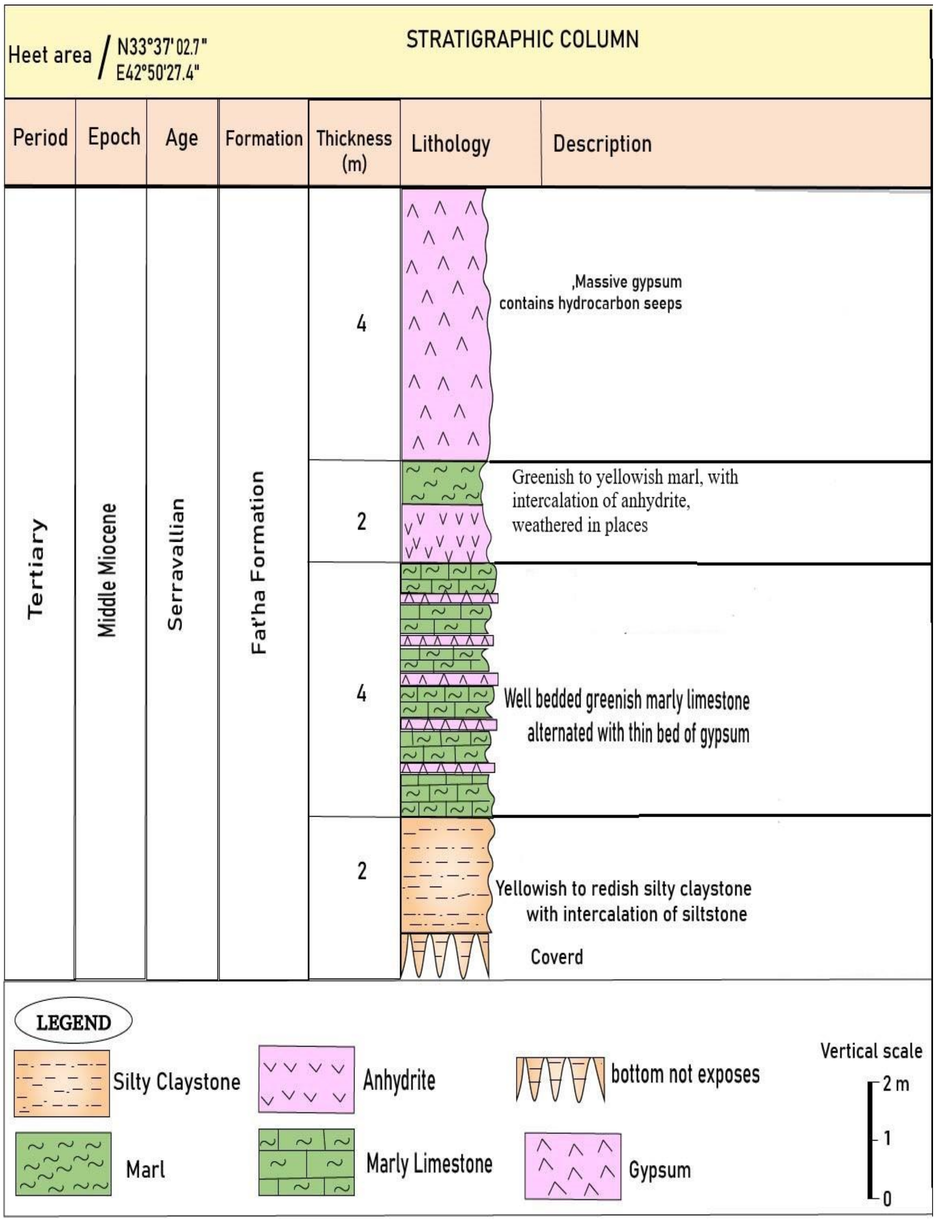

Figure 3-2: Lithostratigraphic section in the Heet area.

Plate 3-7: The hydrocarbon seepages through the gypsum layer of the Fatha Formation in the Heet outcrop.

3-2-2 Sahliyah outcrop section

The Sahliyah section was measured in detail at (N33° 34'13.8", E42°42' 40.2"). It is located to the northwest of the Heet section, approximately 18 km away from it. the total thickness of this section is approximately 22m. It was found to be represented by the Euphrates Formation, which refers to the Early Miocene (Burdigalian). The lithostratigraphic sequence (Figure 3-3), It turns that this outcrop is represents only the uppermost part of the Euphrates Formation. It consists of brecciated and undulated limestone units, that consist of light grey, massive, recrystallized limestone, light green marly to marly limestone, yellowish-white chalky limestone, well-bedded green marly limestone, light grey slightly oolitic limestone, dolomitic limestone, grey fossiliferous limestone. The uppermost part of the Sahliyah section is the hardground surface, which consists thin layer of hard, boring, and burrowing dolomitic limestone which has a thickness of 1m (Plate 3-8). Hardgrounds were defined as sny-sedimentary lithified carbonate sea-floors, which are represent intervals of time during which sedimentation did not take place, cement precipitated, and specialized faunas flourished (Wilson & Palmer, 1992). These surfaces represent a hiatus between the sedimentary layers located below and above it (Yahya et al., 2020). The hardground did observe on the top Euphrates Formation in the Sahliyah outcrop, which could indicate a time gap by missing the Dhiban and Jeribe formations. Generally, this outcrop is characterized by many geological structures such as folds, faults, joints, and undulation (Plate 3-9).

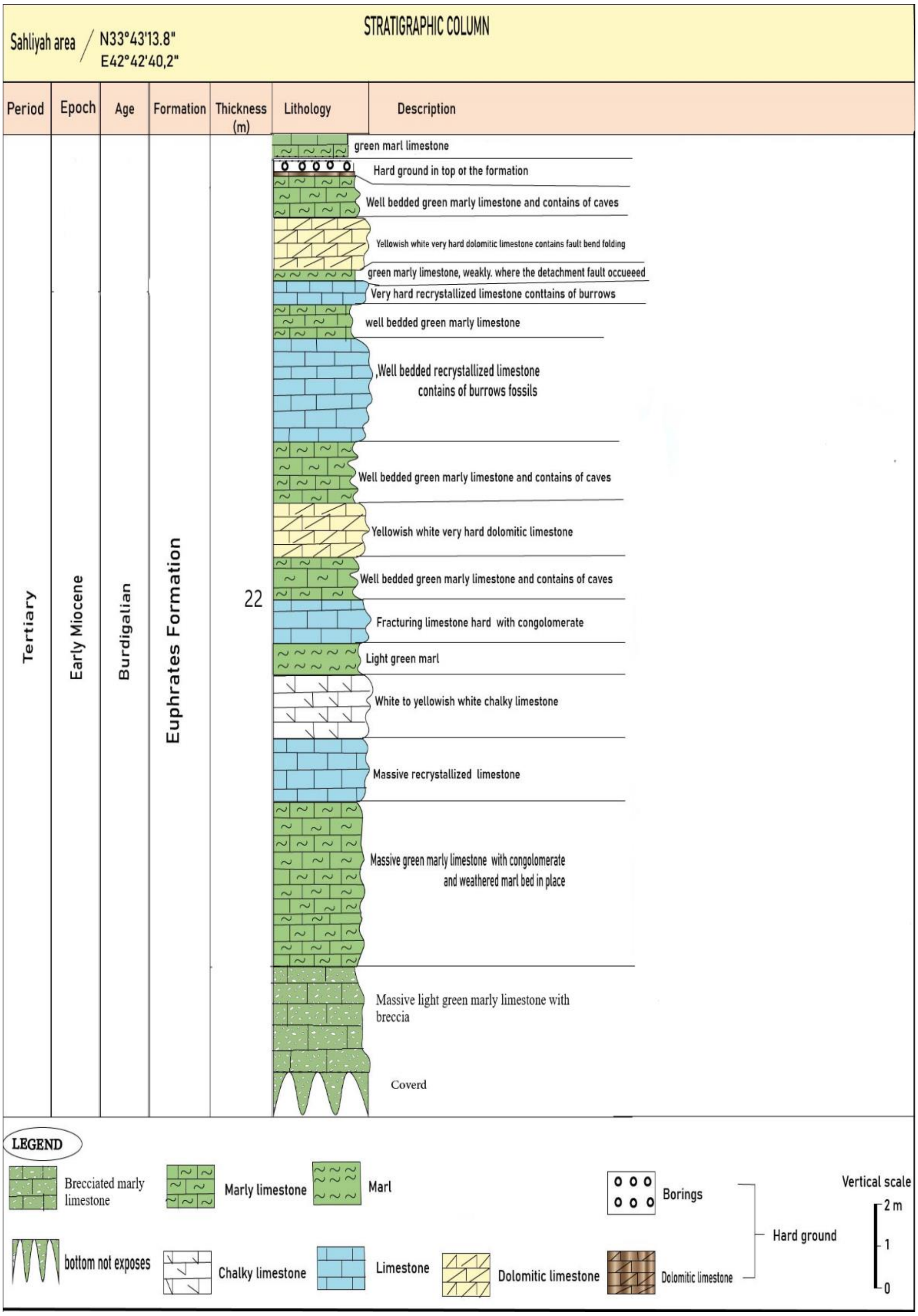

Figure 3-3: Lithostratigraphic section in the Sahliyah area.

Plate 3-8: Hardground bed at the top of the Euphrates Formation in the Sahliyah section.

Plate 3-9: The structures of Euphrates Formation in the Sahliyah outcrop.

3-2-3 Al-Baghdadi outcrop section

The Al-Baghdadi section was measured in detail at (N33° 51'43.7", E42°31' 55.3"). It is located to the northwest of the Sahliyah section, approximately 28 km away from it. The total thickness of this section is approximately 24m. It was found to be represented by Euphrates Formation, which refers to the Early Miocene (Burdigalian).

The lithostratigraphic sequence (Figure 3-4), the lower part of the Euphrates Formation is the basal conglomerate unit which has a thickness of 6 m (Plate 3-10). It consists of limestone pebbles of varying sizes, light grey, and relatively large diameter at the bottom, gradient upward into smaller and more rounded grains, resulting from weathering of older rocks in their places. The basal conglomerate layer is topped by the limestone unit, which has a thickness of 18 m, can be subdivided into lower parts containing thick-bedded to massive limestone, dolomitic limestone, highly fossiliferous. The middle part consists of greenish-white, yellowish, and chalky limestone. The uppermost part contains highly deformed, undulated, and jointed, called brecciated, and undulation unit, which has a thickness of 2 m.

The Fatha Formation appears on the hills in the areas surrounding the Al-Baghdadi area, especially the Al-Dulab area. It consists of alternating layers of green marl and white hard gypsum layers. It is also noted that the gypsum layers form different geomorphological features at the top of the hills, butte, mesa, and plateau, strongly influenced by the weathering processes.

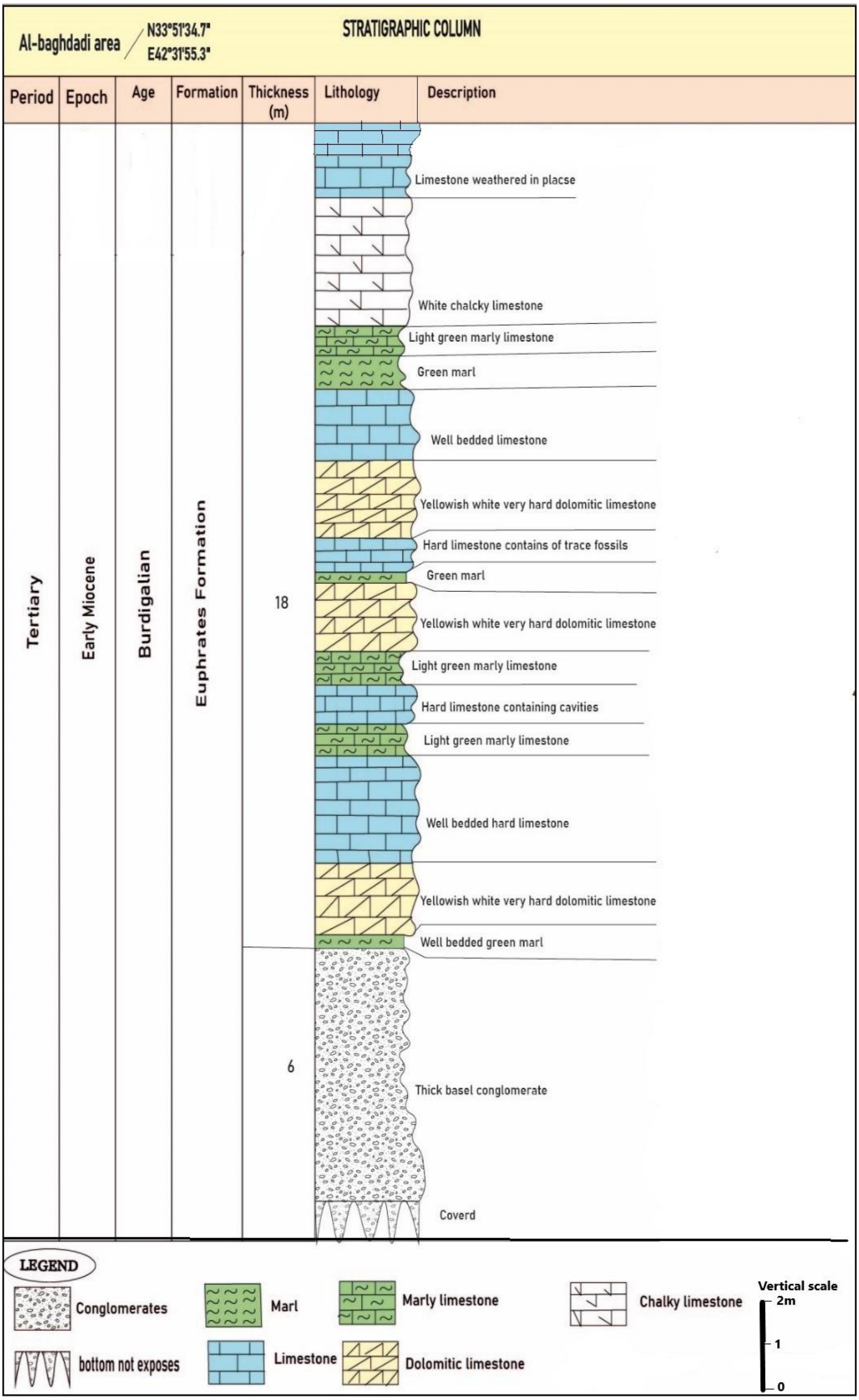

Figure 3-4: Lithostratigraphic section in the Al-Baghdadi area.

Plate 3-10: Basal conglomerate unit and limestone unit of Euphrates Formation in Al-Baghdadi outcrop.

3-2-4 Haditha outcrop section

The Haditha section was measured in detail at (N34° 05'32.2", E42°21' 52"). It is located to the northwest of the Al-Baghdadi section, approximately 42 km away from it. The total thickness of this section is approximately 27m. It was found to be represented by the two formations, the Anah Formation, which refers to the Late Oligocene, and the Euphrates Formation, which refers to the Early Miocene (Burdigalian). The lithostratigraphic sequence (Figure 3-5), the lower part of the section is Anah Formation consists of coralline, hard recrystallized massive limestone which has a thickness of 3m. Above it is the unconformable Euphrates Formation (Plate 3-11). The lower part of the Euphrates Formation is the basal conglomerate unit which has a thickness of 4 m. It consists of limestone pebbles of varying sizes, light grey, and relatively large diameter at the bottom, gradient upward into smaller and more rounded grains, resulting from weathering of older rocks in their places. The basal conglomerate layer is topped by the limestone unit, which unit can be subdivided into lower part that contain well-bedded, light grey, highly fossiliferous, recrystallized limestone with thin layers of marly limestone alternately. The middle part consists of white, bedded, chalky dolostone, limestone, and dolomitic limestone with horizons of green marl. The upper part consists of white, massive dolomitic limestone, deformed and brecciated.

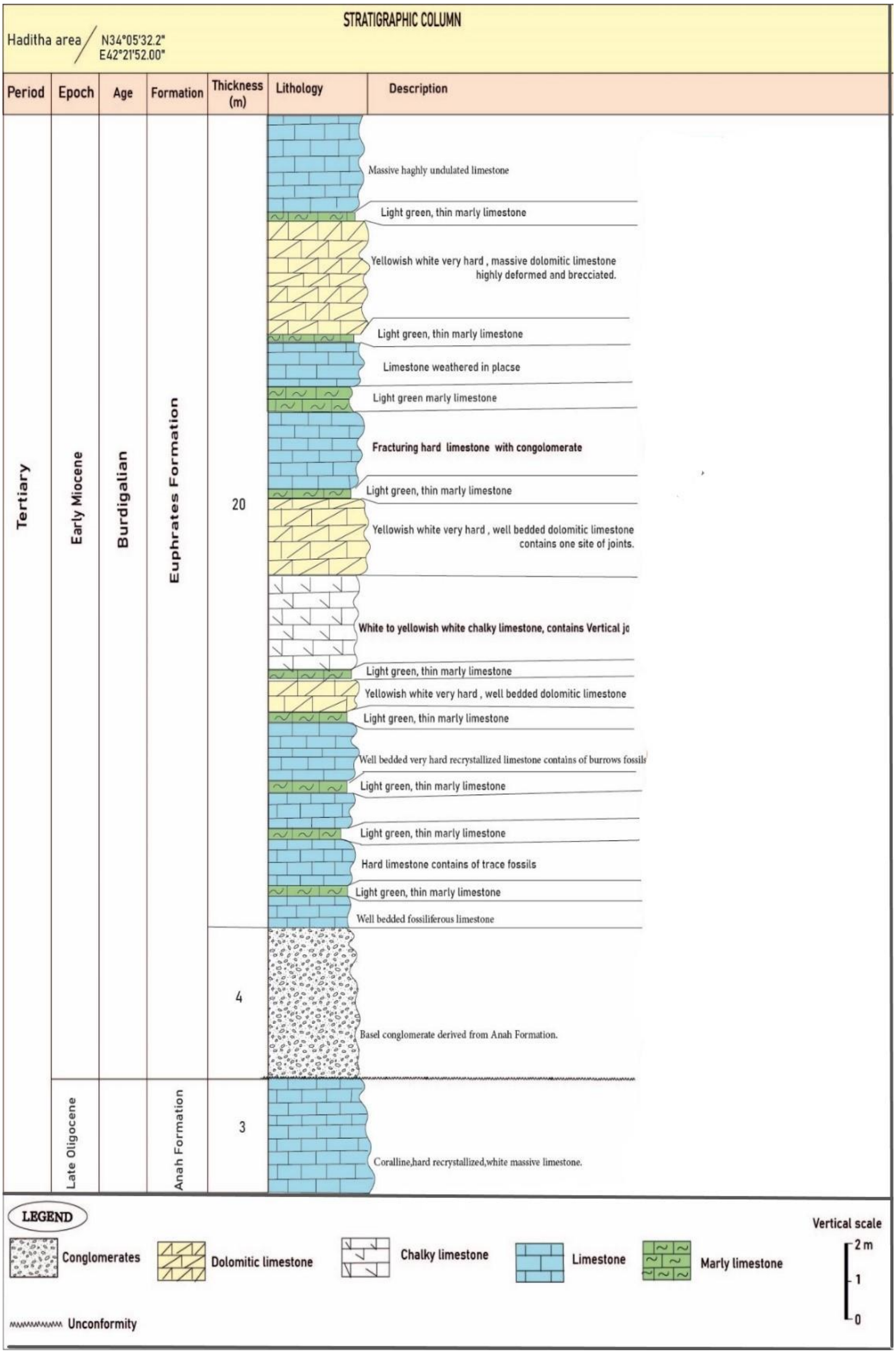

Figure 3-5: Lithostratigraphic section in the Haditha area.

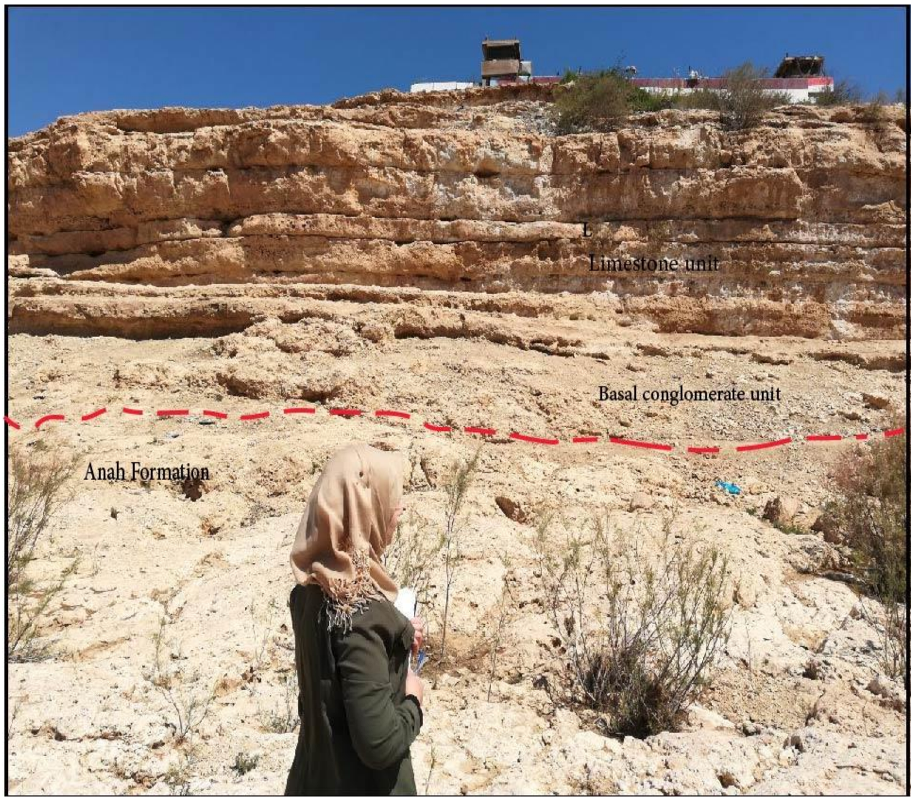

Plate 3-11: Anah and Euphrates formations in Haditha outcrop.

3-2-5 Lithostratigraphic correlation

Through the field study of the surface sections in the study area and relying on the similarity of stratigraphic units. As well as by comparing it with the subsurface sections, represented by Melh-Tharthar well. The Euphrates Formation exposed at these sections can be divided into two distinct units, lower and upper units. Lower unit “basal conglomerate” consists of limestone pebbles of varying sizes, light grey, and relatively large diameter at the bottom, gradient upward into smaller and more rounded grains, resulting from weathering of older rocks “Oligocene formations” in their places. The upper unit “limestone unit” consists of thick-bedded to massive limestone, dolomitic limestone, highly fossiliferous with greenish-white, yellowish, and chalky limestone. While the uppermost part of this unit contains highly deformed, undulated, and jointed beds, called brecciated and undulation units.

Although the distances between the sections are close. It can be observed that is a large variation in the lithofacies laterally and vertically (Figure 3-6). Lithostratigraphic correlation between the sections appears the Anah Formation

(Late Oligocene) begins to appear on the surface towards the northwest, which indicates the uplifting occurs in this direction, while the southeast area remains subsidence due to the local activity of Abu-Jir Fault Zone. A relative increasing thickness of the marly limestone layers of the Euphrates Formation toward the southeast is a good indication of a deep environment related to the northwest of the study area.

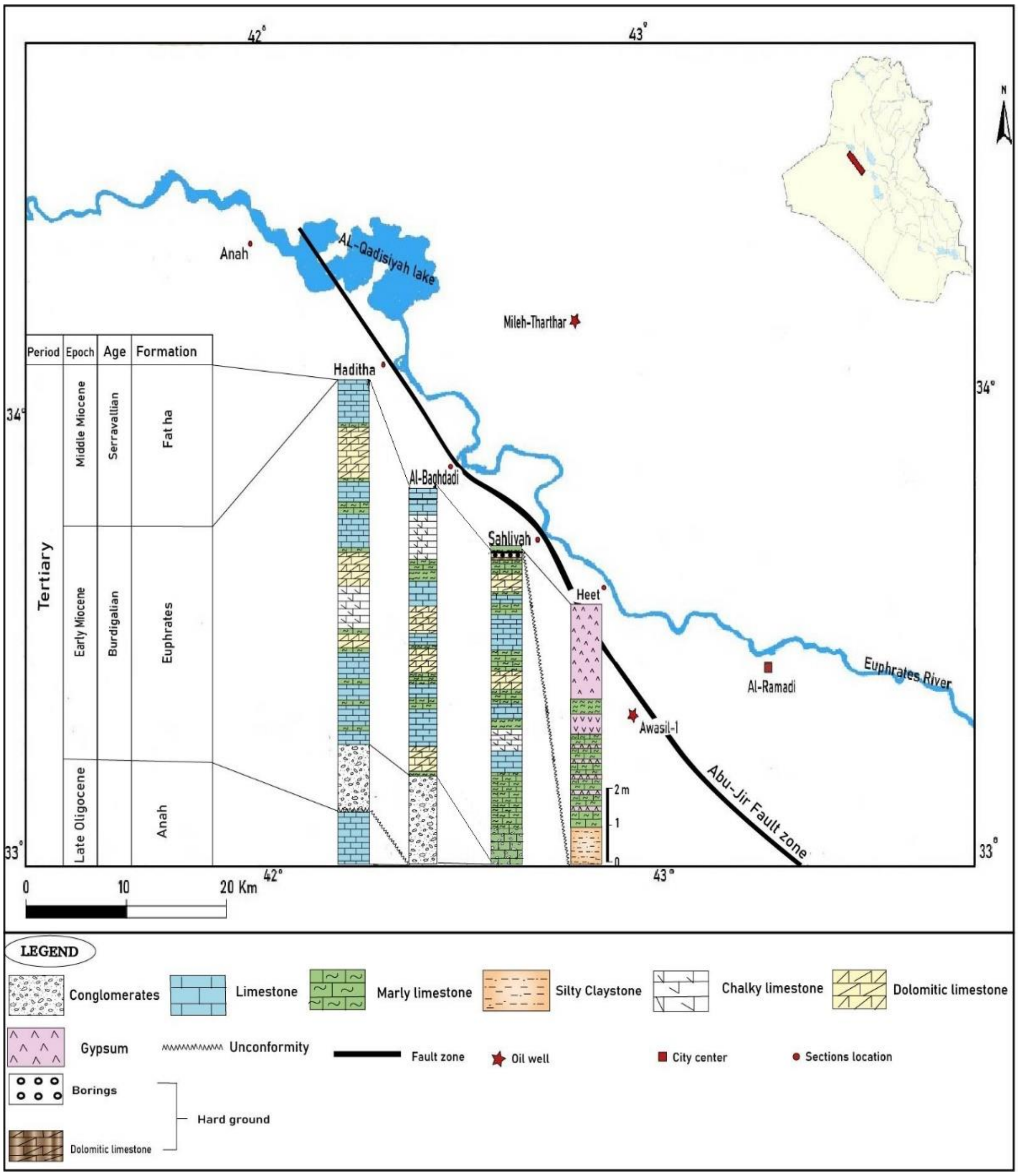

Figure 3-6: Lithostratigraphic correlation of sections in the study area.

Comparing the elevation of the upper boundary of the Euphrates Formation relative to sea level on both sides of Abu-Jir Fault Zone, note the elevations on the western side (73.15 m, 91.5 m, and 112.7 m) represented by the Sahliyah section, Al-Baghdadi section, and Haditha section respectively. On the eastern side (-256m) the Mileh Tharthar well (Figure 3-7) respectively. The deposition of the Jeribe and the Fatha formations with relatively a large thickness to the east of Abu-Jir Fault Zone, while the Jeribe Formation is absent in the study area. It can be considered as an indication of very quick subsidence of the eastern side of Abu-Jir Fault Zone during Late Early Miocene and Middle Miocene due to the elastic isostasy of the Mesopotamian foredeep. Therefore, it is assumed that fault is a basin bounding fault. It may act like a normal fault or a growth fault.

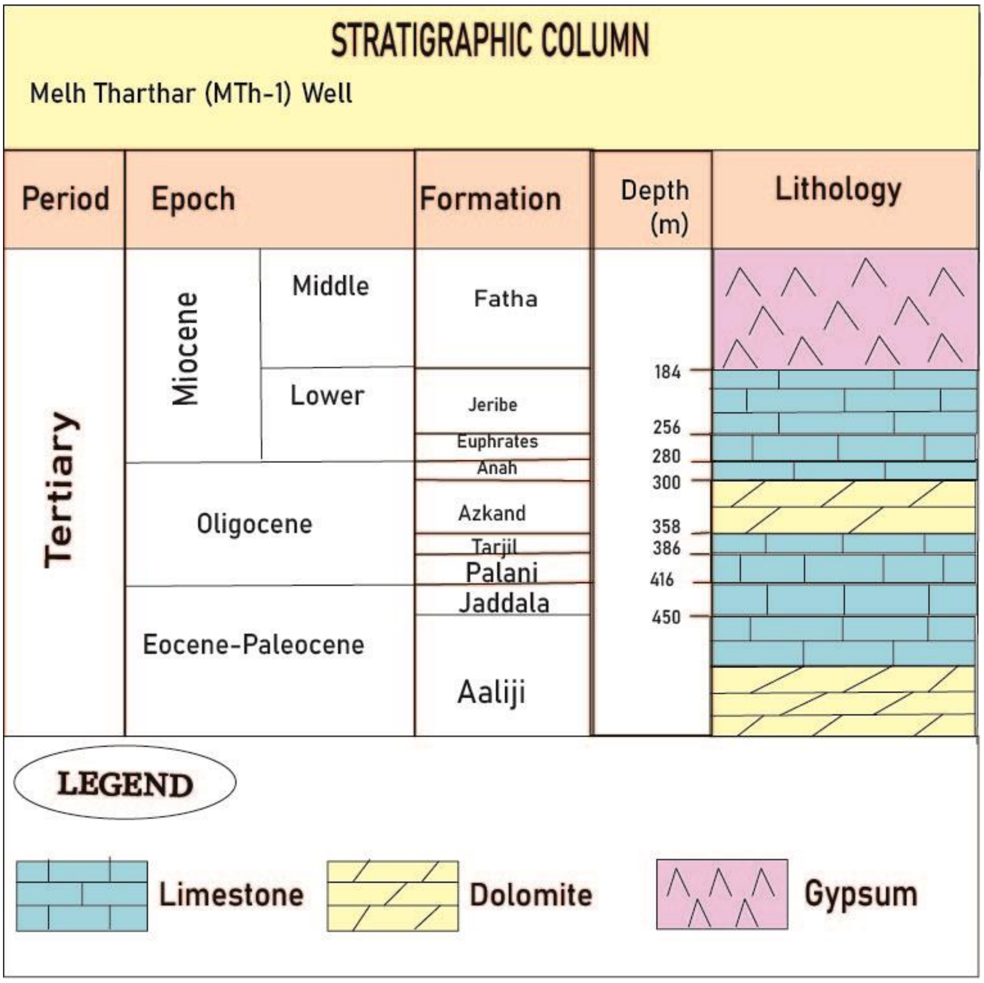

Figure 3-7: Stratigraphic column of Melh Tharthar (MTh-1) well, Modified after (Al-Rawi et al., 2014).

3-3 Geological structures of the study area

We will explain the structures of the Euphrates and Fatha formations along the Abu-Jir Fault Zone between the Heet and Haditha cities, starting from the oldest to the youngest, respectively. There has been no previous study in this area because the quality of seismic data along the northern part of the fault zone is unreliable; the surface studies are required to comprehend the Abu-Jir Fault Zone's behavior in this area. This study is important for understanding the effects of the fault on topography, geomorphology, hydrology, and hydrocarbon seepages, and for applied and academic research.

3-3-1 Structures of the extension stage

Initially, the study area was subjected to an extension stress, as a result of which a main listric normal fault was developed on the Euphrates Formation in the Sahliyah outcrop (Plate 3-12), as it represents the main fault in the study area, which is formed in conjunction with the sedimentation of the uppermost part of the Euphrates Formation, is an extension of a major, sub-surface fault, so it is strongly affected by the stresses to which the region is exposed. It has a strike of 335°, its dip decreases (flattens) with depth along the fault plane, dip direction NE. Listric Faults are types of pull apart curved main normal faults in which the fault surface is concave upwards; its dip decreases (flattens) with depth. The flattening of the fault shows that the ductility of the rocks increases with depth (Shelton, 1984). The shape and complexity of listric normal faults are controlled by ductility contrasts within the rock sequence that is intersected by them (Bally et al., 1981).

We suggest the presence of Relay ramps structures within the Abu-Jir Fault Zone. A segment of relay ramp begins in the northwest Heet area through the Sahliyah area that ends before Al-Dulab area the second segment is the right step between Al-Dulab and Al-Baghdadi along the western bank of Euphrates River.

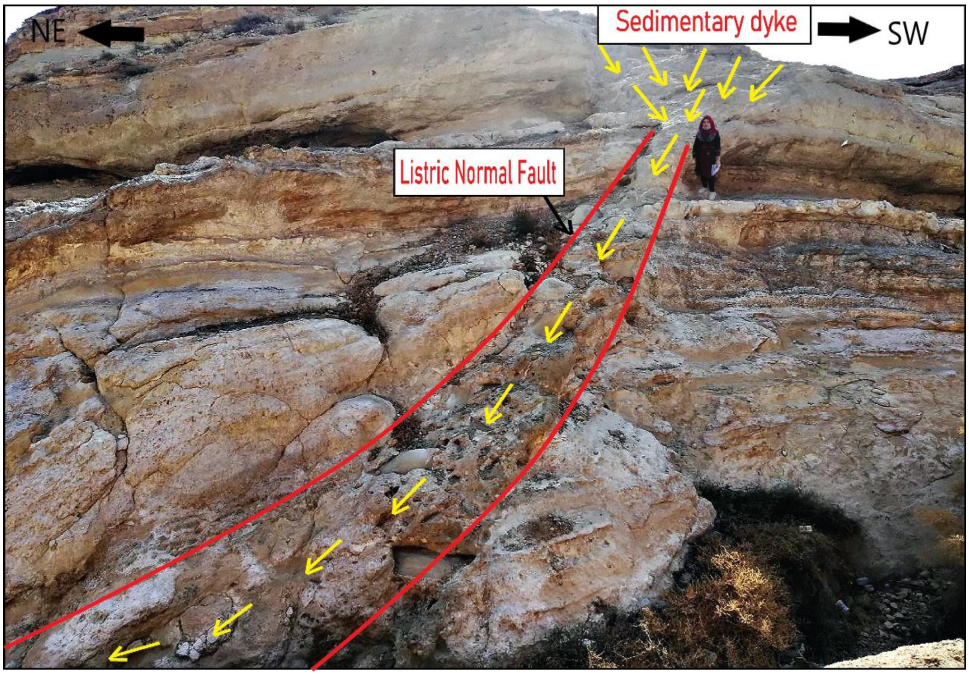

Plate 3-12: The listric normal fault and Sedimentary dyke in the Sahliyah outcrop.

Abu-Jir Fault is not a single fault but was formed by linkage of several segments (Marouf, 1999). Two segments of the normal faults, dipping in the same direction, and which overstep each other in map view are called “overlap zones” (Figure3-8). If the displacement (strain) is transferred across the overlap zone, then the zone is referred to as a “transfer zone” or a “relay ramp” (Peacock & Sanderson, 1991; Childs et al., 1995). Relay ramps are a common structure formed during the growth of normal fault systems in the active extensional areas, as they allow the accommodation of extension between segments fault along the length of the deformation zone (Di Bucci et al., 2006).

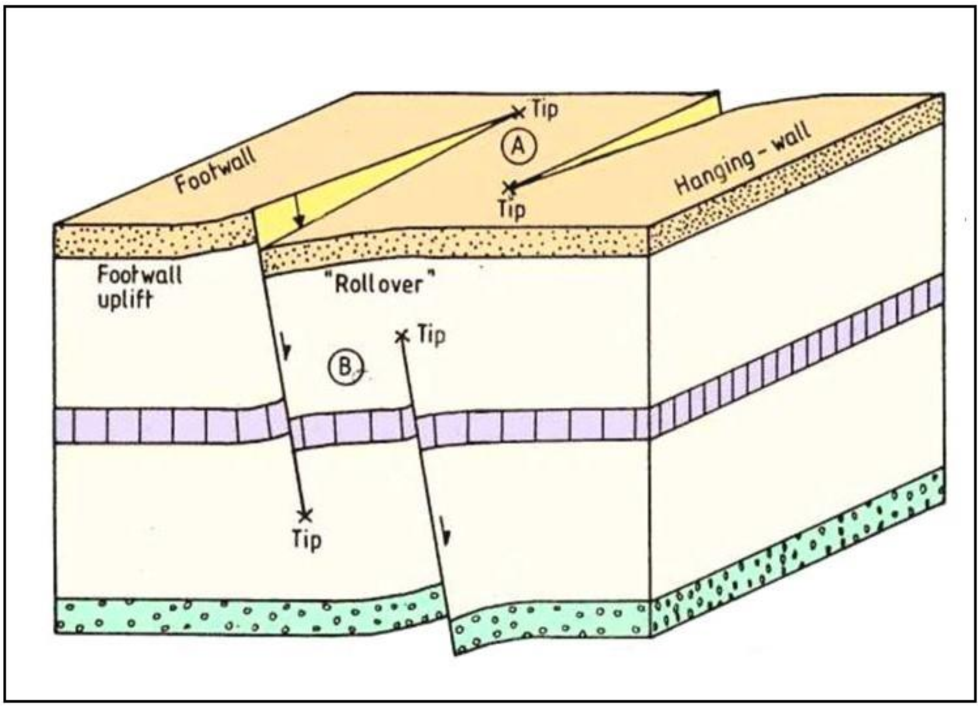

Figure 3-8: Block diagram with cross-section and map view of a pair of overlapping, normal faults (Peacock & Sanderson, 1991).

A sedimentary dyke or (clastic dykes) and many slumps or collapse structures have been observed in the uppermost part of the Euphrates Formation, indicating that the area has been subjected to an extension stress, which in turn formed the main listric fault during the deposition of the uppermost part of the Euphrates Formation, which led to the collapse of the (unconsolidated) part that is located directly above the fault and filling the space between the hanging and foot walls of the listric normal fault (Plate 3-12).A sedimentary dyke is defined as one of the syn-sedimentary deformation structures, discordant, tabular bodies formed of clastic material that is weakly to strongly lithified, it is generated by either passive clastic material deposition within pre-existing or earthquake-induced tensile fissures (Levi et al., 2008). The geometry of the dyke is controlled by the shape of the fault walls (Scholz et al., 2011). The presence of slumps structure (Plate 3-13) in the uppermost part of the Euphrates Formation is a good indication for syn-sedimentary extension structures, where we note the availability of slumps features of different scales and it coincides with the sedimentary dyke. Soft sedimentary deformation characteristics may be seen all across the study area, which stretches from Al-Qaim to the northeast, east, and southeast, passing via Rawa, Anah, Haditha, Haqlaniya, Baghdadi, and Heet (Sissakian et al., 2014).

Plate 3-13: Slumps structures in the Sahliyah outcrop.

3-3-2 Structures of the compression stage

The study area was subjected to the second stage of stress, which is compression stress, due to the strike-slip movement that occurred along the Abu-Jir Fault Zone, which led to the development of several structural features in the area. We begin by presenting the positive inversion that occurred on the main listric normal fault, which involved the uplift of rocks on the hanging-wall of this fault (Plate 3-14). Positive inversion occurs when an area changes from subsidence to uplift, whereas negative inversion occurs when an area changes from uplift to subsidence. Many researchers (Bodenhausen & Ott, 1981; Eubank & Makki, 1981; Glennie & Boegner, 1981) attributed that the cause of the inversion is due to strike-slip tectonics. If the striking slip is considered to be the cause of the inversion, the reverse separations and shallow folding common on inverted structures would require parallel or convergent displacements of the wrench (Harding, 1985).

Plate 3-14: The positive inversion that occurred on the main listric normal fault in the Sahliyah outcrop.

The positive inversion on the main listric normal fault was occurred during a short time interval between the extensional and compressional stages, according to the assumption Cooper et al. (1989), that the positive inversion on the fault system occurs by a short time interval between the extensional and compressional phases, this is probably due to the attenuated lithosphere, which is not thermally calibrated, is relatively weak, and is prone to easy reactivation under any compressional stress.

During inversion, the beds in the cover sequence are shortening before the net extension at an earlier level has been canceled. This shortening in the sedimentary cover is generating folding and back-thrusting in the still downthrown hanging wall block (Figure 3-9). It is difficult to invert the steeply dipping faults by dip-slip movement, as these faults form buttresses for displacement on both shallow and deep levels but gently in inclined basement faults. However, positive structural inversion in the hanging wall of steeply dipping normal faults often development in two cases of strike-slip or oblique-slip movements (Gillcrist et al., 1987). Strike-slip faults are commonly found in regions of active tectonics and basins may undergo both extension and inversion in the same fault system (McClay, 2000). The above suggestions strongly support that the positive inversion that occurred on the steeply dipping main fault in the shallow level (Plate 3-14) is the result of a strike-slip movement.

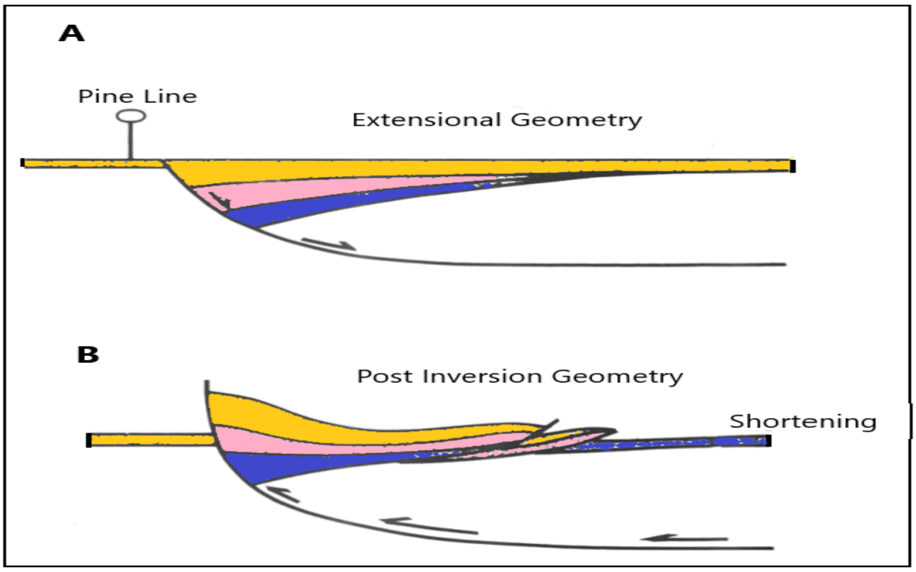

Figure 3-9: A, the excessive bed Length in the cover sequence to an asymmetric half-graben, and B, the accommodation structures that develop during inversion of the half-graben, after (Hayward & Graham, 1989).

Several systematic joints have developed in the hanging wall of the main listric inverted fault, specifically in the lower part of the Euphrates Formation. We will classify the joints in the study area based on the geometric classification. The base of the geometric classification is the three mutually perpendicular axes (a, b, and c) where a-axis is perpendicular to hinge line of the fold and parallel to the bedding plane, b-axis is parallel to hinge line and c-axis is perpendicular to plane which contains a and b axes, there are three types of joint sets (ab), (ac) and (bc). Each set contains two axes and the third axis is perpendicular to the joint plane (Figure 3-10). There are four types of joint systems hko, hol, okl, and hkl where h, k and l are equivalent axes a, b, and c respectively. Each joint system intersects two axes and is parallel to the third except the last joint system (hkl) intersects all tectonic axes (Figure 3-11). The joints in the study area are of the (hol) system type (Figure 3-11C). In which the joint planes are parallel to the (b) axis and intersect (a, c) axes. These planes create an acute angle with the bedding plane.

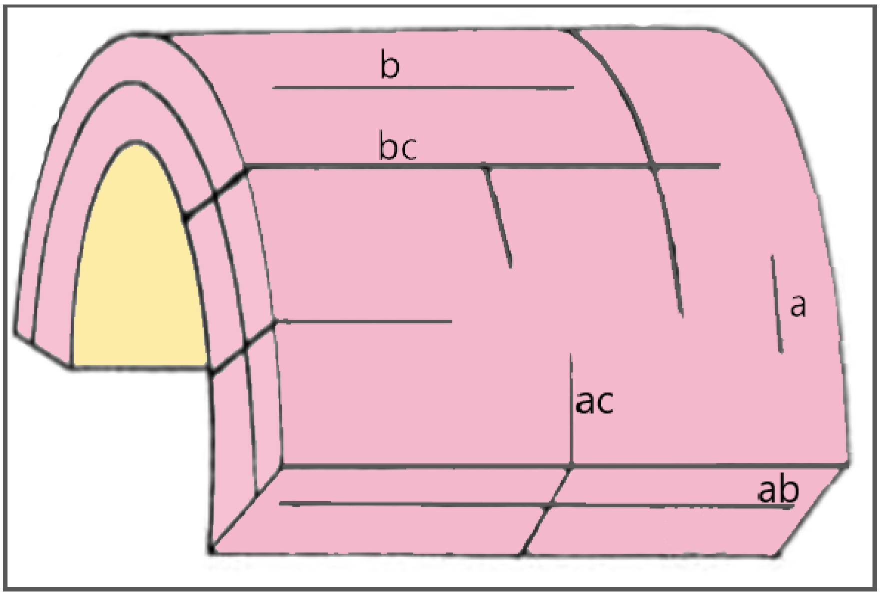

Figure 3-10: Geometry relation of sets joints (ab, bc, and ac) with fold axis and bedding plane.

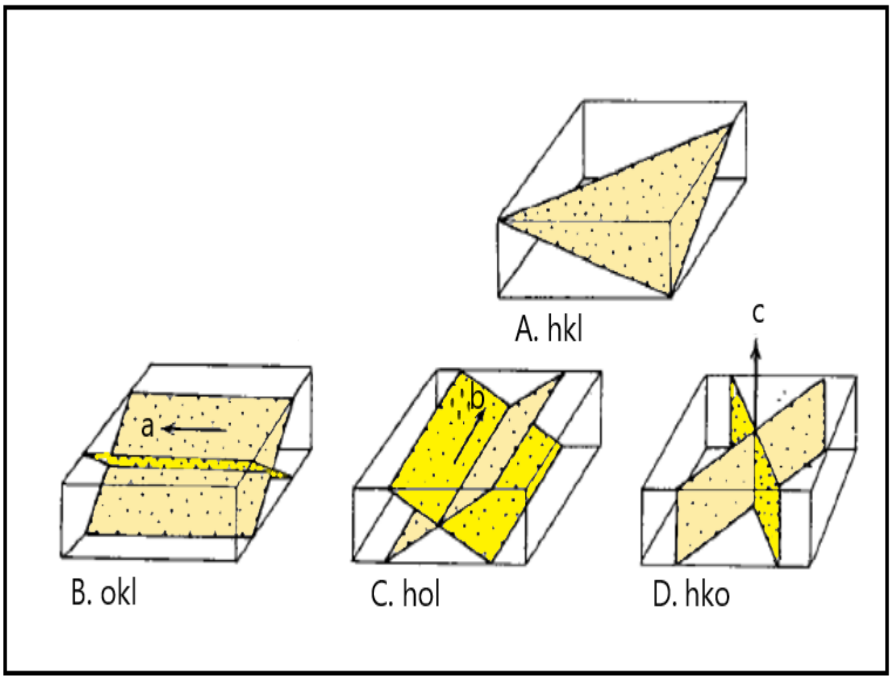

Figure 3-11: Types of joint systems.

This system was divided into two conjugate subsystems: The first is hol acute about (a) subsystem, where the two sets of this subsystem are bisected by the tectonic axes (a) and (c), and forms an acute and obtuse angle around each of them respectively. The two principal stress axes (σ1& σ3) are parallel to (a, c) axes respectively. The second is hol acute about (c) subsystem, which is subsystem is also consisting of two conjugate shears trending parallel to the (b) axis, and the tectonic axis (c) bisects the acute angle between the two sets of this subsystem, whereas the tectonic axis (a) bisects the obtuse angle (Al-kubaisi & Shakir, 2015). We note the presence of both sub-systems in abundance in the outcrop of the Euphrates Formation in the study area.

The hol>c type appears as a conjugate system in the lower part of the Sahliyah outcrop. The planes of this system intersect tectonic axes a &c and parallel to b. This system consists of two intersected sets (S1 and S2) making an acute angle (66º) bisected by tectonic axis c and obtuse angle bisected by tectonic axis a (Plate 3-15). The (S1) set is NW-SE direction which has strike and dip angle are 160º and 54º toward SW respectively, while (S2) set is NW-SE direction also which has strike and dip angle is 340º and 60º toward NE respectively. The direction of the main stress (σ1) calculated from the conjugate hol system is 340°and its plunge is 88° (Figure 3-12).

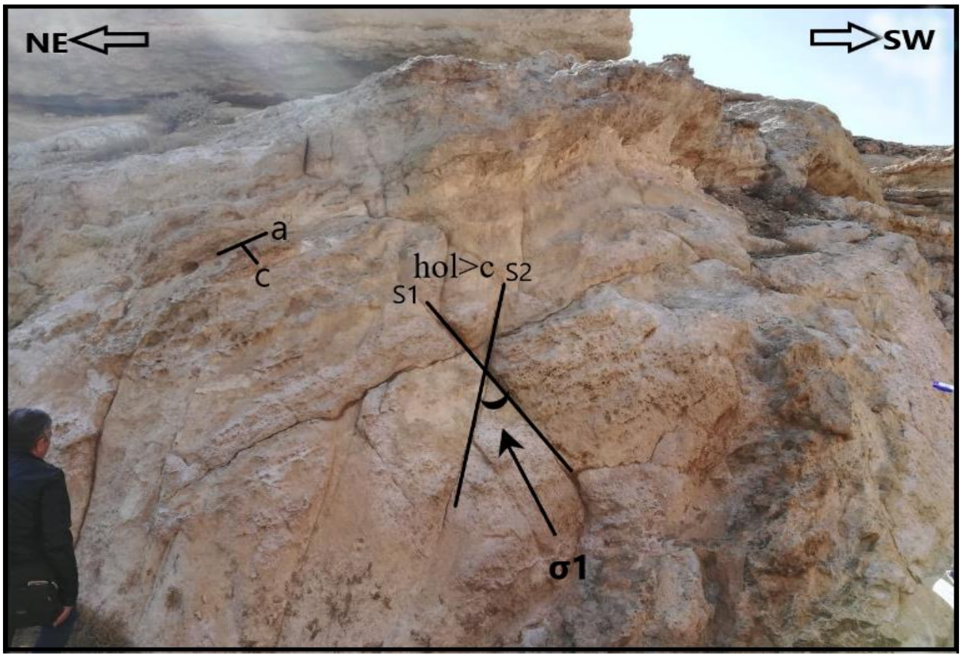

Plate 3-15: hol>c joint system in Euphrates Formation in the Sahliyah outcrop.

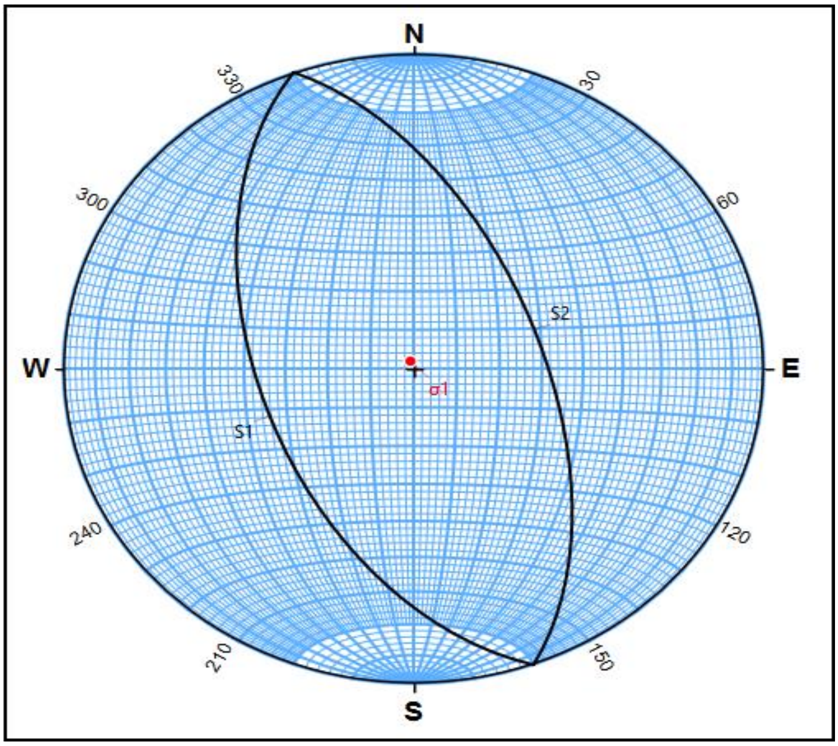

Figure 3-12: The stereo-net plots of the hol>c system data.

The presence of several secondary reverse faults in the lower part of the Sahliyah ridge, within the thick limestone layers of the Euphrates Formation. These faults are convex, spaced, and parallel to each other, which are flattened upwards to develop a one side of the positive flower structure (Plate 3-16), which has a strike of ranging 130°-155° and dip angle is variable toward NE. This is consistent with the opinion of Harding et al. (1983), that the fault architecture is not necessarily symmetric, but in some places, the secondary faults may diverge toward only one flank of the structure.

Flower structures form in seismic sections either as a result of strike-slip or dip-slip inversion. The flower structures develop from single to tightly clustered minor fault strands that dip sharply and diverge upward to develop fault arrays. They show either flattens downward extensional displacements or dominantly flattened upward high angle reverse displacements that generate negative or positive flower structures (McClay, 2000). These structures are a collection of faults in a strike-slip fault zone that meets at deep to form a near-vertical fault plane, but the structure diverges near the earth's surface, resulting in shallower dips. there is a component of pushing on the faults in a positive flower structure, while there is a component of normal faulting in a negative flower structure (Pluijm & Marshak, 2004).

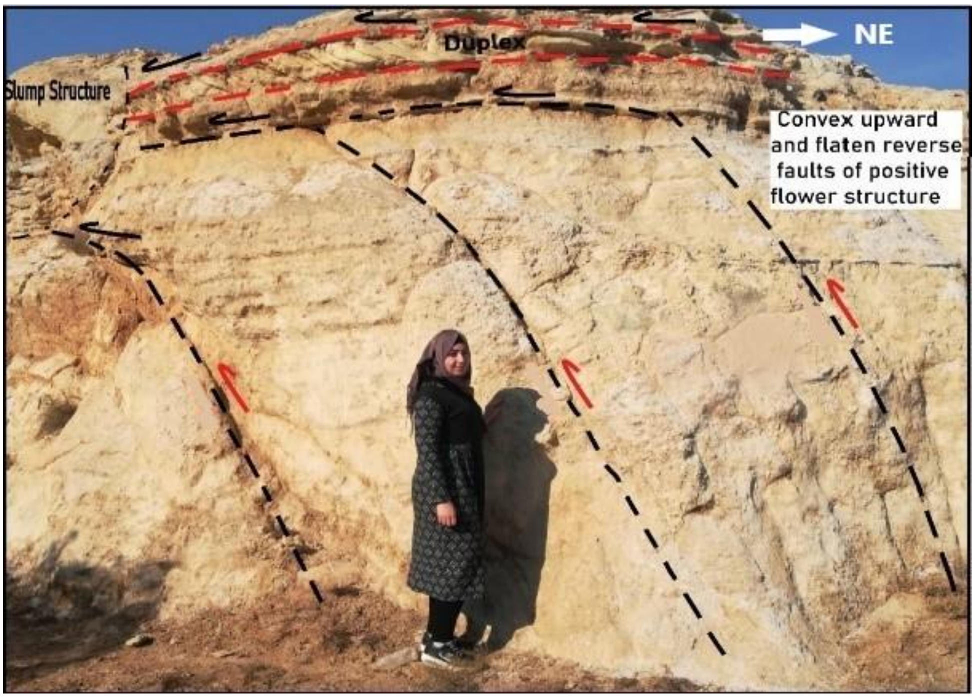

Plate 3-16: Part of the positive flower in the lower part of the Euphrates Formation in the Sahliyah outcrop.

Flower structures do not form along a strike-slip fault randomly, but rather are localized near the fault terminations (Sylvester, 1988). Positive flower structures are linear antiforms that are severed longitudinally along their apex by the upward-diverging strands of a wrench fault (Figure 3-13a). They are marked by the sudden upturn of bedding in a zone parallel to and on either side of a through-going wrench fault. The wrench fault is characterized by a sub-vertical main strand and upward-diverging and flattening, inward dipping secondary faults with dominantly reverse separation. These secondary faults have profiles varying from steep up-thrust to shallow-dipping thrust and merge at depth with the main strike-slip displacement zone (Harding et al., 1983). Positive flower structures mainly develop within wrench zones where blocks move parallel to each other (i.e., pure strike-slip faults) and move with a portion of convergence (i.e., transpressive or convergent wrench faults), particularly easily occur in the regions of restraining bends and step overs along these wrench faults, in which the slip-on subsidiary faults have a thrust-sense component (Harding, 1985; Pluijm & Marshack, 2004) (Figure 3-13b).

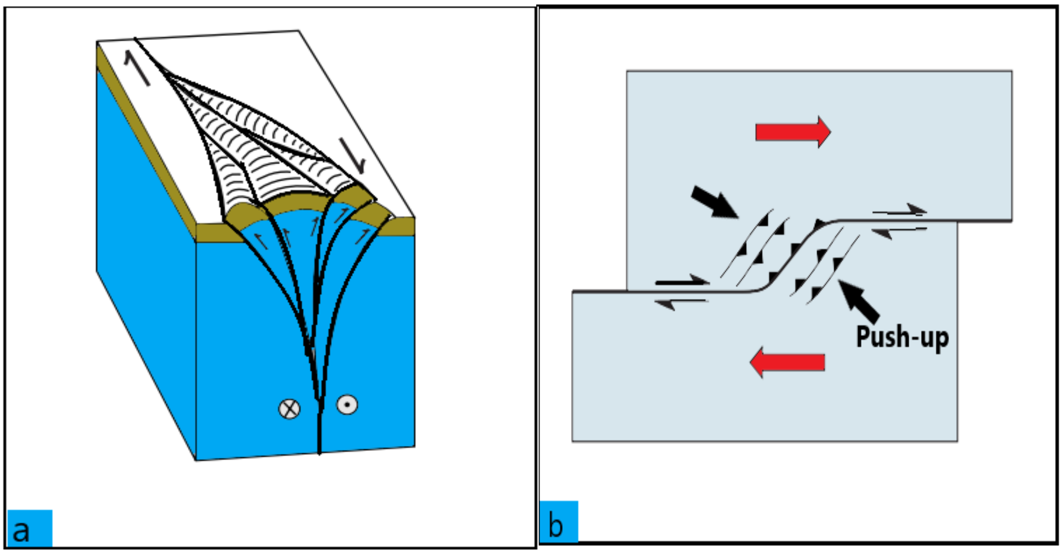

Figure 3-13: (a) Block diagram of a positive flower structure. (b) Map-view models of Restraining bend at which thrust faults have formed, after (Pluijm & Marshak, 2004).

A typical duplex structure was developed directly above the positive flower structure in the upper part of the Euphrates Formation (Plate 3-17). The duplex structure has a conjugate system of hol>a type. The planes of this system intersect tectonic axes a &c and parallel to b. This system consists of two intersected sets (S1 and S2) making an acute angle (64º) bisected by tectonic axis a and obtuse angle bisected by tectonic axis c. The (S1) set has NW-SE direction which has strike and dip's angle of 300º and 30º toward NE respectively, while (S2) set has NW-SE direction too which has strike and dip angle of 120º and 30º toward SW respectively. The direction of the main stress (σ1) calculated from the conjugate hol system is 30°and its plunge zero (Figure 3-14). Duplex is a type of thrust system formed two parallel thrusts (detachment) faults (the roof and floor thrusts) within a sedimentary sequence, such as the top and base of a relatively strong layer bounded by two relatively weak layers. Which are bound by a series of subsidiary thrust faults that curve asymptotically into the roof and floor thrusts. A duplex can also be defined as an imbricate series of horses (Mitra & Boyer, 1986; Pluijm & Marshack, 2004).

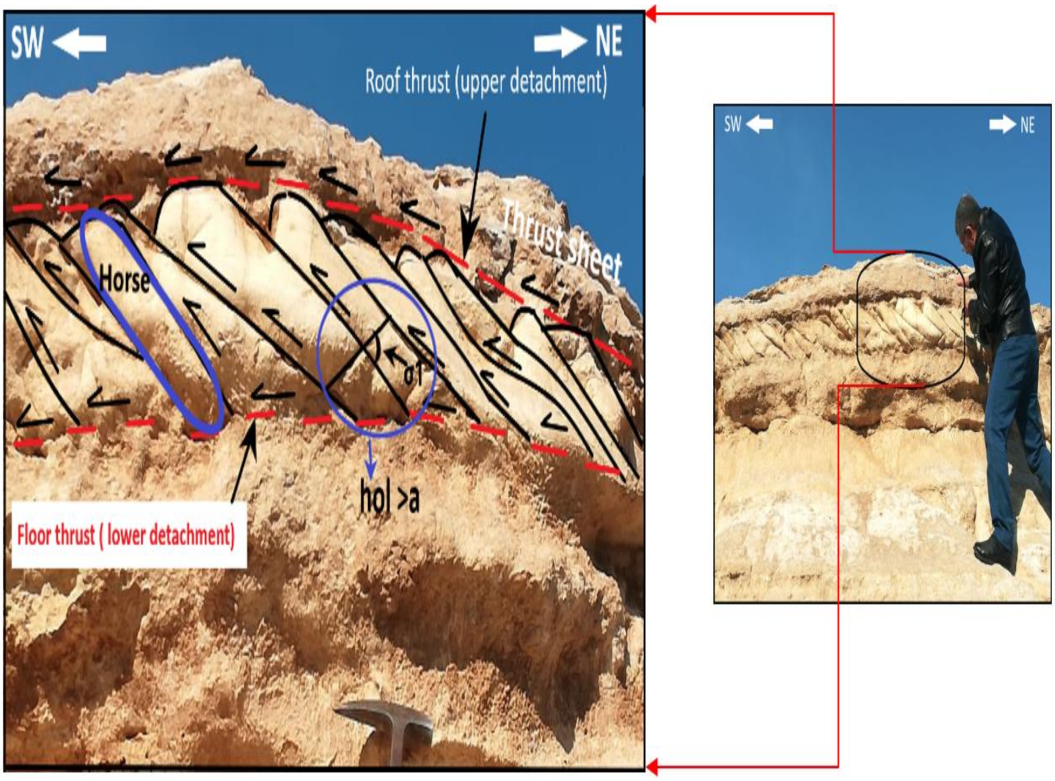

Plate 3-17: The duplex structure in the upper part of the Euphrates Formation in the Sahliyah outcrop.

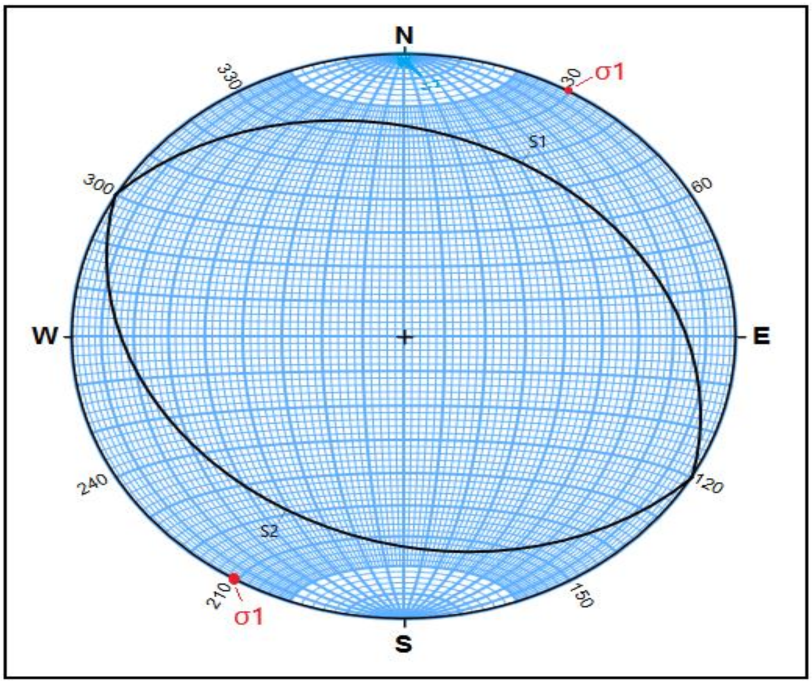

Figure 3-14: The stereo-net plots of the hol>a system data.

Detachment or (décollement) is horizontal to a sub-horizontal fault. Floor thrust is forming the base of the duplex; it is a lower detachment of a duplex, while Roof thrust is forming the upper detachment of a duplex. The horse is a lens of rock in a duplex entirely encircled by faults. A thrust sheet is a hanging-wall block that has been moved as a result of sliding above a thrust surface (also called a thrust slice) (Pluijm & Marshak, 2004).

The presence of a fault-bend fold within the upper part of the Euphrates Formation in the Sahliyah outcrop. This fold is a type of fault-related fold style. Folding, which is directly linked to fault activity (Yan et al., 2016). At first, the thrust system occurs as the detachment fault, which develops within the (17 cm) marly limestone layer under fault-related fold (Plate 3-18). The term "detachment" refers to the separation or detachment of rock above and below the fault during movement. Detachments are more likely to form in weak rock types like shale or evaporite (Pluijm & Marshack, 2004).

Plate 3-18: The detachment fault within marly limestone in the upper part of the Euphrates Formation in the Sahliyah outcrop.

Note the folding that occurs after the formation of the thrust is called a fault-bend fold (Plate 3-19). Fault-bend folding is a structure formed when the fault surface is non-planar and the fault blocks are bending as they ride over these fault surfaces (Figure 3-15).

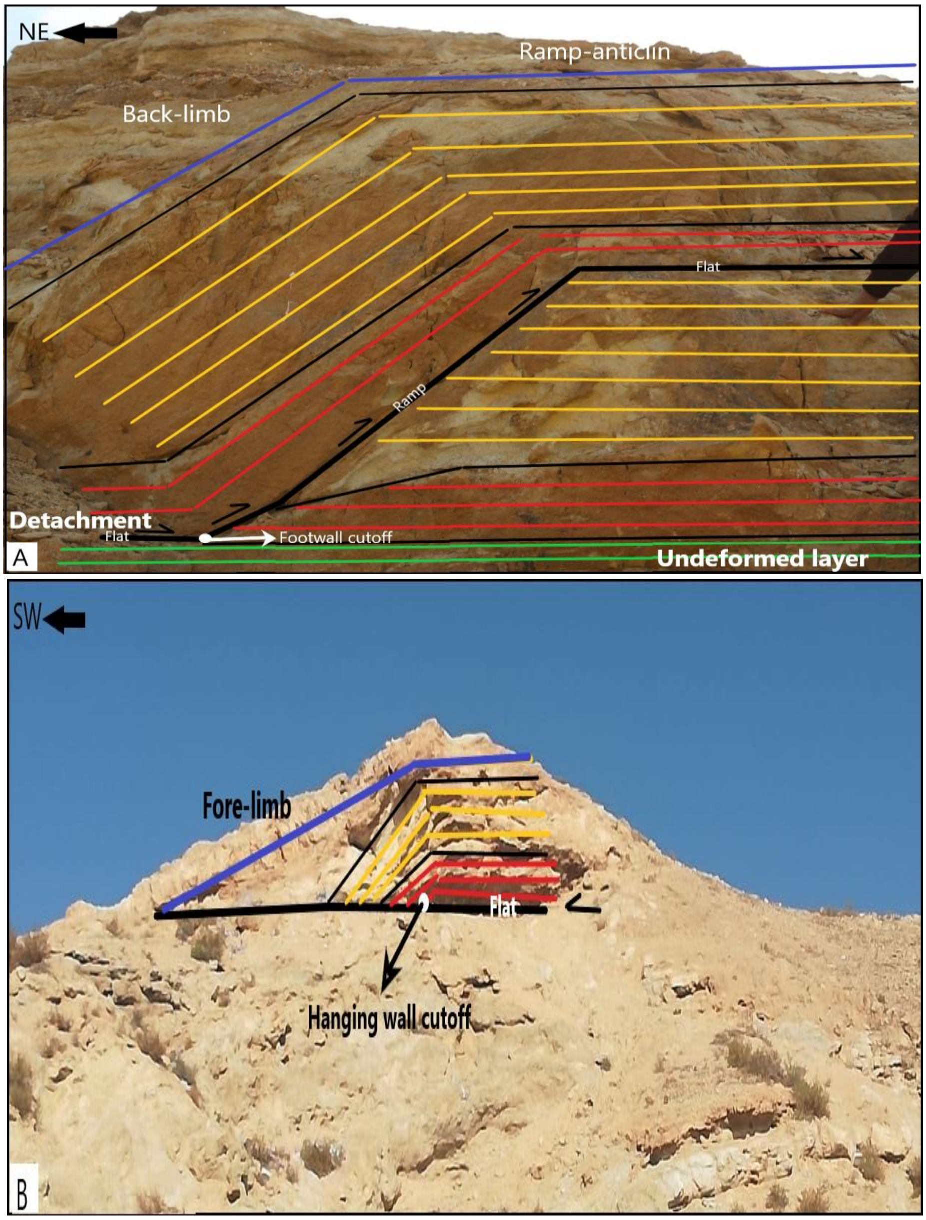

Plate 3-19: Fault-bend folding structure in the upper part of the Euphrates Formation in the Sahliyah outcrop. A. back-limb. B. fore-limb.

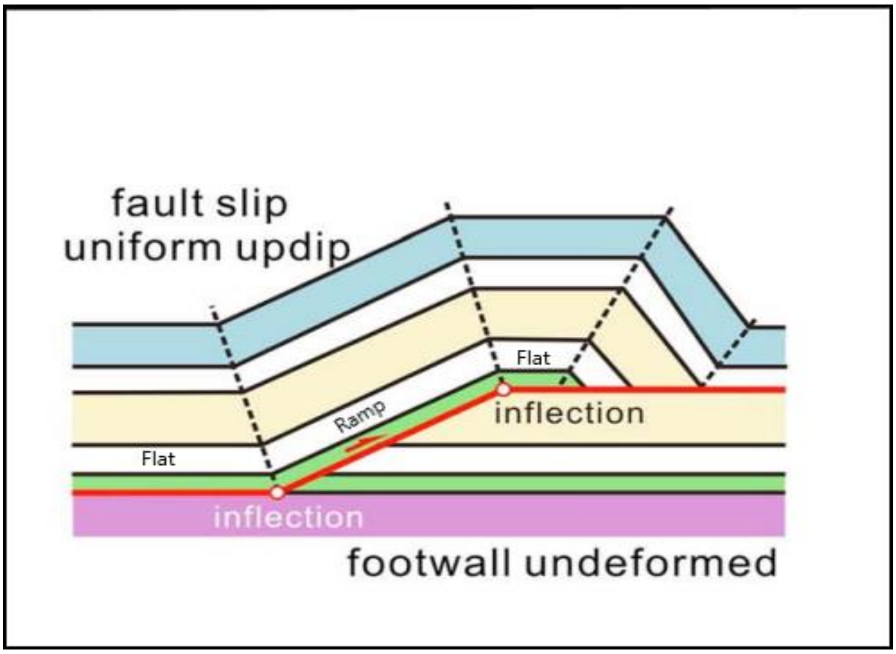

Figure 3-15: Cross-sectional model of a fault-bend fold (Yan et al., 2016).

The back-limb of this fold (Plate 3-19 A) has an NW-SE direction. Its mean strike and dip angles are 155º and 50º toward NE respectively, and the fore-limb (Plate 3-19 B) has an NW-SE direction also. Its mean strike and dip angles are 150º and 65º toward SW respectively. The back-limb of the fold follows the footwall ramp, the fore-limb is shorter and steeper than the back-limb, strata of the footwall remain flat-lying (Pluijm & Marshack, 2004).

We also observe that the uppermost part of the Euphrates Formation appears in the form of brecciated and undulated limestone units along the study area (Plate 3-20). We will focus strongly on the intensity of the undulation in the upper part of the Euphrates Formation, where we notice through the picture that the intensity of the undulation decreases towards the northwest. As the undulations in the Al-Fahimi valley are very simple compared to the Sahliyah area and the surrounding areas.

Sissakian et al. (2014) studied the genesis and deformation style of the soft-sediment within brecciated the undulated limestone units in detail, which forms the uppermost part of the Euphrates Formation. The area extended on both banks of the Euphrates River, beginning from the Iraqi-Syrian borders and running east and southeast-wards to wadi-Hauran. As they called these deformation styles the term (Seismites), because it reveals the seismic influence on the formation of breccia during sedimentation, implying that the breccia is of syn-sedimentary origin, most likely owing to tectonic disturbances that induced seismic shocks in the depositional area. The undulations vary in breadth and shape, ranging from less than 1 m to 10 m in width, having amplitudes ranging from a few centimeters to 5 m, and are sometimes parallel to the underlying brecciated unit's deformation. The deformational features in the brecciated unit are syn-sedimentary structures, formed before lithification of the sediments. That is, syn-sedimentary deformation structures, or soft sediment deformation structures, are deformation structures created during the interval from deposition to the start of diagenesis. Although many researchers have focused on the non-tectonic deformation of soft sediments caused by earthquakes. However, some scientists have stated that some soft sediment deformation has tectonic meaning. The boudinage structure development within the Brecciated Unit implies syn-sedimentary extension structure, whereas compression wrinkles imply syn-sedimentary compression structure (Hongbo et al., 2006). Both structures are found in the top part of the Euphrates Formation's Brecciated Unit. The presence of compressional forces imposed by the Savian Orogeny throughout the Early Miocene and onwards is confirmed by the latter (Sissakian et al., 2014).

Plate 3-20: Brecciated and the Undulated Limestone Units, forming the uppermost part of the Euphrates Formation: (A) Sahliyah area. (B, C, and D) Al-Dulab area. (E and F) Al-Baghdadi area. (G) Al-Fahimi valley.

The presence of a fault-propagation fold in the lower part of the first cycle of the Fatha Formation in the Heet outcrop (Plat 3-21). The fault in this fold has an NE-SW direction. Its mean strike is 020º toward NW. The fault-propagation folding is a style of fault-related folding, that occurs when a propagating thrust fault loses slip and ends up-section by transmitting its shortening to a fold forming at its tip (Mitra, 1990; McClay, 2011). Some thrust faults, it is suggested here, do not propagate quickly as pure fractures, but rather gradually as slip accumulates. The slip drops to zero at the fault tip at each instant during propagation and is absorbed in folding. The fault-propagation folding kinematic process is proposed as an explanation for the typical connection of asymmetric folds with one steep or even overturned fore-limb near to thrust faults and a less steep back-limb. The fore-limb is narrow, whereas the back-limb is wide (Figure 3-16) (Suppe & Medwedeff, 1990).

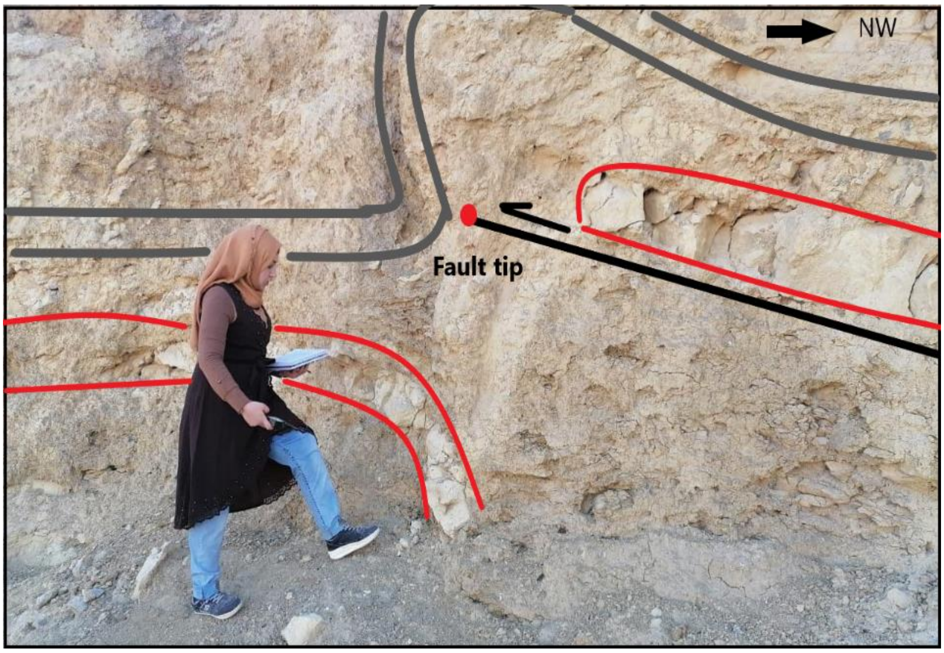

Plate 3-21: Fault-propagation folding structure in the lower part of the first cycle of the Fatha Formation in the Heet outcrop.

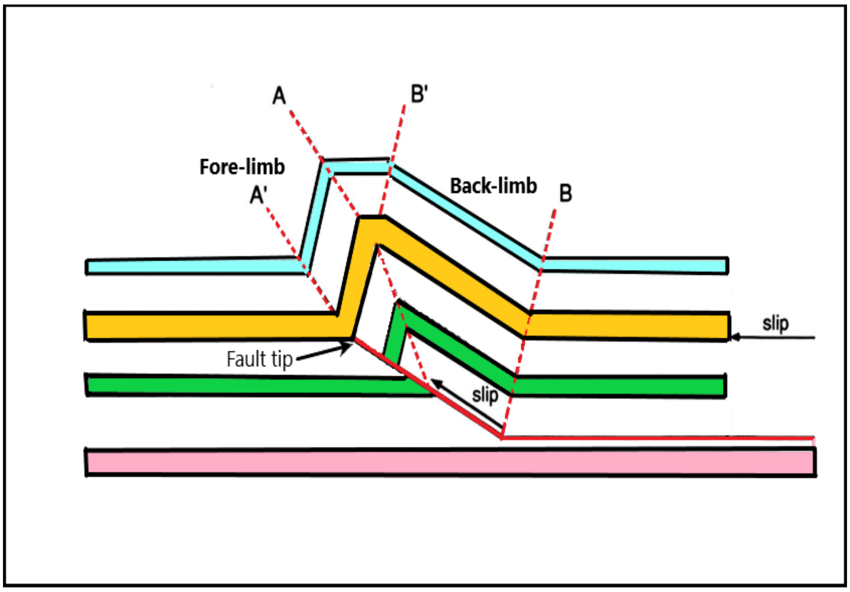

Figure 3-16**:** Cross-sectional model of a fault-propagation fold. The dashed lines are the traces of axial surfaces, modified after (Suppe & Medwedeff, 1990).

3-4 Tectonic interpretation

The detailed field study of the surface structures of the Euphrates and Fatha formations indicates two distinct tectonic phases in the tectonic evolution of the study area during the Miocene.

3-4-1 Late Early Miocene extension

The tectonic development of the study area was initially marked by extension during the Late Early Miocene. The existence of several structures in the study area, which indicate the extension phase, the main listric normal fault developed which cut off the entire Euphrates Formation (Early Miocene) and runs downward in the Suhailiya outcrop (Plate 3-12). Another indication is the presence of a sedimentary dyke between the two fault blocks, as its materials are from the carbonate rocks of the uppermost part of the Euphrates Formation before solidification (Plate 3-12). There are also many slumps or collapse structures in the uppermost part of the Euphrates Formation (Plate 3-13).

There are two possibilities for extension, the first possibility, which is the most likely possibility, the extension occurs as a result of the tilt of the Mesopotamia sequence is took place as a result of the collision between Arabian and Iranian plates. The tilt created an extension zone along the axis of flexure, west of the Abu-Jir Fault System (Alhadithi, 2013). During the Mid-Late Miocene, the Mesopotamian basin experiences rapid subsidence (Jassim & Goff, 2006). Therefore, when comparing the height of the upper boundary of the Euphrates Formation relative to sea level on both sides of Abu-Jir Fault Zone, note along Abu-Jir Fault Zone (73.15 m, 91.5 m, and 112.7 m) represented by the Sahliyah, Al-Baghdadi, and Haditha sections respectively. On the eastern side (-256m) the Mileh Tharthar well. It can be considered as clear indications of very quick subsidence of the eastern side of Abu-Jir Fault Zone during the Late Early Miocene and the Middle Miocene due to the elastic isostasy of the Mesopotamian foredeep. Therefore, it is assumed that the fault is a basin bounding fault of the Mesopotamian foredeep. It may act as a normal fault or a growth fault.

the second possibility for extension, the strike-slip movement along the Abu-Jir Fault Zone. This is consistent with of McClay (2000), the basins can experience both extension and inversion in the same strike-slip faults system.

3-4-2 Middle Miocene compression

The tectonic evolution of the study area was characterized by compression during the Middle Miocene due to the strike-slip movement that occurred along the Abu-Jir Fault Zone. The main listric normal fault experienced a positive inversion, which caused the uplift of rocks on the fault's hanging-wall (Plate 3-14). In the lower part of the Euphrates Formation, several systematic joints hol>c conjugate system type has developed in the hanging wall of the main listric inverted fault (Plate 3-15) in the Sahliyah outcrop. The direction of the main stress ($\sigma 1$) is from bottom to top as it bisects the acute angle between the two sets of joints.

The secondary reverse faults in the lower part of the Sahliyah outcrop (Plate 3-16). These faults are diverging toward only one side of the structure in the study area. Since these secondary faults are located within the western block of the Abu-Jir Fault Zone and branch in a southwestern direction, it means that the western block is the one moving to the north relative to the eastern block, thereby developing a right lateral strike- slip movement along the Abu-Jir Fault Zone.

We suggested that the Abu-Jir Fault is not a single fault, but is a zone as it consists of linkage several segments. Between the two segments, a bend known as the Relay ramp structure is restrained. When this bend is subjected to push-up forces, several thrust faults will be produced, thus developing a structure known as the positive flower structure (Figure 3-13). Flower structures do not develop at random along a strike-slip fault, but typically near the fault ends.

It can be seen that the intensity of the deformation of the brecciated the undulated limestone units in the upper part of the Euphrates Formation is very high in the Sahliyah area and the surrounding areas and decreases towards the northwest (Plate 3-20). This indicates that not all segments of the Abu- Jir fault zone were experiencing the same intensity of activity at that time. A fault-propagation fold developed in the lower part of the first cycle of the Fatha Formation in the Heet outcrop (Plat 3-21). This means that the Abu-Jir Fault Zone is still active even after depositing the first cycle of the Fatha Formation.

The hydrocarbon seepages come out through cracks and fractures in the gypsum layer in the upper part of the first cycle of the Fatha Formation in the Heet outcrop (Plate 3-7). Hydrocarbon seepages are abundant within the Abu-Jir Fault Zone in western Iraq, reach into the earth's surface, especially in the Fatha Formation according to (Al-Aslami, 2015 and Al-Khafaji et al., 2020), who was previously mentioned in the previous studies in chapter one. This indicates the activity of the Abu-Jir Fault Zone during the Middle Miocene and It also constitutes a path for the vertical migration of oil with the water of the springs but when it reaches the gypsum bed within the spring, it migrates horizontally through the fractured gypsum bed then seeps in other places.

3-5 The direction of the main compressive stress

The current study revealed the inversion of the Abu-Jir Fault Zone during the Late Early Miocene and Middle Miocene. Since we can suggest that the compressive stress that causes the right lateral strike-slip movement of the Abu-Jir Fault Zone comes from the south, which leads to the western block of the Abu-Jir Fault Zone moves northward relative to the eastern block. We have validated this suggestion by studying the surface structures in the Euphrates and Fatha formations in the study area. There is a lot of evidence to support this suggestion, including: 1) All the reflective seismic sections, the southwestern part of Abu-Jir Fault Zone, show that the negative flower structure appears as a result of the Abu-Jir Fault Zone subjected to a strike-slip movement, while in the northeastern part, grabens appear as a result of its behavior as a normal fault (Alhadithi, 2017). This is indicating that the western block of the Abu- Jir fault zone was displaced in a shear movement relative to the eastern block, and that the forces causing the strike-slip movement of the Abu-Jir Fault Zone are come from the south and not from the north as was previously believed; 2) The Anah graben wasn't completely inverted, the inverted western part of the graben suddenly terminated against the Abu-Jir transcurrent fault zone, according to seismic profiles (Fouad, 1997); 3) Anah structure is divided into two parts: the eastern, subsurface graben, and the western, inverted graben (Figure 3-17). The eastern extensional part is isolated from the western inverted part by intra-graben lateral ramp generated by the meeting of the Abu-Jir Fault Zone with the Anah structure. The western block of the Abu-Jir Fault Zone is moving northward, relative to the eastern block (Marouf, 1999).

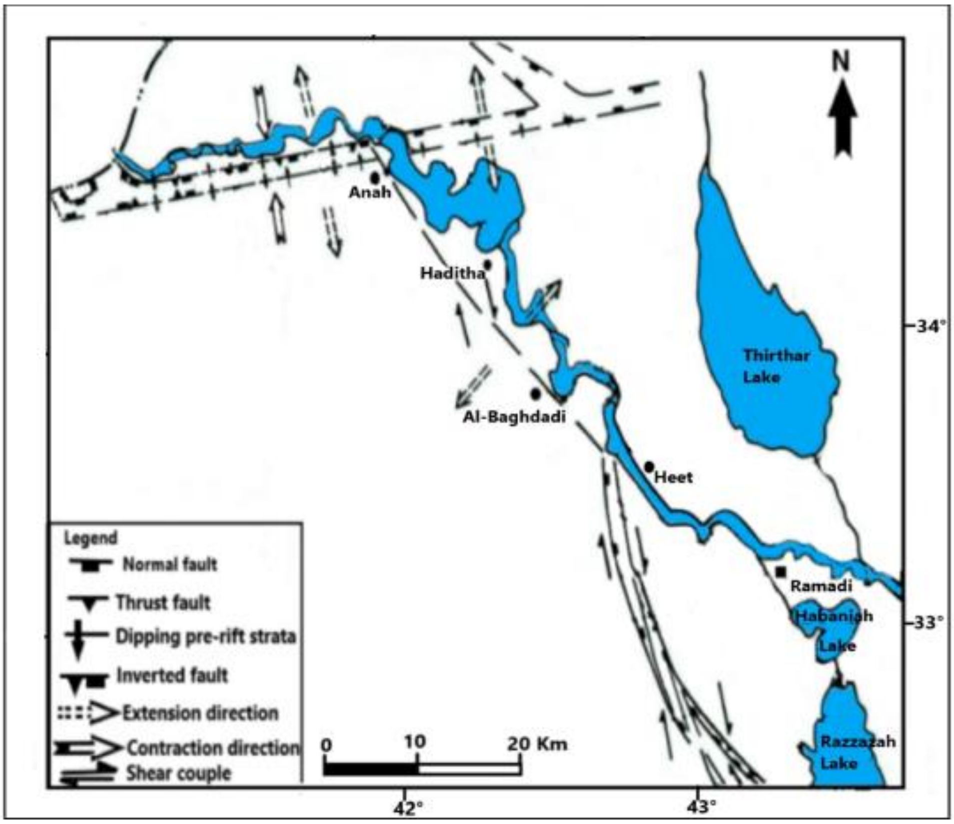

Figure 3-17: Subsurface tectonic map placed on the surface geologic map of Anah graben and Abu-Jir Fault Zone and their related, after (Marouf, 1999).

The activities throughout both the Anah and the Abu Jir structures were generally connected and probably contemporaneous (Marouf, 1999). This means that the inversion of the western part of Anah graben, occurred also during the Late Early Miocene and Middle Miocene as per our current study. Accordingly, our study contradicts Fouad's (1997) study; 4) The Al-Jazira area includes many subsurface extensional structures, Such as the eastern part of Anah, Tayarat South, Tayarat North, Khleissia, and Tel Hajar Structures (Figure 3-18). By analyzing the reflection seismic sections, it was observed that there were no signs of inversion in all the grabens except Tel Hajar structure had undergone positive structural inversion, when the compressional phase reached its apex during the Plio-Pleistocene although the area is bounded by two inverted structures; Sinjar and western part of Anah from north and south, respectively (Fouad & Nasir, 2009); 5) The Sinjar-Abd el Aziz structure experience major uplift during the mid/late

Pliocene-Recent, as result structural inversion along with several of the faults (Brew et al., 1999). Two hypotheses for the nature and timing of folding of the Sinjar Anticline; Firstly, that folding occurred during the Tertiary in progression with deposition of the different formations. Secondly, that folding occurred throughout the Pliocene as a paroxysmal episode of Alpine folding. The second hypothesis is supported by circumstantial evidence from the field (Numan & Al-Azzawi, 2002).

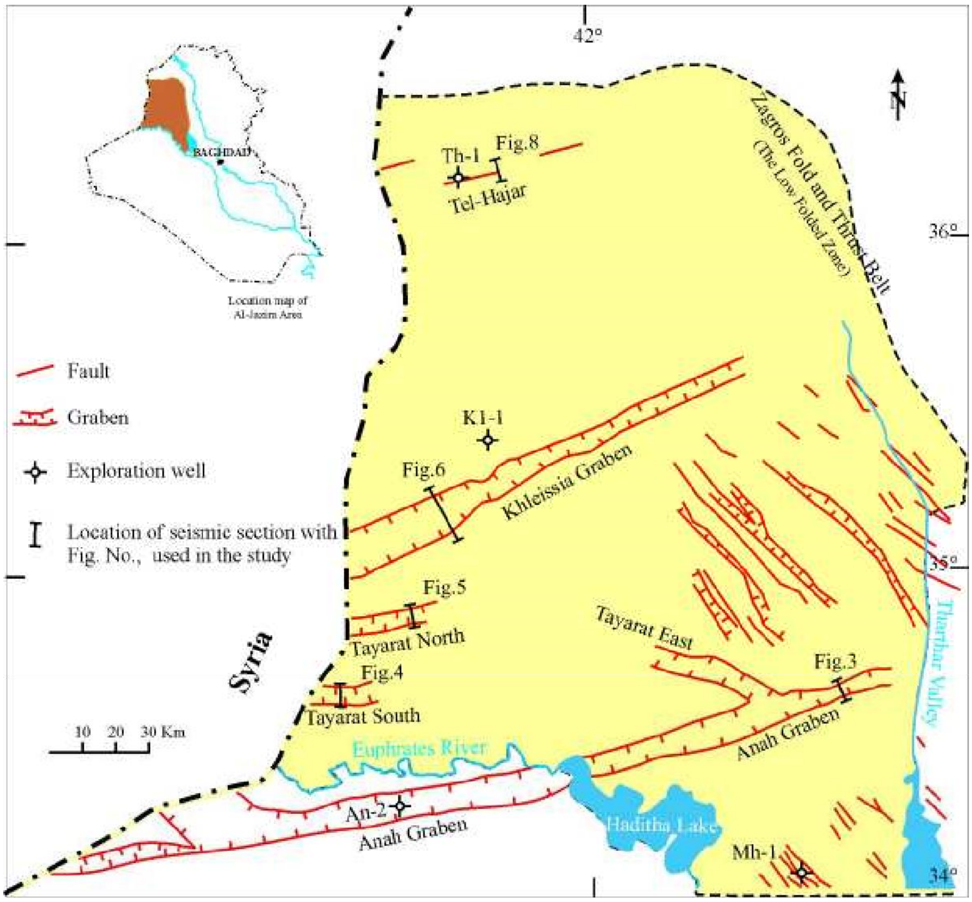

Figure 3-18: Structural map to show the subsurface rifting structures of Al-Jazira area (Fouad & Nasir, 2009).

To know the main sources of the forces that led the movement of the Arabian Plate towards the north, we must use the following studies. The hot material is offset eastward beneath Arabia, not beneath the northern Red Sea noting mantle flow from the Afar hotspot. This channel's position beneath volcanic rocks formed after rifting began 30 million years ago (Figure 3-19), suggests that flow moves with Arabia Plate (Chang et al., 2011).

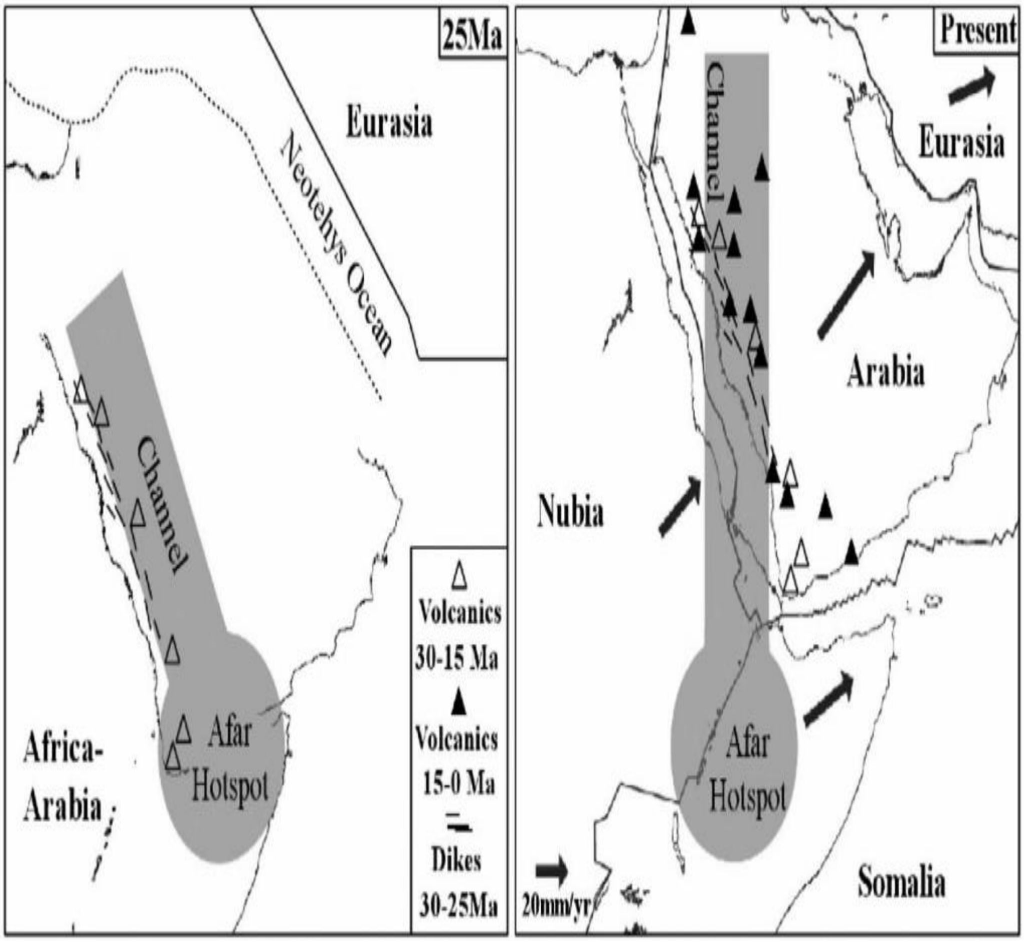

Figure 3-19: Sketch model for the development of the low velocity channel, given flow from a fixed hotspot has been diverted by Arabia's northeastward absolute movement (Chang et al., 2011).

The combined effects of an upwelling mantle of Afar and the subduction of the Hellenic plate pulled the Arabian Plate toward the collision (Figure 3-20). The magmatism migrated northward from Ethiopia–Yemen to the Arabia–Anatolia collisional zone. The Afar plume's isotopic signature may be traced all the way to Turkey's Karacadağ neovolcanic area, which would be in the far north of the Arabian Peninsula (Faccenna et al., 2013). These findings support the hypothesis of northward driven mantle flow (Yarmolyuk et al., 2004), with the Afar plume head channeled beneath Arabia (Hansen et al., 2006), and further north beneath eastern Anatolia after slab breakoff (Keskin, 2007). Arabia was first separated from Africa by mantle upwellings in the Afar–Arabia, which later moved Arabia northward to Eurasia. The development of a slab window, around ~8–10 Ma and progressively expanding westward (Cosentino et al., 2012). With respect to Eurasia, the Arabia–Anatolia–Aegean (AAA) velocity field has an anti-clockwise toroidal pattern, with rising velocities near the Aegean trench (Faccenna et al., 2013).

Through the use of the above-mentioned studies, we can prove that the main force that led the movement of the Arabian Plate is coming from the south towards the north, which is the result of the upwelling mantle from the Afar hotspot and its offset beneath the western part of Arabian Plate, with the help of the plate pull force. In particular, the upwelling mantle influence from the Afar plume reached the current study area during the Miocene (20 Ma), which is the one that activates the western block of the Abu-Jir Fault Zone and push it towards the north relative to the eastern block (Figure 3-20 b & f). Although the slab was broken off during ~10 Ma, the Afar plume continues to push the Arabian Plate toward the collision zone, then works to rotate the plate counterclockwise (Figure 3-20 c & g). This means that the main factor that drives the plate to move is the upwelling mantle from the Afar plume.

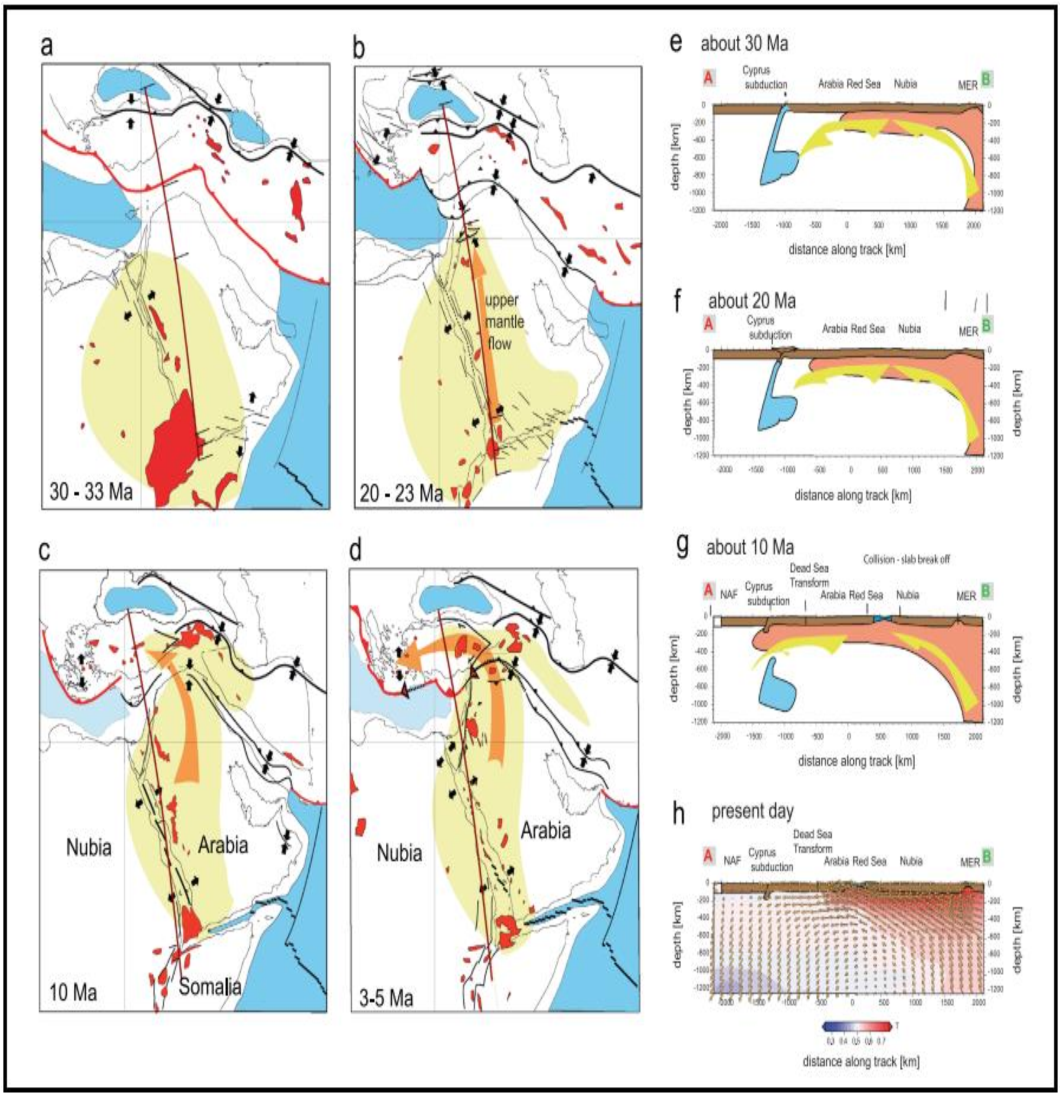

Figure 3-20: Tectonic development of the AAA system at four phases: 30–33 (a), 20–23 (b), 10–12 (c), and 3–5 Ma (d) as well as equivalent, ideal cross sections (e)-(h). Active volcanic fields (undistinguished) are indicated by red lines; deep basins are indicated by blue lines; active subduction zones are indicated by red lines; collisional thrust systems are indicated by black lines; regions influenced by the Afar plume is indicated by yellowish background areas; and arrows indicate mantle flow direction (Faccenna et al., 2013).

CHAPTER FOUR

CONCLUSIONS

4-1 Conclusions

1. Anah Formation (Late Oligocene) begins to appear on the surface towards the northwest, this indicates that the uplifting occurs in this direction, while subsidence took place to the southeast due to the local activity of Abu-Jir Fault Zone.

2. Towards the southeast a relative increase in thickness of the marly limestone layers of the Euphrates Formation, that means the depositional basin is deeper than the northwest.

3. A very rapid subsidence of the eastern side of the Abu-Jir Fault Zone occurred during Late Early Miocene and Middle Miocene due to the elastic isostasy of the Mesopotamian foredeep. Therefore, it is assumed that the fault is a basin bounding fault. It may act as a normal fault or a growth fault.

4. The study area was subjected to two types of stress during Miocene. The first one is extension in response to the tilt of the Mesopotamia sequence is took place as a result of the collision between Arabian and Iranian plates during or after the end of the Early Miocene. The second type of stress is the inversion due to the strike-slip movement that occurred along the Abu-Jir Fault Zone during the Middle Miocene.

5. The presence of some structures such as duplex and positive flower structures indicate that the Abu Jir fault is not a single fault, but is a zone as it consists of linkage several segments. Relay ramp structures are restrained between two segments.

6. Not all segments of the Abu-Jir Fault Zone were experiencing the same intensity of activity during the Late Early Miocene and Middle Miocene, and the force that inversions the study area comes from the south.

7. The Afar plume is main factor that drives the Arabian Plate to move, as the upwelling mantle influence from the Afar plume reached the current study area during the Miocene, which is the one that activates the western block of the Abu-Jir Fault Zone and pushes it towards the north relative to the eastern block.

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المستخلص

اشتملت الدراسة الحالية على أربعة مكاشف صخرية هي: هيت والسهلية والبغدادي وحديثة، ومقارنتها ببئر ملح الثرثار -1. لقد استخدمنا دراسة ميدانية مفصلة لتقييم الآثار التكتونية لمنطقة صدع أبو جير على منطقة الدراسة. واستنتجنا من خلال الدراسات الطباقية للمكاشف الصخرية والمضاهاة بينها، أنه على الرغم من أن المسافات بين المكاشف الصخرية متقاربة، إلا أن هناك تباينًا كبيرا في السحنات الصخرية أفقيًا وعموديًا. حيث ان طبقات الجير المارلي في تكوين الفرات تكون أكثر سمكًا باتجاه الجنوب الشرقي. يعد ذلك مؤشرا جيد لبيئة أعمق من الشمال الغربي ضمن منطقة الدراسة.

لقد تبين وجود هبوطًا سريعًا جدًا للجانب الشرقي من منطقة صدع أبو جير خلال أواخر العصر الميوسيني المبكر والميوسين الأوسط بسبب التوازن المرن لحوض بلاد بين النهرين العميق. لذلك، يُعتقد أن هذا الصدع هو أحد انواع الصدوع المحيطة بالحوض. قد يكون صدع طبيعي أو صدع النمو. لقد كشفت الدراسة الهيكلية أن منطقة الدراسة تعرضت لنوعين من الإجهاد خلال العصر الميوسيني. الأول هو التمديد استجابةً لإمالة حوض ما بين النهرين نتيجة الاصطدام بين الصفائح العربية والأوراسية أثناء أو بعد نهاية العصر الميوسيني المبكر. أدى الميل إلى إنشاء منطقة امتداد على طول محور الانثناء غرب نطاق صدع أبو جير. النوع الثاني من الاجهاد هو ضغط نتيجة الحركة الانزلاق المضربية التي حدثت على طول منطقة صدع أبو جير خلال العصر الميوسيني الأوسط. حيث ان الكتلة الغربية من منطقة صدع أبو جير تتحرك شمالاً نسبتا الى الكتلة الشرقية نتيجة لحركة الانزلاق المضربية.

أن القوى الرئيسية المؤدية إلى حركة الانزلاق المضربية في منطقة الدراسة قد تأتي من الجنوب خلال أواخر العصر الميوسيني المبكر والاوسط، ومصدر هذه القوى هو عمود عفار (Afar plume)، حيث وصل تأثير الوشاح الصاعد من عمود عفار إلى منطقة الدراسة الحالية خلال العصر الميوسيني (20 مليون سنة)، وهو بالتأكيد الذي يعمل على تنشيط الكتلة الغربية لمنطقة صدع أبو جير ودفعها باتجاه الشمال بالنسبة للكتلة الشرقية.

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قسم الجيولوجيا التطبيقية

التأثيرات التكتونية لنطاق صدع أبو جير على تكويني الفرات والفتحة بين هيت وحديثة غربي العراق.

رسالة مقدمة الى مجلس كلية العلوم - جامعة الأنبار
وهي جزء من متطلبات نيل شهادة الماجستير في
الجيولوجيا

قدمت من قبل

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إشراف

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