Surface and Subsurface Structural Analysis of Al-Burdia Area, the Eastern Part of Marmarica Uplift, NE Libya.

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A dissertation submitted to partial fulfillment of the requirements for the master degree in Science of Geology.

(Structural Geology)

University of Benghazi
Faculty of Science

Benghazi - Libya

2018

UNIVERSITY OF BENGHAZI
FACULTY OF SCIENCE
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BENGHAZI - LIBYA

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Acknowledgements

First and foremost, I would like to thank Allah for all that I have been given.
I wish to devote this page to express my deep appreciation to the individuals who contributed to the achievement of this study.

Firstly, I am deeply indebted to my supervisors Dr. Ahmed M. Muftah, Associate Professor of the Micropaleontology and Biostratigraphy ,Department of the Earth Sciences, Benghazi University, I extend my deep thanks to Dr. Maher A. El Amawy, Professor of the Structural Geology and Geotectonics, Department of Geology, Banha University, Arab Republic of Egypt. For their invaluable helps in determining the point of research, advices during the fieldwork and constructive guidance during the preparation of the general Stratigraphy and the Structural analysis and revision of this work.

I am grateful to AGOCO management of Technical Data Library (TDL), for their generous help for providing me with unlimited access to the subsurface data, and their continuous support throughout this study especially Mr.Abd-Alhamed Shahlol and Mr. Anwar Al wazry. Furthermore, special thanks to Mr. Waleed Alkhufify for photographing thin sections.

Special thanks are also extend to the staff members of the Geological Laboratory of Sirt Oil and Gas Company for the preparation of thin sections.

Special thanks to Dr. Ali Abdallah from Ain Shams University for providing us with the win-tensor software.

Thanks also extends to all staff members in the Department of the Earth Sciences especially Dr.Ali El-Arnauti, Dr. Mohamed El Faitoury and Mr. Fathi Salloum for their valuable advices, help, encouragement during all phases of this work including the logistic help for the field visits as well as their guidance during all of my academic years in the department.

Also I would like to express my everlasting gratitude, to my family for their unconditional love, encouragement and support, as I will always be in debt for my parents, wife, son and family members .

Finally Special thanks to all my friends in department of earth sciences, thank you for the wonderful years that we shared.

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List of Abbreviations

2D: Two dimensional

3D: Three dimensional

β: Beta

σ: Sigma

AGOCO: Arabian Golf Oil Company

C.I: Contour Interval

M.S: Main Shearing

M.D: Measuring Depth

NDSF: Northern Dextral Shear Fault

NOC: National Oil Corporation

R: Riedel shears

$R^{/}$: conjugated Riedel shears

SDSF: Southern Dextral Shear Fault

TD: Total Depth

TWT: Two way travel time

Abstract

Marmarica uplift extends approximately E-W along further the northeastern coastline of Libya and delimits the northeastern margin of Cyrenaica Platform. It is considered as structure inversion via the deformation of dextral strike-slip tectonics .

Folds are recognized, based on their intensity and style, into three phases (F_1, F_2, and F_3). F_1 folds are the oldest and recorded in Al Majahir with Al Bayda formations. They recognized as overturned types with axis oriented approximately ENE-WSW and extends some of them for about 2km. F_2 folds are developed at minor scale about 5.5km northwest of Al Burdia, in Al Faidiyah Formation. These folds are trending NE-SW with a general vergence SSE. Their styles are tight, overturned, open and asymmetric. F_3 phase of folding is a major and represents the final phase of folding. It is plunging SW and ended by the present morphology of gentle and elongated folding during Oligocene to Miocene ages.

Faults are most prominent in the study area and markedly concentrated in Al Burdia area and recognized by three main trends; the NW-SE dextral strike-slip faults (synthetic shears), N-S to NNE-SSW sinistral strike slip faults (antithetic shears), and E-W fault trends. Other array of the NNW-SSE normal faults are also encountered and run approximately perpendicular the folding axes. Kinematic indicators along these faults are documented in the field on the slickensides, flower structures, small scale of dextral and sinistral displacement, and pop up structure indicated that the sequence of faulting is initiated by pure wrenching and, in part, transpression in Late Cretaceous -Oligocene then continued with pure wrenching afterwards until the Miocene.

Joints are distinguished into two types; shear and tensional joints. In the present area, the joints are regular and, sometimes, irregular and along their planes there are little or no displacements. Subsurface structural interpretation confirms the integration of surface structural analysis the inversion via strike-slip tectonics in Late Cretaceous

Chapter One
Introduction

1.1. Introduction

The exposed Late Cretaceous, Oligocene and Miocene rocks in Al Burdia area and some parts within the eastern part of Marmarica uplift are chosen for the detailed field mapping and structural analysis. As a matter of fact, the previous geologic studies in Al Jabal Al Akhdar were mainly focused on the stratigraphy, sedimentology, and paleontology. However, the structural analysis and tectonic evolution are still lacking.

The present study will be re-assessed based on more detailed fieldwork, and analysis of the different kinematic shear indicators as well as the variations of sedimentation type and thickness of strata. The Upper Cretaceous-Miocene rock units of the study area are separated from each other by unconformity surfaces and are represented from the oldest to youngest as: Al Majahir, Al Bayda, Al Abraq, Al Faidiayah and Al Jaghbub formations. Elsewhere, these formations are unconformably overlain by Quaternary deposits. Tracing the regional structural elements via satellite image with local analysis will facilitate the extension of Al Burdia area to involve the eastern part of Marmarica uplift, in order to clarify the structural evolution and shed light on some ambiguities within the stratigraphic sequence during Late Cretaceous - Miocene times.

1.2. Location of Study Area.

The study area is represented by the eastern part of Marmarica uplift and limited by the longitudes 24^{o} 37`00`` - $25^{o}$ 03` 30``E and latitudes 31^{o}42` 00`` - $32^{o}$ 00`00`` N. The main way in the A1 Burdia area is the coastal road that serves to the main towns Musaid, Al Bardia, Qasr al Gadi, Bir Al Ashhab, Kambut and continues farther west to Tobruk (Fig. 1.1).

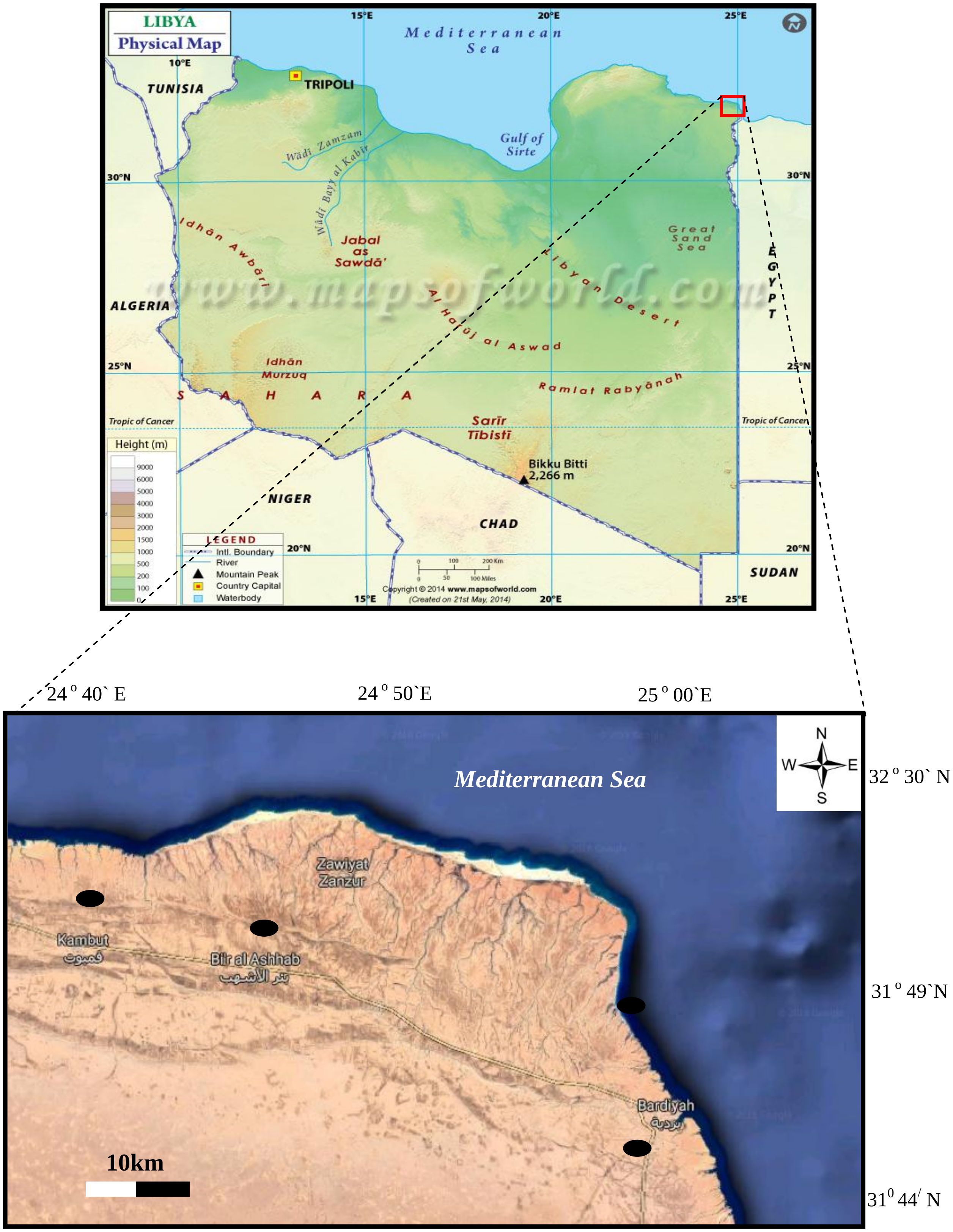


Fig. (1.1) Location map and land sat image of the study area.(source :Google earth)

1.3 Purpose and the objectives of this study

The main scientific problem in Al Burdia area is the confused and controversial about the name and the age of the dolomitic marly limestone Al Khowaymat Formation (Upper Eocene –Lower Oligocene), as introduced by Deftar and Issawi (1977). They described the outcrops as compact fine- grained dolomitic limestone containing abundant planktonic foraminifera, Globigerina sp thick, yellowish white, hard. They considered these outcrops as equivalent to the Lower Member of Al Khowaymat Formation in the type area and don't mention any of Cretaceous sequence in the area of Al Burdia, especially in Wadi Al Raheb.

The objective of the study involves the following:

1) A new detailed structural analysis and field mapping at small and regional scales of number of structure elements (e.g. folds, joints and faults, etc.) to make achieved careful study either in the outcrops from the field or by satellite images.

2) Construction a new structural map, composite columnar section and several geological maps of the study area.

3) Review of the stratigraphy in light of the most recent published studies and explaining of the structural evolution, which shed light on some ambiguities within the stratigraphic sequence during Late Cretaceous - Middle Miocene times.

4) Studying the subsurface stratigraphic and structural elements and getting on a persuasive analysis by the end of the study.

1.4 Data Collection

1.4.1 Fieldwork

The field check and observations are important to give the solution of number of problems. The field work was carried out, in more detail, within Al Burdia area during October 2016 and vicinity in the eastern part of Marmarica uplift to cover as much as possible the following:

1.4.1.1 Stratigraphy work

The stratigraphic work was performed in the field by measuring and collecting rock samples from different localities (Fig.1.2) and to do the following points:

- Lithological description of rock units after Dunham's classification (1972).
- Constructing the boundaries of the exposed formations and plotting them, as shown in the field, on geological map.

1.4.1.2 Structural work

About 38 waypoints have been selected for measuring the dip and strike of beds for outlining the type and axes of different styles of folds (Fig.1.2). The fault and joint elements are identified by measured both strike and dip of the planes to identify the movements and type of faults by determining the stresses (σ_1, σ_2 and σ_{3}).

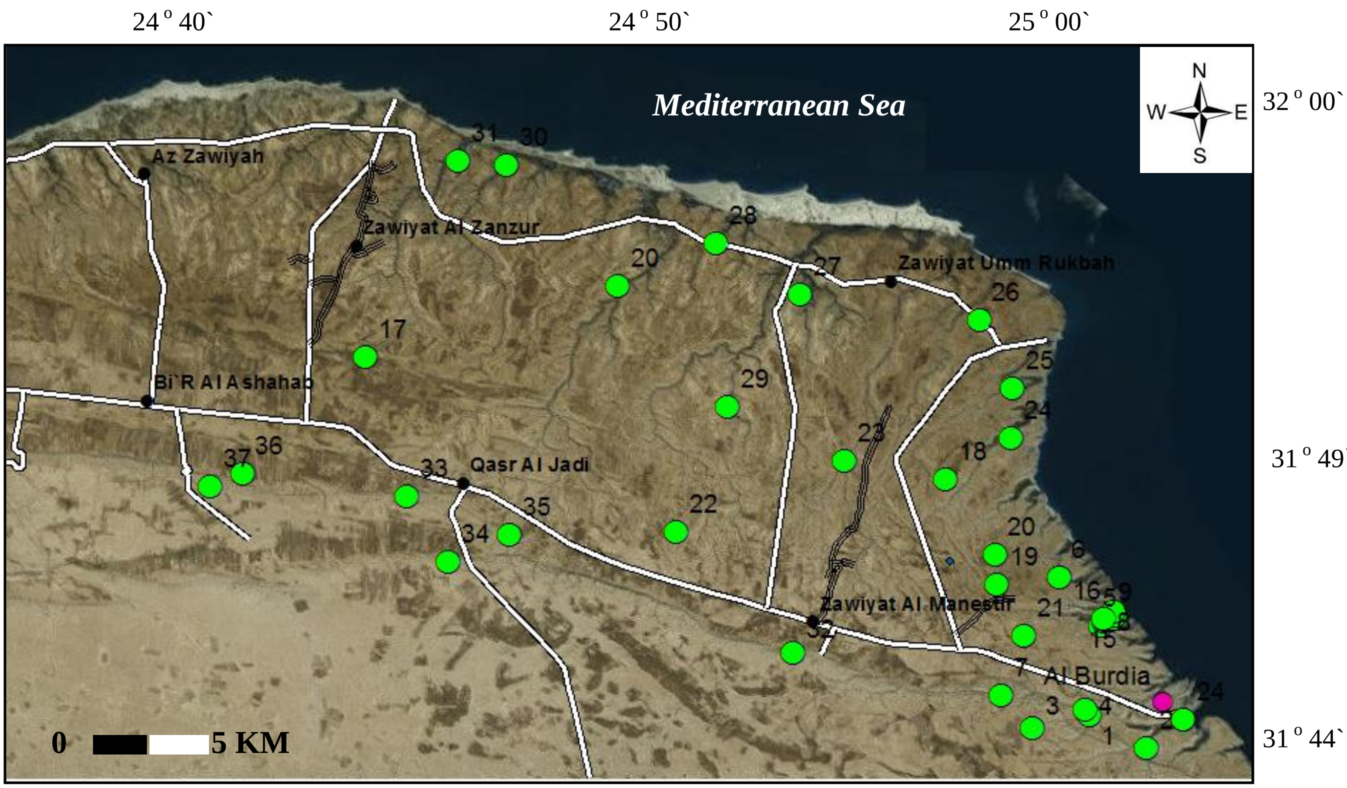


Fig. (1.2) Selected stations during the field trip in the study area.(source: from GIS arc map)

1.4.2 Laboratory Analysis and Data Base

This analysis includes preparation of the geologic map using different scales of topographic maps, landsat images and measurement on the bedding, fault and joint planes together with the field observation and investigation of rock samples. This map involves the distribution of different rock units, dip and strike of beds, faults, joints and fold axes.

The database containing information about structural features such as faults, folds and fractures was conducted in the form of GIS thematic layers enabling interpretation and analysis by using the software (Arc GIS v10.2.2).The Geographical Information Systems (GIS**)** used for data capture, storage, analyses, prognostication, presentation, and follow-up and constitutes an excellent tool for modelling work. It is important to start building of the GIS database at an early stage of any project, enabling data interpretation and prognostication as soon as enough data have been entered into the system. the main purpose of conducting this remote sensing interpretation is to identify faults and fractures as well as major stratigraphic boundaries. Imagery data were used for this study because it provided the highest resolution data and is available free. The structural interpretation was performed digitally on-screen using ArcGIS software and then summarized as major faults in the region.

Attitude of beds and measurements of fault, folds, joints and other linear fabrics are plotted on equal area lower hemisphere projection (Schmidt net) by using computer software's (GEOrient.v9.5 and Dips v6.0**)**. Furthermore, the (Win-Tensor v5.0.1) software was utilized to determine the principle stress axes of faults in the study area (Fig.1.3).

Subsurface data from AGOCO (area 60) is used to support and enhance the understanding of the tectonic frame work of the surface. Taking in consideration, the subsurface study represents only 20% where the obtained data is poor quality, very few and very old, while the surface study represents about 80% of this work.

The subsurface data include four wells; (B1-33, C1-33, A1-LP7C and B1-LP7C). B1-33 and A1-LP7C and B1-LP7C wells are located on the north of Marmarica uplift, while C1-33 well is located to the south on the Marmarica terrace. In addition, two seismic lines 2D, bouguer gravity map , and depth structure maps are also provided for this study. Four wells are checked carefully and studied using their composite logs, and the available data from well files and recent regional report.

The (Petrel 2016) software will be used for visualization and extracting different constructing stratigraphic and structural cross sections.

Fig. (1.3) Snapshots showing the various type of computer software's used in the study.

1.5 Previous Work :

Al Burdia area (including Wadi al Rahib) is considered to be a very difficult area to understand stratigraphically, a fact reflected in the long list of studies concerning the subject. One of the first studies was carried out by Schiettecatte (1972), He discovered a new Cretaceous outcrop in northeastern Cyrenaica in Al Burdi Area, based on foraminiferal microfossils. El Deftar and Issawi, (l977), who subdivided the stratigraphical units in the study area to the Al Khowaymat Formation (Lower Member of Middle Eocene and Upper Member of Early Oligocene), the Al Faidiyah Formation (Late Oligocene-Early Miocene) and the Al Jaghboub Formation (Middle Miocene). Megerisi and Mamgain, (1980) proposed to replace the term Al Khowaymat Formation with Al Majahir, Darnah and Al Abraq formations, based on age difference. Muftah et.al (2017), reviewed the stratigraphy and spatial distribution of rock units of Tobruq-Al Burdia area, using lithology and foraminiferal content, replaced the term Lower Member of Al Khowaymat Formation with Darnah Formation; and the Upper Member of Al Khowaymat with Al Faidiyah Formation for the western part of the study area. Also, Al Majahir Formation replaced the term Lower Member of Al Khowaymat Formation at Wadi al Rahib section.

Several authors have been studied and described the tectonic and structural geology of the North East Libya, such as: Klitzsch,(1970) presented the structural and facies development of Central Sahara, including Libya and Egypt. and introduced the three major periods of structural development in the middle part of North Africa from the Precambrian to the Late Tertiary.

Röhlich (1980) discussed the tectonic history of Al Jabal Al Akhdar and defined three structural stages initiated in Late Cretaceous and ended in Middle Miocene .El Arnauti and Shelmani (1985) described the stratigraphy and structural development of the Paleozoic and Mesozoic sequences in the subsurface of the Cyrenaica region including the Triassic sediments. El Hawat and Shelmani (1993) and El Hawat and Abdulsamad (2004) considered Al Jabal Al Akhdar as the mobile Cyrenaican part in the north separated from the stable part of Cyrenaican platform to the south by E–W to ENE–WSW Cyrenaican fault system. They recognized the folds in Al Jabal Al Akhdar as an array of ENE–WSW en echelon inlier structures attributed to the structural inversion and uplifting during Santonian.

El Arnauti et al. (2008) studied the structural styles in NE Libya and recognized the E-W or ENE-WSW fault as rift fault during Late Jurassic- Early Cretaceous, however later this trend change in a sense of horizontal movement.

Farag (2009) study the Western part of Al Jabal Al Akhdar with emphasis on Jardas Al Abid area, He conclude that the deformation synthesis on the ductile and brittle structures, showed four phases of folding (F_1, F_2, F_3 and F_4) related originally to the movement on consistent series of faulting started intensively in Late Cretaceous then continued mildly until the Miocene time. F_1 to F_3 represent ductile deformational phases within and before outlining the final shape of Jardas Al Abid fold.

El Amawy et al. (2010) studied the karst development and structural relationship in the Tertiary rocks of the western part of Al Jabal Al Akhdar, NE Libya in Qasr Libya area. They recognized that the structural configuration represents a development of concurrent assemblage of WNW-ESE dextral strike slip faults, N-S sinistral strike slip faults and unmappable flower structures and NNW-SSE normal fault within ENE-WSW principle dextral shear zone.

El Amawy et al.(2011) studied the Wrench structural deformation in Ras Al Hilal-Al Athrun area, NE Libya and made a new contribution in Northern Al Jabal Al Akhdar Belt. They classify The deformation within this system into three phases of consistent ductile and brittle structures (D1, D2, and D3) which are conformable with three main tectonic stages during Late Cretaceous, Eocene, and Oligocene–Early Miocene times respectively.

Abd El-Wahed and Kamh.(2013) described the deformation in the central part of Al Jabal Al Akhdar, as manifested by E-W right-lateral strike-slip fault zones that form a conjugate system with the N-S left-lateral strike-slip faulting. The dextral wrench-dominated transpression is responsible for the formation of strike slip duplexes, en echelon folds, and thrusts that deform the Cretaceous-Eocene sedimentary sequences.

Chapter Two

Geological Setting

2.1 Introduction

Al Jabal al Akhdar has been interpreted as an anticlinorium by Chrisite (1955), who described the geological structure of the region. This structure extends from the boundary of Binghazi to about 345km in length, 75km in width and involves a maximum thickness 2000m of Upper Cretaceous, Paleocene, Eocene, Oligocene and Miocene. Because of the core of the structure has been uplifted since Late Cretaceous time, the Cenozoic successions are generally thick on the flanks of the anticlinorium (e.g. in well A1-36) (Abdulsamad and Barbieri 1999), whereas towards the crest they are thin and interrupted by unconformities. The Upper Cretaceous rocks are strongly folded and faulted, whereas the Eocene, Oligocene and the Miocene rocks are slightly folded and commonly dip at angles 10o (Chrisitie, 1955).

2.2 Tectonic setting

2.2.1 Marmarica Uplift

This geotectonic element occupies the central part of the study area and extends along the eastern coastline of the study area and probably continues eastwards into the coastal area of the Western Desert of Egypt. It is characterized by thick Upper Jurassic/Lower Cretaceous syn-rift sediments (Fig.2.2) of the North Cyrenaica rift which were deformed and uplifted during the Late Cretaceous/Early Tertiary (i.e. 'Syrian Arc Orogeny’). However, WNW-ESE rift trends are shown by mapped surface faults and faults recognized from seismic interpretation (El-Arnauti et.al. 2008).

2.2.2 Marmarica terrace

This geotectonic element represents a faulted step-down of the northern margin of the Cyrenaica platform (Fig.2.2). Many extensional faults are affected the Palaeozoic and reached up to the Upper Jurassic/Lower Cretaceous sequence. The Upper Cretaceous/Tertiary is significantly thicker here as compared with the area of Al Jabal al Akhdar uplift (El-Arnauti et. al. 2008).

2.2.3 Cyrenaica platform

This platform occupies the south western part of the study area and has a gently NE-dipping Palaeozoic section that range from the Ordovician in the west to Permian in the NE, and subcrops Mesozoic/Tertiary cover (El-Arnauti et al. 2008) (Fig.2.1).

An infra-Cambrian basin is interpreted as occupying a large part of the central and southern sector of the platform. The northern and north eastern part of the platform has a northward-thickening, fault-controlled Triassic section with NW- SE-oriented faults. The overlying Mesozoic and Tertiary section is relatively unstructured, flat-lying and generally displays coherent seismic character. Faults control the northern and southeastern edges of the Cyrenaica Platform (El-Arnauti et al. 2008).

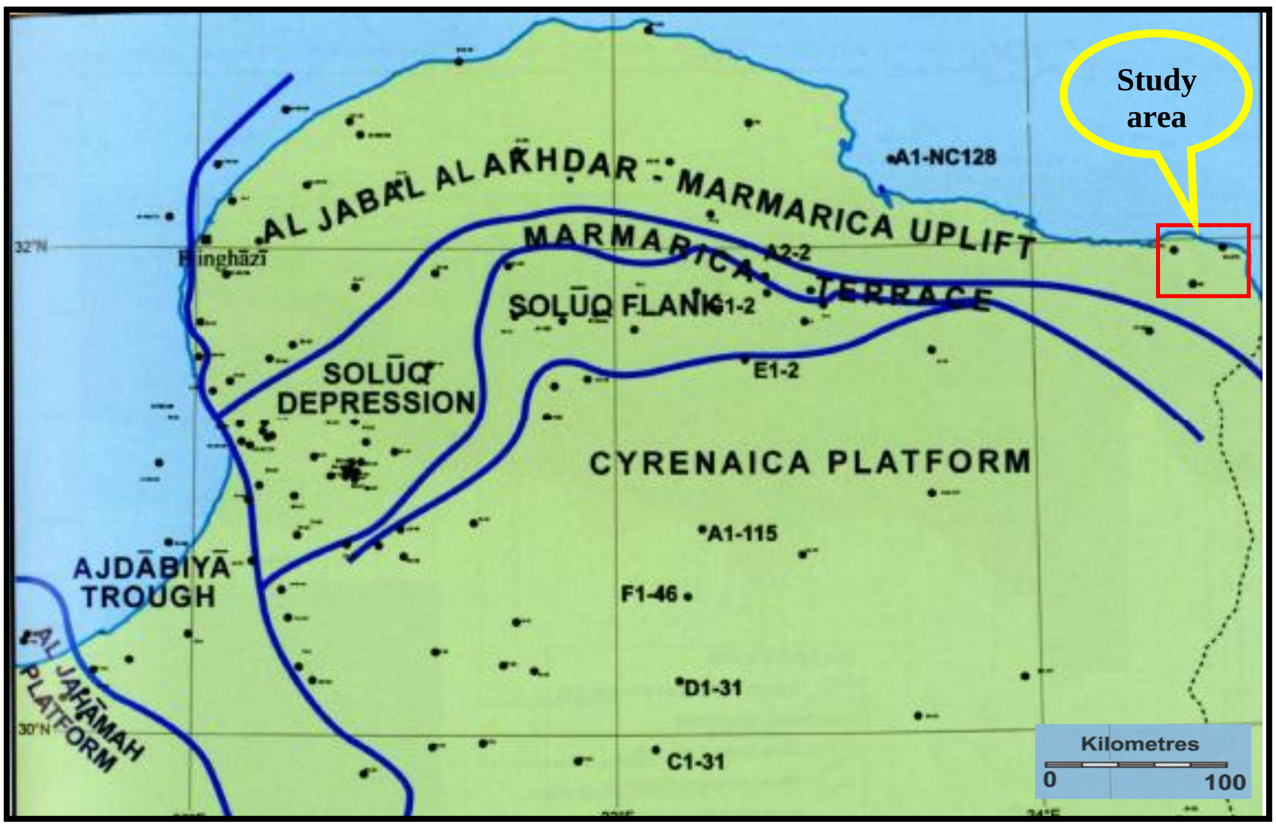


Fig. (2.1) Major structural elements of North East Libya (after El-Arnauti et. al. 2008).

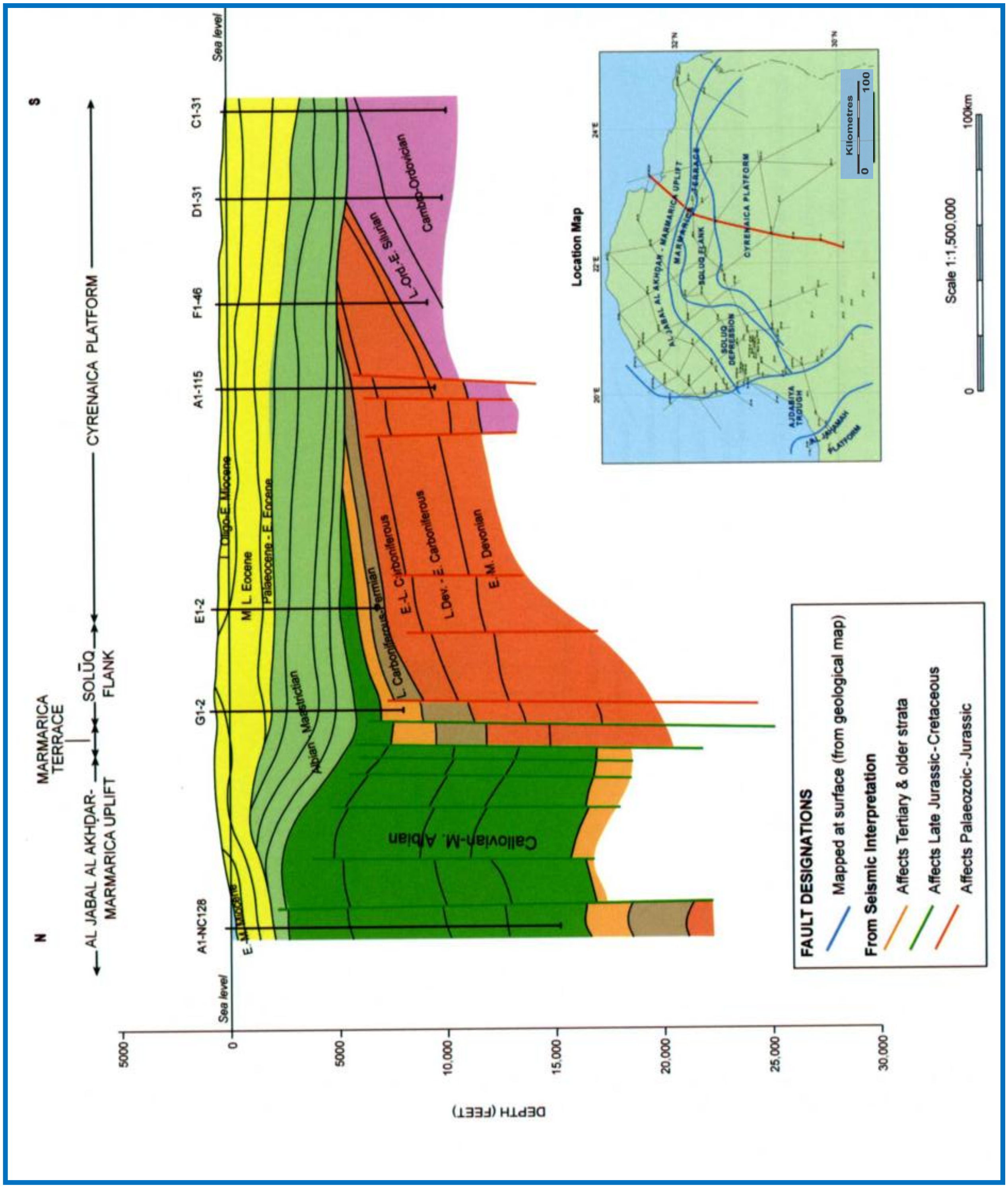


Fig. (2.2) N-S cross-section through Cyrenaica platform, Marmarica terrace and Marmarica-Al Jabal al Akhdar uplifts (El-Arnauti et. al. 2008).

2.3 Depositional Setting and Stratigraphy

2.3.1 Surface Stratigraphy

Chrisite (1955) described the geological structure of the entire region as an anticlinorium. This region mainly consists of marine carbonate rocks. The measured stratigraphic section in the study area is represented by five formations ranging in age from Late Cretaceous up to Middle Miocene. These rock units separated from each other by major unconformities which are developed in response to tectonic forces (e.g. extension and compression) that produce relative sea level fluctuations.

These formations from the oldest to youngest are: the, Al Majahir, Al Bayda, Al Abraq, Al Faidiayh, and Al Jaghbub formations. Several authors studied and described these formations from the surface outcrops differently of Al Jabal Al Akhdar and Marmarica regions such as : Gregory (1911), Klenismeide and Van Den Berg (1968), Barr and Weegar (1972), Schiettecatte, (1972), Klen (1974), Röhlich (1974), Zert (1974), El Deftar and Issawi (1977), Banerjee (1980), Megerisi and Mamgain (1980), El Hawat and Shelmani (1993), Abdulsamad and Barbieri (1999), El Hawat and Abdulsamed (2004) and Muftah et al. (2017).

The geological map of the study area shows different post Oligocene rocks and the Quaternary deposits developed along the plateaus, beach and at the floor of the wadies. However, the unmapped Cretaceous and Oligocene rocks are not represented on the map because of their small thickness. On the other hand, the areal distribution of Al Jaghbub formation occupies 90 % of the whole area (Fig, 2.3).

The presented composite columnar section (Fig. 2.4) yielded a total thickness of100m represented the exposed rock units in the study area. Based on the field observations and petrographic description, the exposed successions of the mapped area have been described, and differentiae as follows :

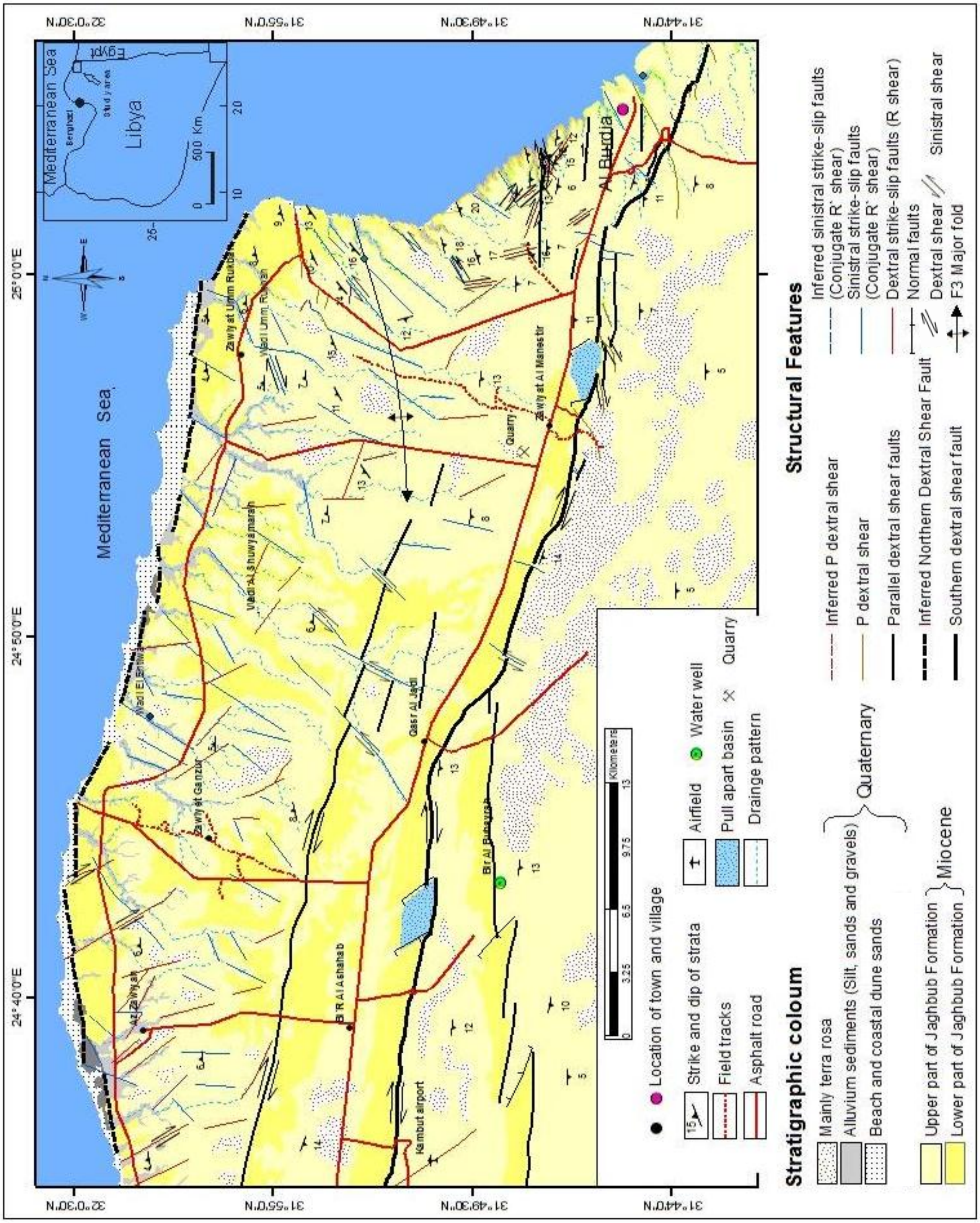


Fig. (2.3) Geological map of Al Burdia area.

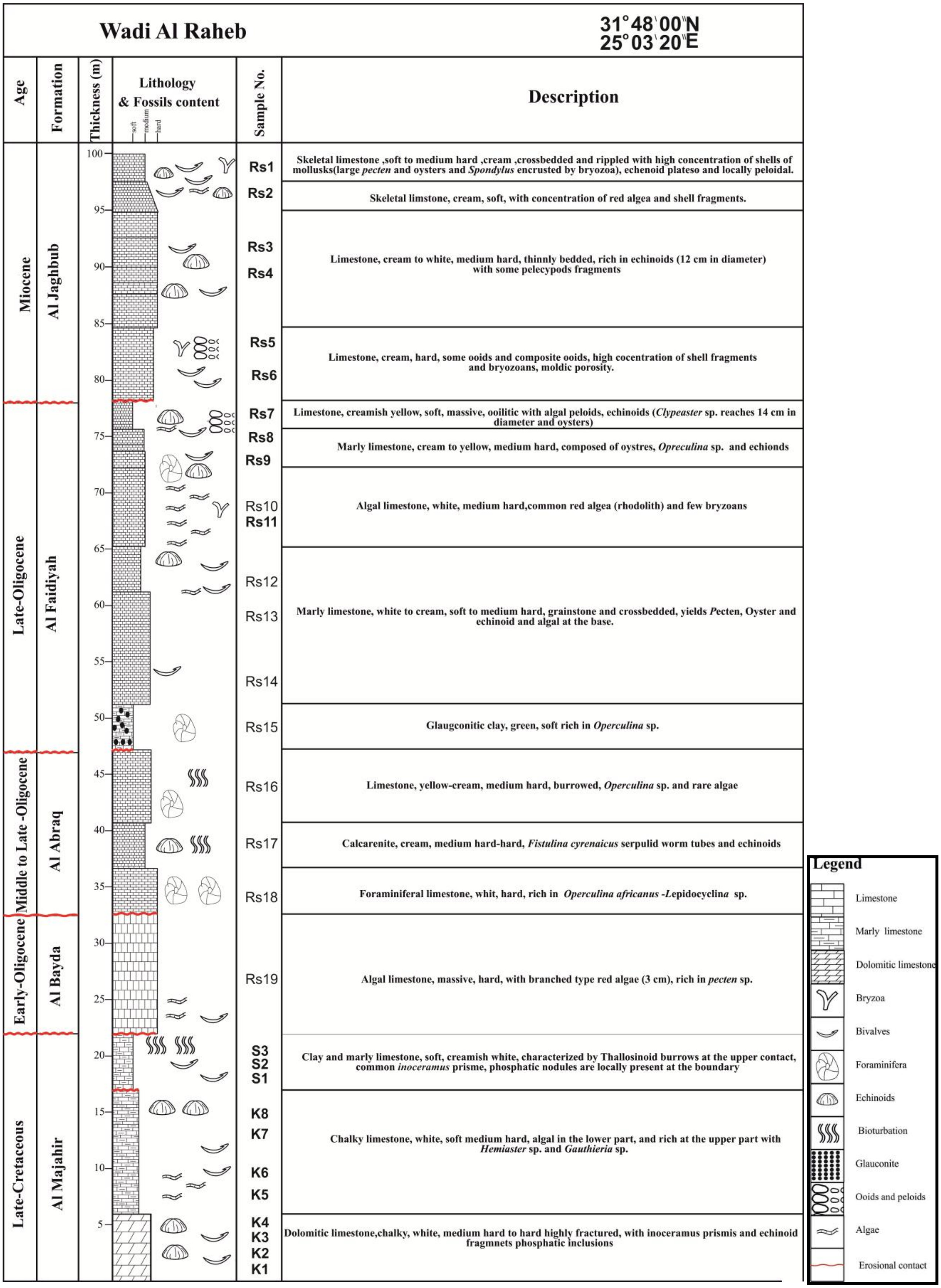


Fig. (2.4) Stratigraphic composite columnar section at Wadi al Rahib in Al Burdia area.

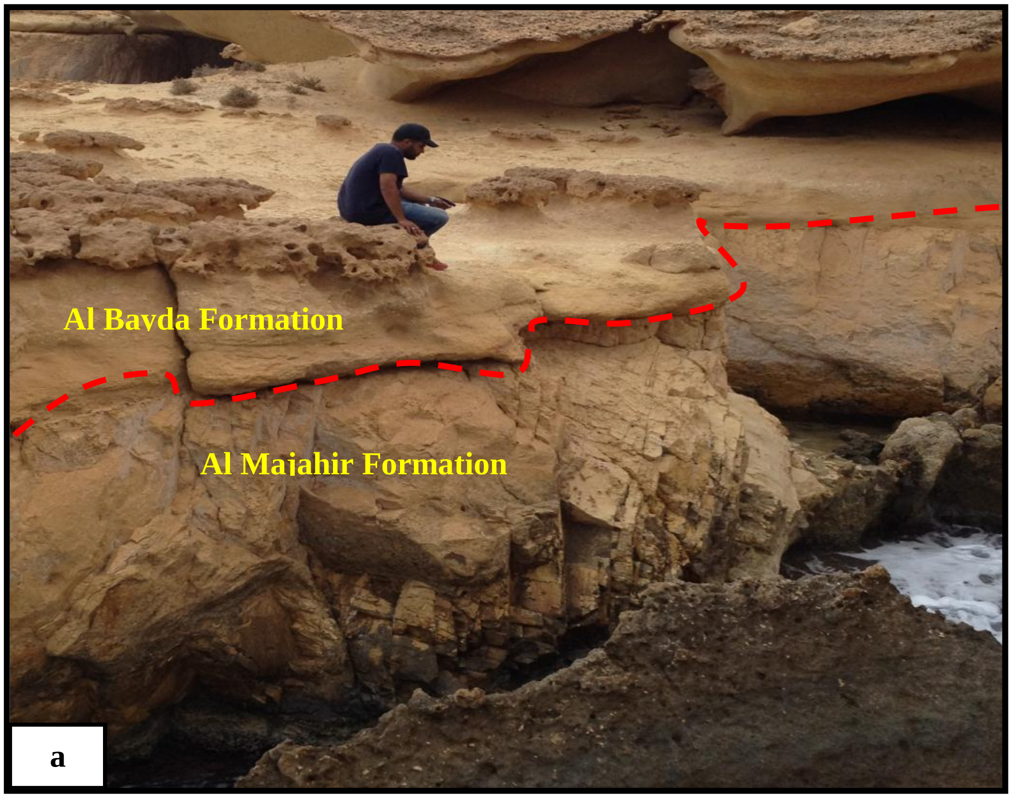
2.3.1.1 Al Majahir Formation.

About 20m are measured and described based on the lithological characteristic and paleontological content (Fig.2.4). It is mainly composed of limestone grading to dolomitic limestone at some horizon ,which is characterized by yellowish grey to yellow, hard to moderately hard, thick to medium bedded with macrofossils especially gastropods and pelecypods, echinoids and shell fragments. (Fig. 2.5).

Petrographically, this unit is characterized by dolomitic matrix of mudstone texture (Fig. 2.6). It composed of euhedral dolomite crystals with thick rim, the fossil are represented by some planktonic foraminifers such as: *Dorothia sp.* With echinoid (some *Hemiaster sp*. And rare *Gouthiera sp.* which are newly reported in Al Majahir Formation (Fig. 2.7).

On the coast near Al Burdia, Schiettecatte (1972) described a small exposure of 15m thick section made of chalky limestone yielded Campanian foraminifera, this suggests that Al Majahir Formation extends in the subsurface at least as far as the Egyptian border. In the Zawiyat Masus sheet (Mazahar, and Issawi, 1977) and in the Bi'r Hakim sheet (Swedan et.al.1977) Al Majahir Formation was assigned to the Eocene-Oligocene Al Khowaymat Formation, where the subsequent study by (Megerisi and Mamgain, 1980) assigned the lower unit of the Al Khowaymat Formation to the upper part of the Cretaceous Al Majahir Formation.

Muftah et al. (2017) studied the faunal suite of the Cretaceous inlier at Wadi al Rahib, based on the recognized sedimentological and paleontological reported fossils. They assigned this formation to the Campanian age based on evidence by few representatives of *Globotruncana* cf. *fornicata*, *Hedbergella* spp., *Globotruncana* sp., and *Heterohelix globulosa* as well as rare *inoceramus* prisms.



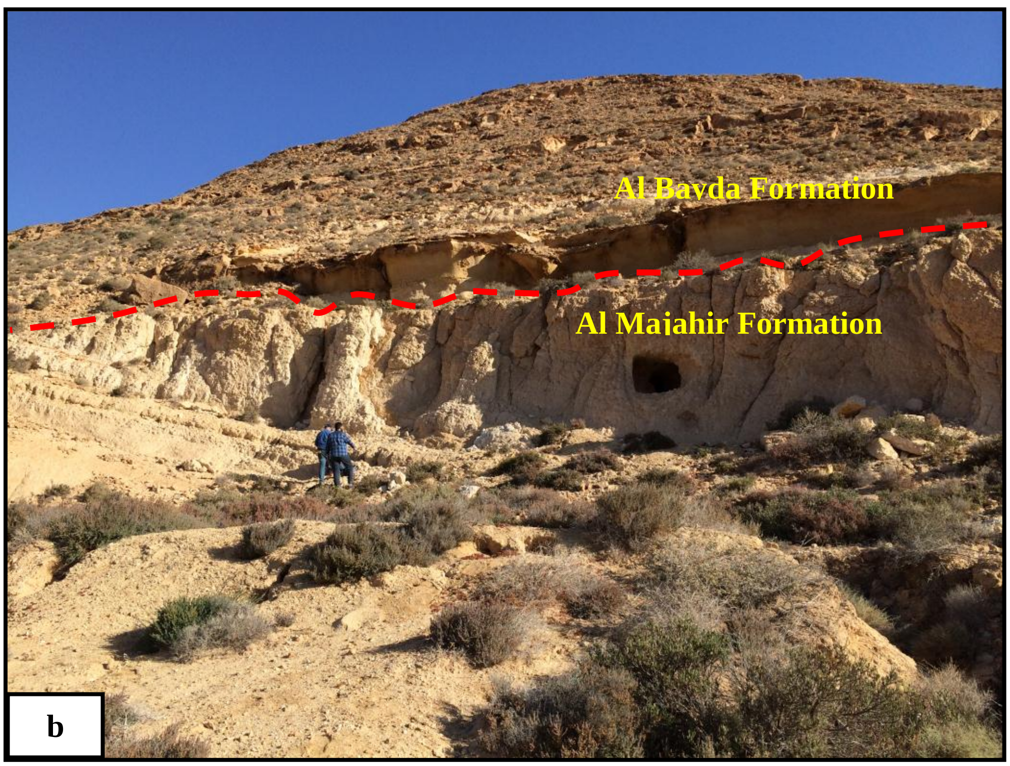


Fig. (2.5) Close views of the Cretaceous /Tertiary boundary as indicated by the angular unconformity at two localities ,(a) at Wadi al Shaqqah Station #11,(b) at Wadi al Rahib Station #14. Al Burdia area ,NE Libya. (Both looking NE).

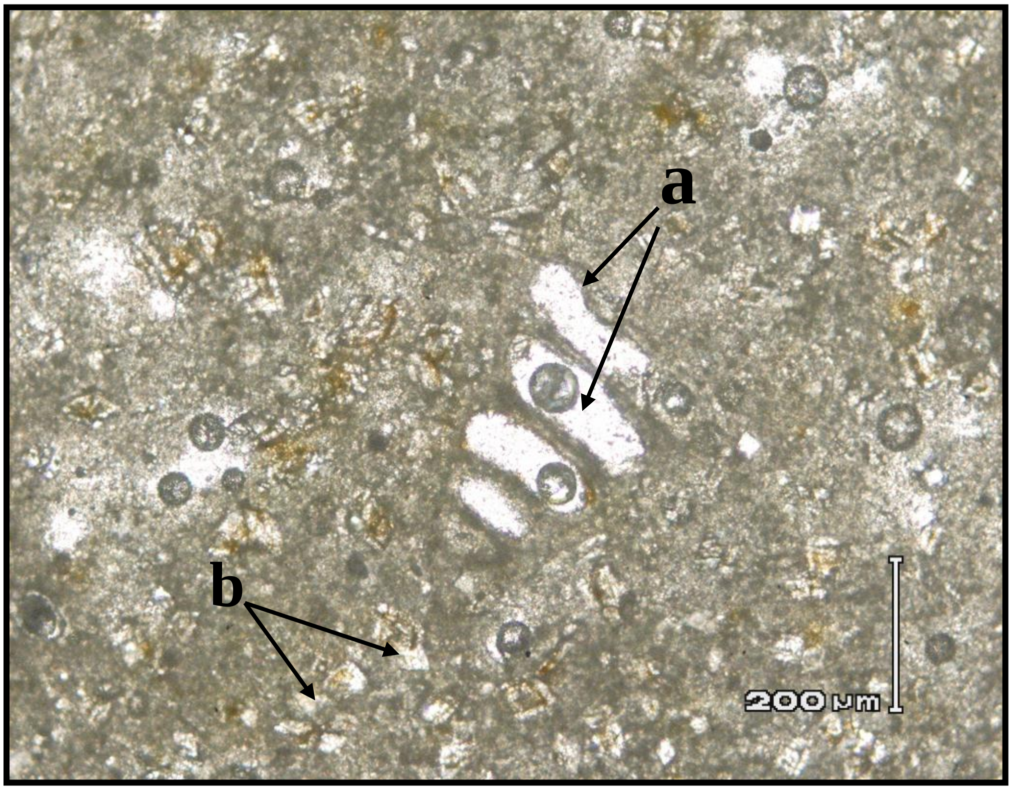


Fig.(2.6) Photomicrograph of mudstone texture in the middle part of Al Majahir Formation, with (a) sprite cement filling the *Dorothia.sp* champers (b) euhedral dolomite crystals**.** PPL

Fig. (2.7) Shows the *Hemiaster sp*. And *Gouthiera sp;*of Al Majahir Formation, Wadi al Rahib, Al Burdia area.

2.3.1.2 Al Bayda Formation

Al Bayda Formation was described by Röhlich (1974) as Early Oligocene in age. It is subdivided into two members ,Shahhat Marl Member in the lower part and Algal Limestone Member in the upper part (Kleinsmeide and Van Den Berg 1968). In the study area ,only the Algal Limestone Member is exposed (Fig.2.4).

2.3.1.2.1 Algal Limestone Member

This member is also exposed at Wadi al Rahib and attaining about 10m thick ,it consists of greyish to white limestone ,hard to moderately hard, medium to thick-bedded with abundant coralline red algae associated with *Nummulites* sp, echinoids, pelecypods and skeletal fragments (Fig.2.8).

Petrographically, the studied sample characterized by grainstone texture, with common sparite cement and abundant coralline red algae, molluskan shell fragments and rare foraminiferal tests (Fig.2.9), becomes finely to coarsely crystalline in parts.

The contact of this member with the overlying Al Abraq Formation is marked by a disconformity surface.

Based on the paleontological evidences, Al Bayda Formation is regarded as Early Oligocene in age, according to the reported Early Oligocene foraminiferal species including: *Nummulites vascus* and *N.* cf. *fichteli* Röhlich (1974).

The stratgraphic distribution of Algal Limestone Member of Al Bayda Formation at Susah-Cyrene road cut indicate a shallowing – up trend following the deep neritic condition of Shahhat Marl Member. However, the Algal Limestone Member was deposited within reefal-range environment (shoal-edge/back-reef to fore-reef) (Muftah and Erhoma, 2002).

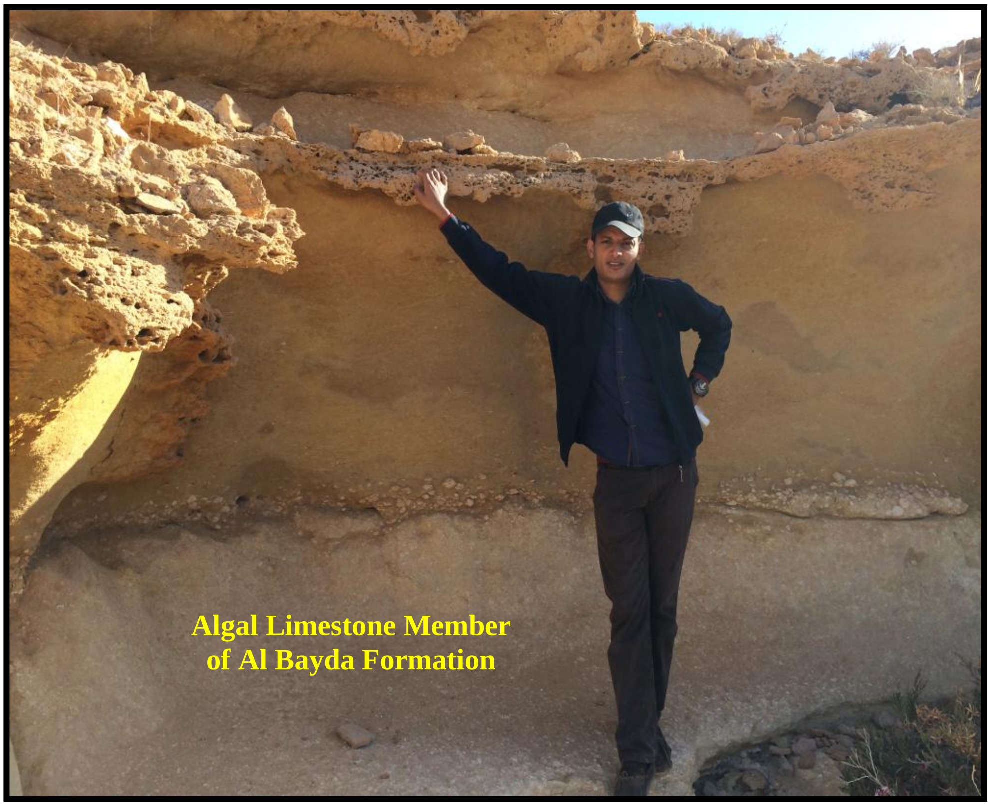


Fig. (2.8) Lower Oligocene section of Al Bayda Formation at Wadi al Rahib, Station #15(looking SW).

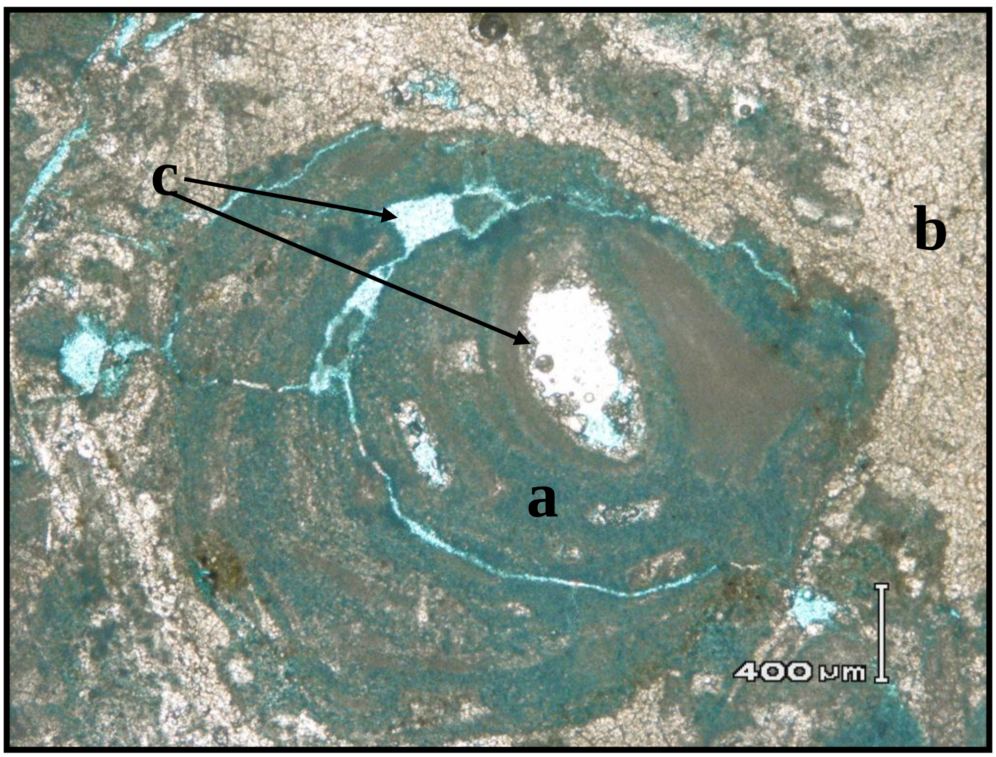


Fig. (2.9) Photomicrograph of the Algal Limestone Member of Al Bayda Formation, shows coralline red algae(a), sparite cement (b), solutional intraskeletal porosity (c),PPL.

2.3.1.3 Al Abraq Formation

Al Abraq Formation is described by Röhlich (1974). In the western part of the mapped area it measures about 15m thick. It consists mainly of marly limestone, and characterized by yellow to creamy colored, medium to thick-bedded, moderately hard to hard with common *Nummulites* spp, pelecypods, gastrpods and echinoids (Fig.2.4).

The nature of the contact with the underlying Al Bayda Formation is a disconformable surface (Fig.2.10).

Petrographically, two samples from this formation are collected and examined , the first unit (Echinoidal Marly Limestone)of packstone texture with medium to coarse grains of molluscan fragments, calcareous red algae, echinoid fragments and foraminiferal "*Operculina complanata and Lepidocyclina*. *sp* (Figs.2.11 and 2.12).

The second unit is characterized by packstone texture with rare glauconitic grains, bryozoan fragments, *Operculina discoidea*, and some *Amphistegina* sp. (Figs.2.13and 2.14).

Al Abraq Formation is dated as Middle-Late Oligocene as indicated by the paleontological and stratigraphical evidences, El Hawat and Abdulsamed (2004).

Röhlich (1974) on the other hand, pointed out a deep neritic environment to a shallow-marine nature of this formation and assigned Early to Late Oligocene based on the foraminiferal species of *Nummulites fichetli*, *N. vascus* and *Operculina discoidea*. Abdulsamad and Barbieri (1999) reported an Early to Late Oligocene benthic foraminifera including *Nummulits* cf. *fichteli*, *Operculina complanata* and some planktonic species such as *G. angulisuturalis* and *Paragloborotalia opima nana*.

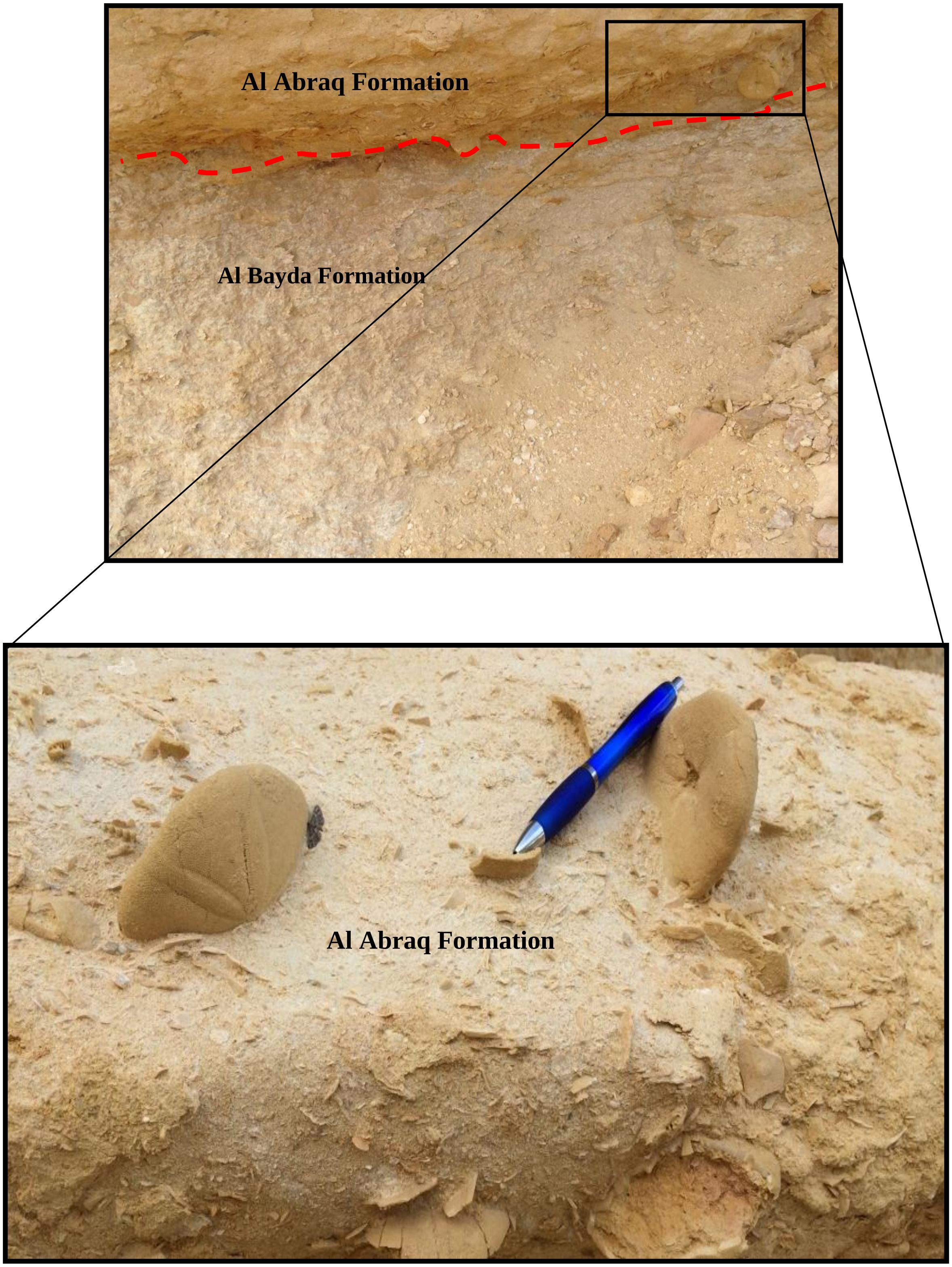


Fig. (2.10) Field photographs in Station #17 show *Echinolampas sp*, and skeletal fragments of echinoidal marly limestone Al Abraq Formation. Note the disconformable surface with the underlying Al Bayda Formation in the upper photograph .

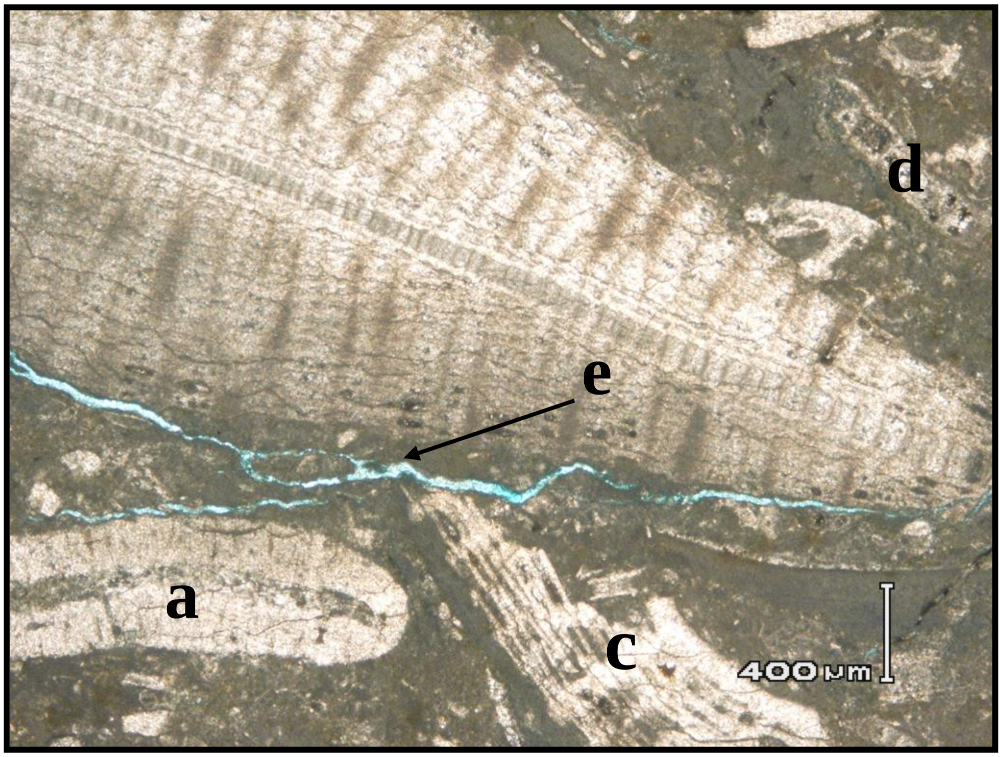


Fig. (2.11) Photomicrograph of unit (1) Marly limestone showing packstone texture of Al Abraq Formation, *Operculina complanata* (a), *Lepidocyclina .sp* (b) micrite matrix (c) shell fragments (d) fracture porosity (e). PPL.

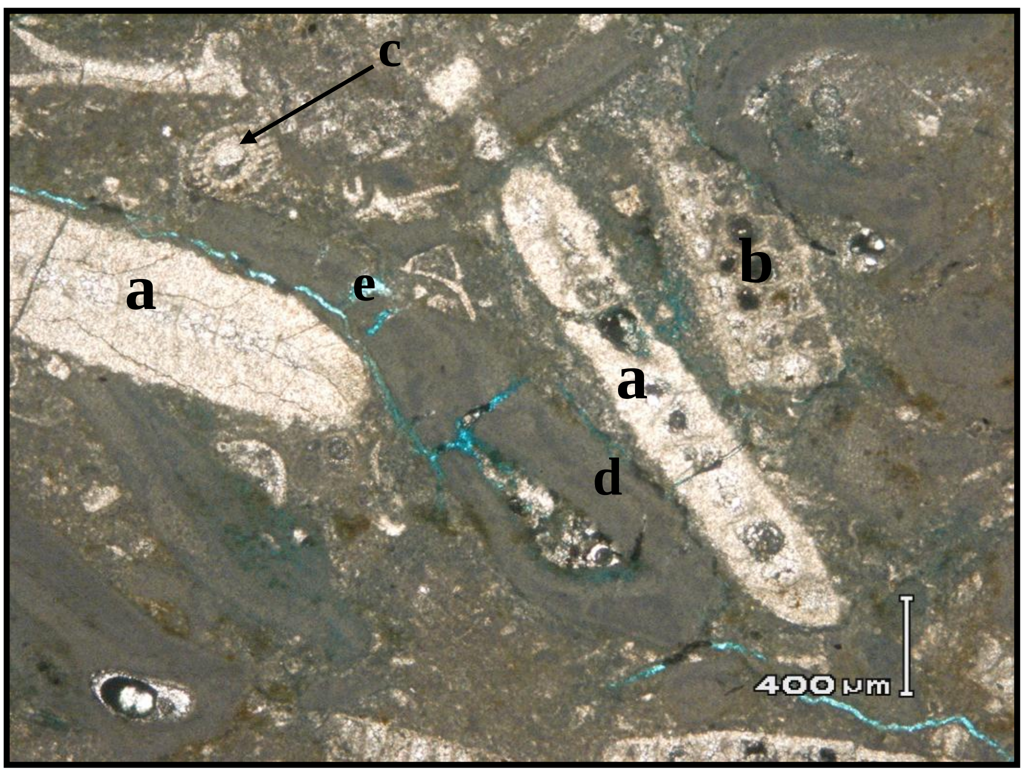


Fig. (2.12) Photomicrograph of unit (1) showing marly packstone texture with common micrite matrix of the Al Abraq Formation, *Operculina complanata* (a), bryozoan fragments (b), echinoidal spine (c), red algae (d), fracture porosity (e), PPL .

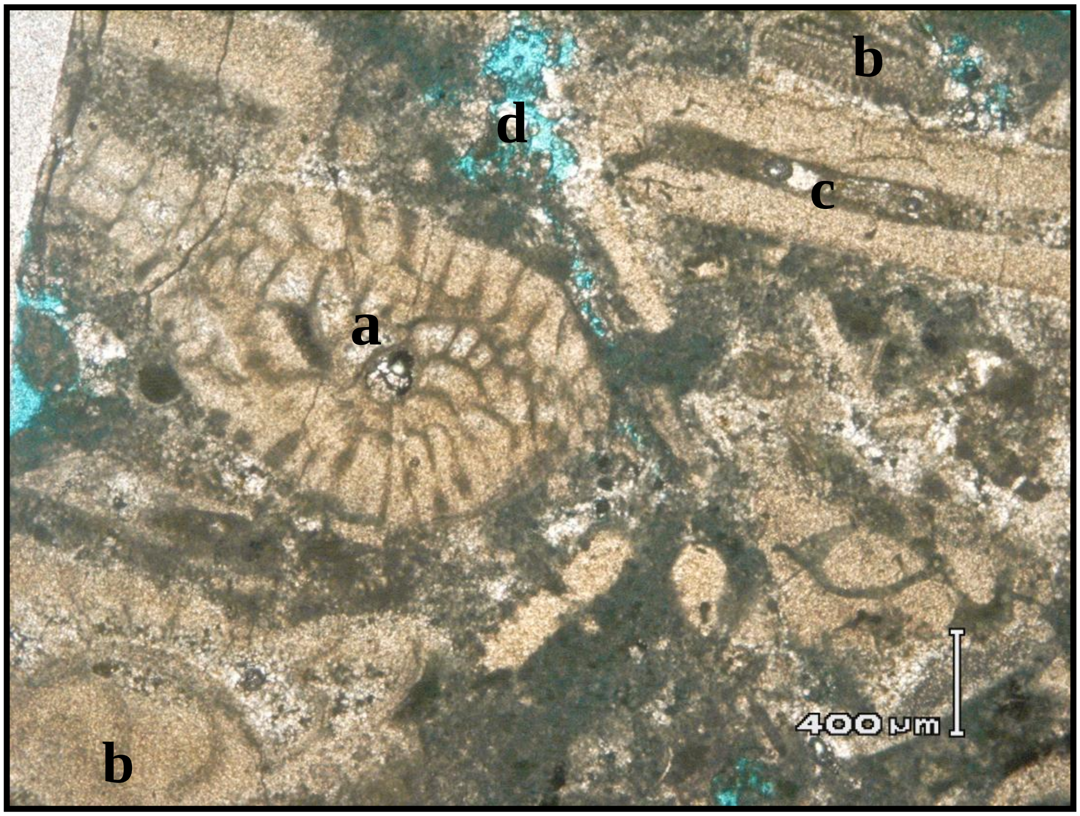


Fig. (2.13) Photomicrograph of unit 2 foraminiferal packstone of Al Abraq Formation., *Hetrostigina sp* (a), echinoids fragment (b), *Operculina* (c), interskeletal porosity (d), PPL.

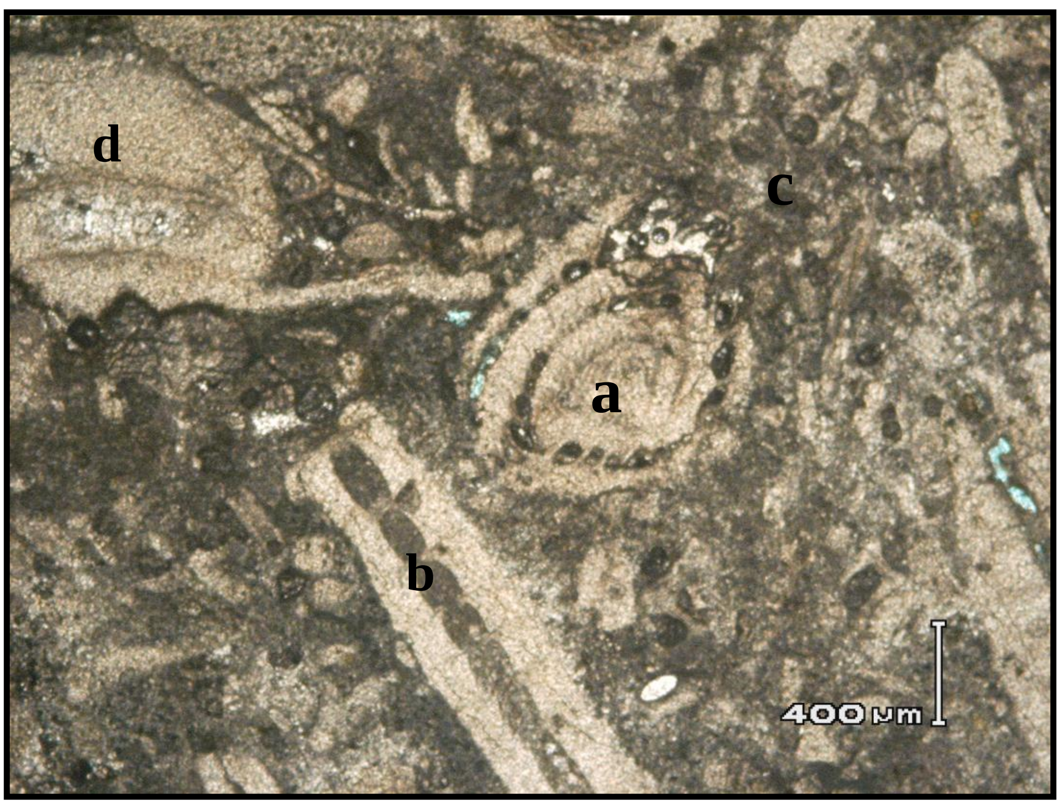


Fig. (2.14) Photomicrograph of unit 2 packstone of Al Abraq Formation. Shows *Amphistegina .sp* (a), *Operculina* (b), micrite matrix (c), echinoid fragment (d), PPL.

2.3.1.4 Al Faidiayh Formation

Al Faiydiah Formation was introduced and described by Pietersz (1968). The detailed mapping of this formation in northeast Libya has been achieved by several geologists such as Rohlich (1974) , Zert (1974) and El Hawat and Shelmani (1993).

Lithologically, about 25m of alternating limestone and marly limestone with subordinate clay beds containing *Operculina* sp. have been measured here in (Fig.2.4). The beds unconformable underlain the A1 Jaghbub Formation. The formation at the outcrop is characterized by yellowish to green thick to thin-bedded and highly fossiliferous. (Fig.2.15).

Petrographically, the studied sample are characterized by packstone texture with common micrite matrix and intra-skeletal porosity. The main foraminiferal suite encountered include common *Operculina africana, Operculina. Complanata* and *Lepidocyclina* sp with some red algae fragments (Fig.2.16).

Based on the occurrence of *Nummulites fichteli* from Al Jabal al Akhdar by (Rohlich, 1974) Al Faidiyah Formation has been dated as Late Oligocene to Early Miocene. However later on El Hawat and Shelmani, (1993) and El Hawat and Abdulsamad (2004) believed that the Al Faiydiah Formation is Early Miocene, as they attributed the occurrence of the Nummulites and other older fossils to reworking from older Oligocene formations, which had been eroded from the adjacent highs that evolved in response to deposition of the shallow Oligocene sea. However, Abdulsamad and Barbieri (1999) have reported some Miocene larger foraminifera and planktonic foraminifera in Al Faiydiah Formation. Such as *Borelis melo* and *Praeorbulina glomerosa* respectively.

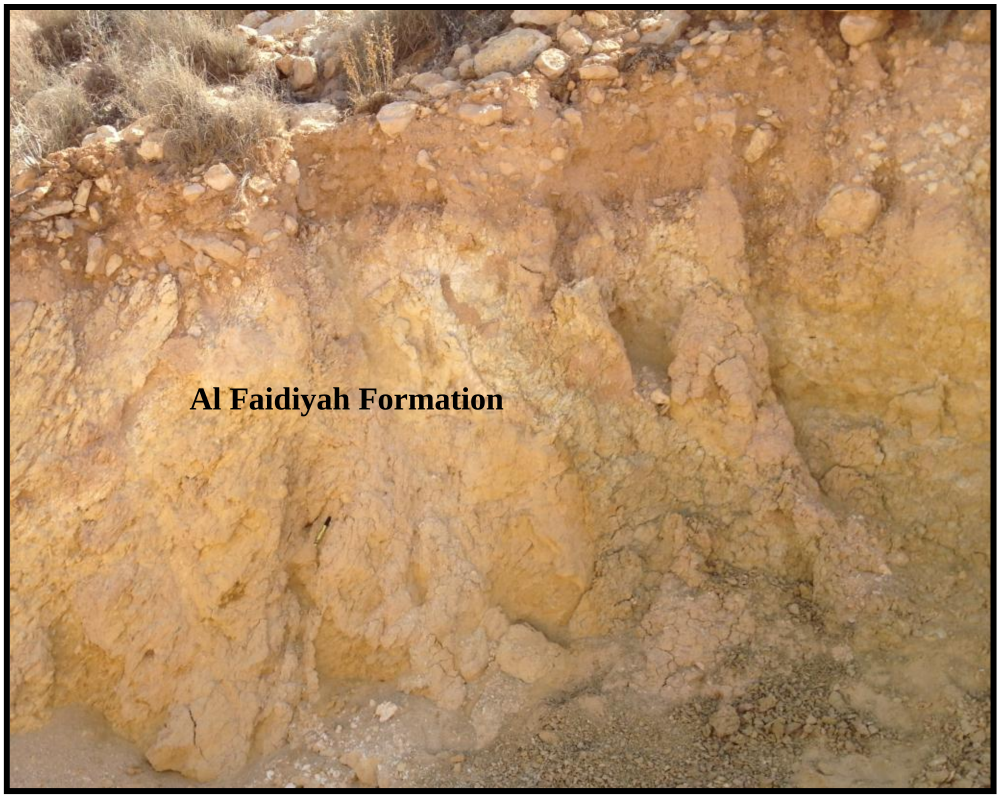


Fig. (2.15) Field photographs in Station #19 show Al Faidiyah Formation, at Wadi al Rahib, Al Burdia area.

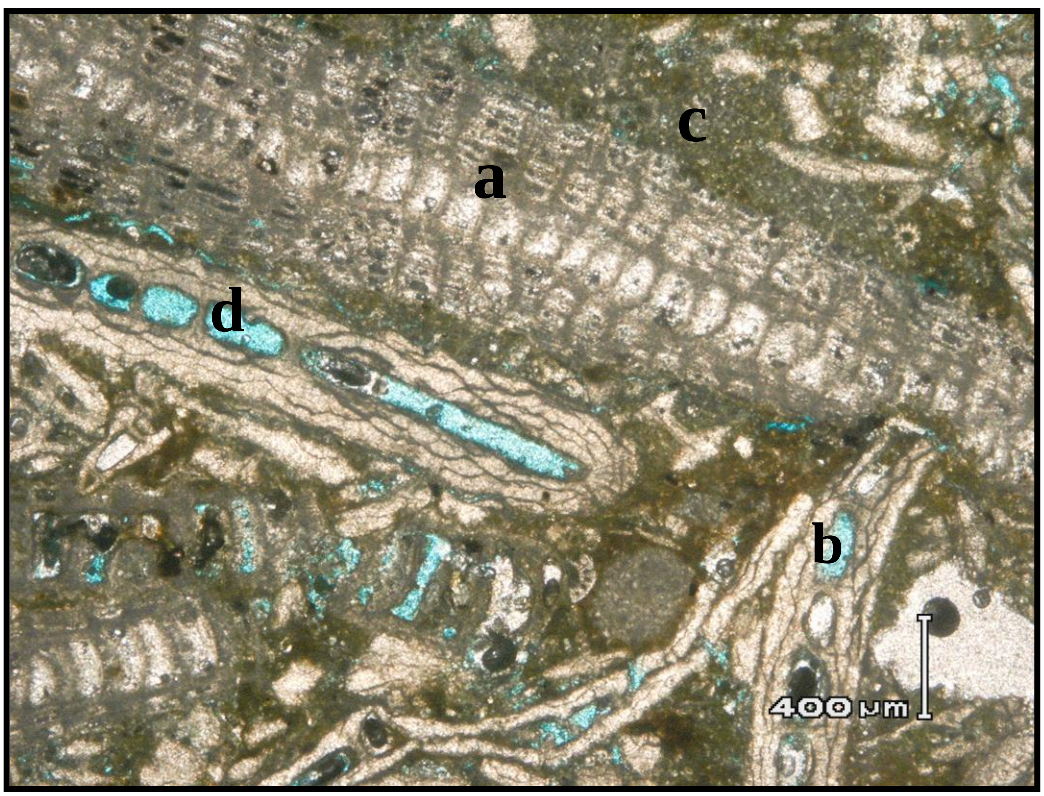


Fig. (2.16) Photomicrograph of (unit 1) of Al Faidiyah Formation. shows packstone texture with *Lebidocyclina.sp*. (a), *Operculina complanata* (b), micrite matrix (c) Intraskeletal porosity (d), PPL.

2.3.1.5 Al Jaghbub Formation

The Al Jaghbub Formation was introduced by Desio (1928) for a series of limestones and marls with thin sands overlying Early Miocene rocks at the Al Jaghbub oasis and over a large area of the eastern Cyrenaican Platform.

The outcrops of Al Jaghbub Formation are extensively distributed around Al Burdi and on the sea cliffs south of the town, with thickness reaches 140m (Fig. 2.4).

Based on change in tone color from the satellite image (Fig. 2.17) as well as the lithology and fossil contents during the field investigation. Al Jaghbub Formation in the study area can be subdivided into two main parts (Fig. 2.3).The lower part consists of hard yellow limestone, rich in bryozoan. (Fig. 2.16).While the upper part is highly fossiliferous consists mainly of white, soft ,skeletal limestones interbedded with clay and marls, containing gastropods with bivalves, echinoids, oysters and Balanus sp. with ripples and cross bedded (Fig. 2.17).

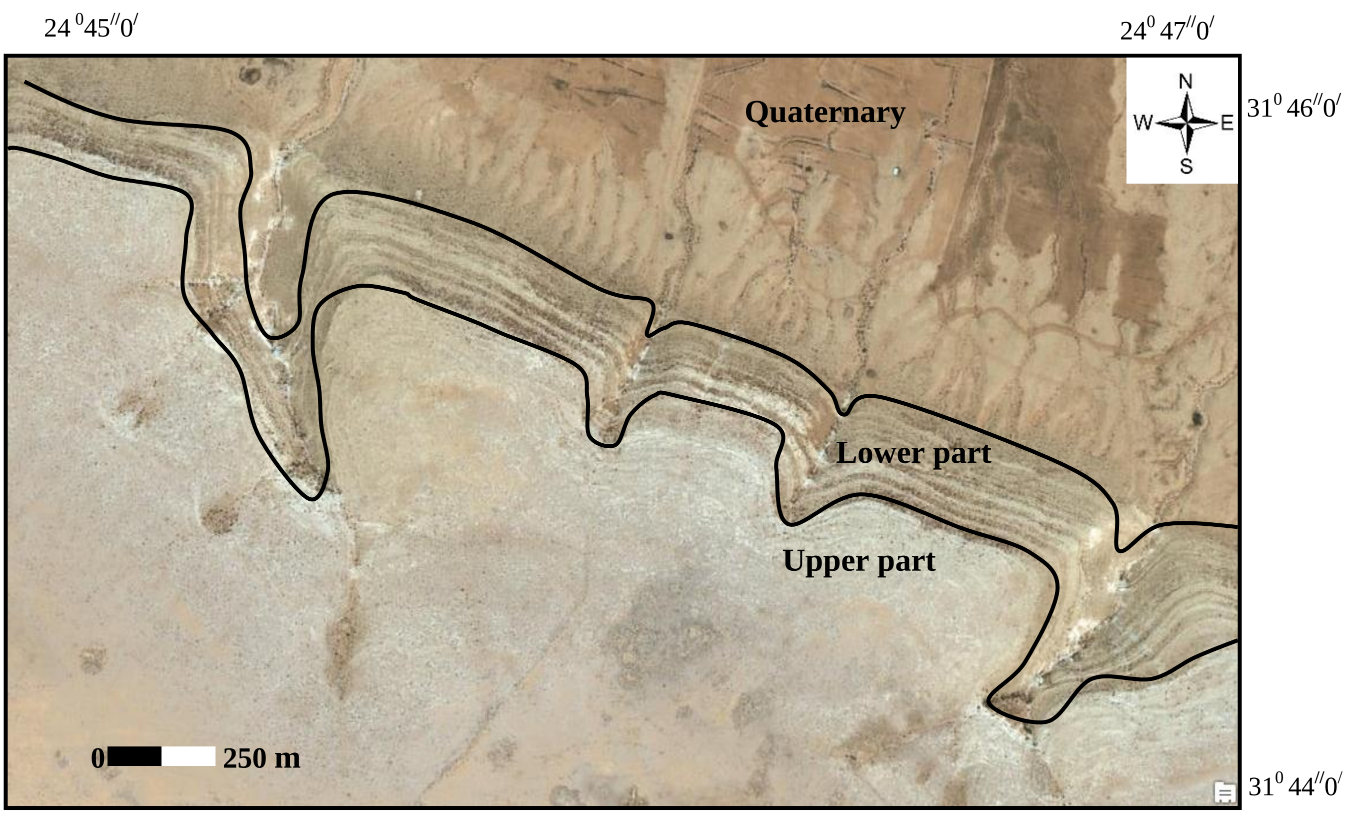


Fig. (2.17) Satellite image along the southern escarpment showing the variation in tone color in the lower and upper parts of Al Jaghbub Formation in Al Burdia area.

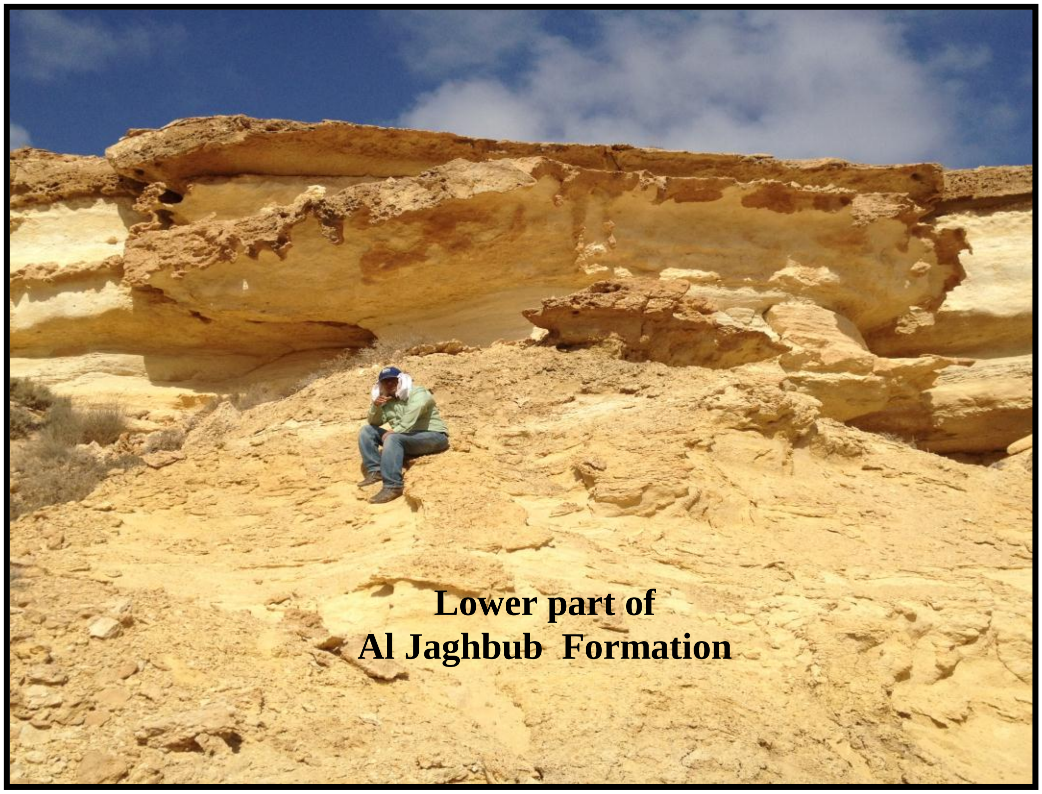


Fig. (2.18) Field photo of the lower part of Al Jaghbub Formation outcrop in Al Burdia area, (looking NE).

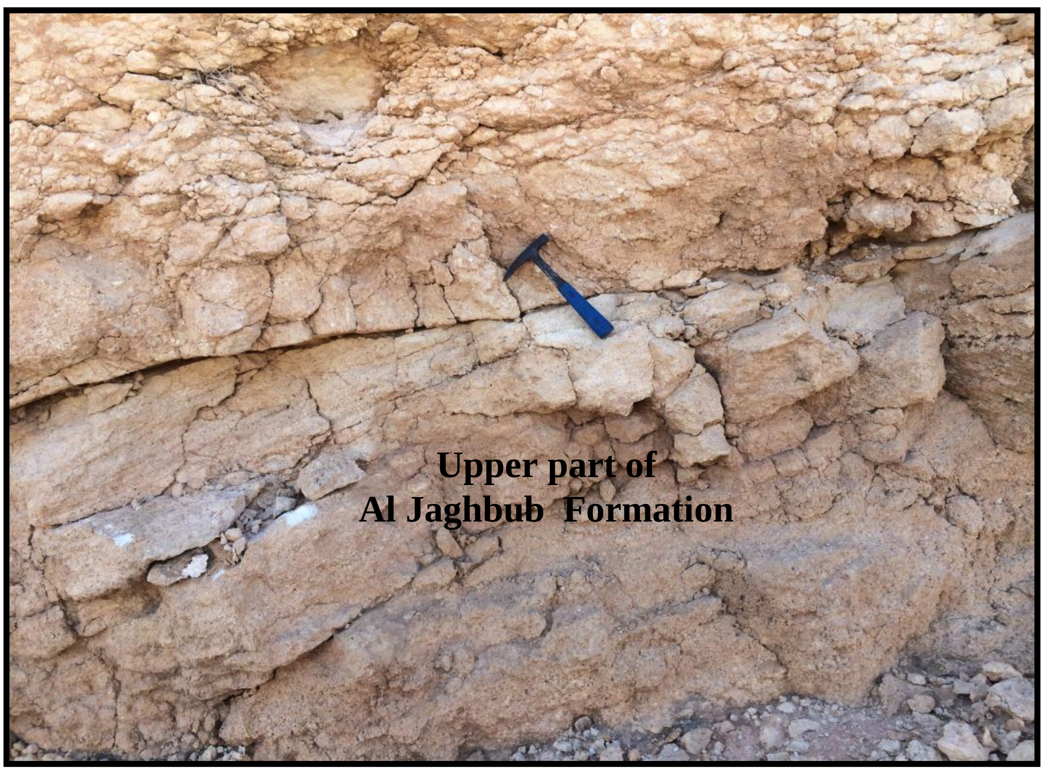


Fig. (2.19) Field photo of the upper part of Al Jaghbub Formation in Al Burdia area, note the cross bedded (looking NE).

The following are the main units in the Al Jaghbub Formation with their established subunits :

2.3.1.5.1 Lower Jaghbub unit (I)

Lithologically, this unit is represented by limestone cream to white , hard ,with common of red algae, echinoids and bryozoa .

Petrographically, it is composed of packstone to grainstone texture with abundant various bryozoan remains and molluscan debris ,the bryozoan colonies are commonly developed and some diagenetic process are observed such as filling with sprite and particularly leaching which increase porosity of the rock (Fig.2.20).

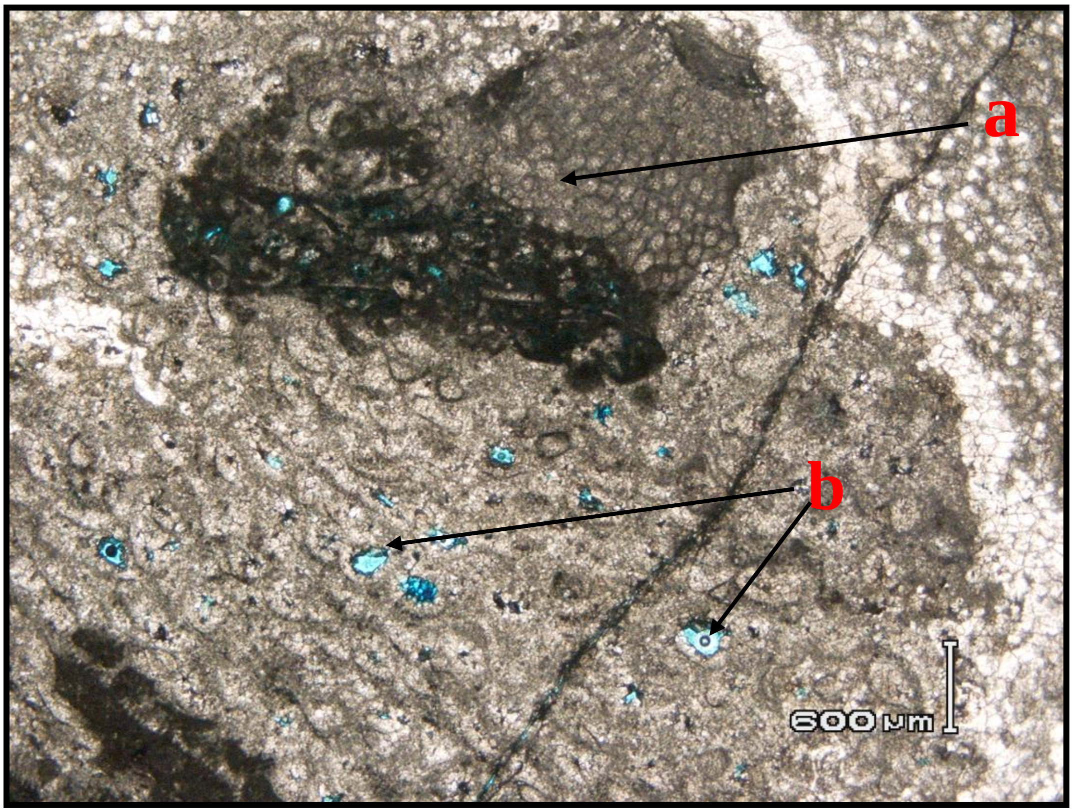


Fig. (2.20) Photomicrograph of Al Jaghbub Formation (unit 1) shows (a) Bryozoan colony with two types of encrusted bryozoan shows zooids filled with sparite cement(a), and intraskeletal porosity (b).(sample #RS6).PPL.

2.3.1.5.2 Lower Jaghbub unit (II)

Lithologically, it is represented by limestone (bryozoan biosparite) cream to white, hard, fossiliferous, with large bryozoan colony and Pelecypod shell fragments.

Petrographically, the rock is composed of molluscan debris and various bryozoan remains which are the main allochemical constituents of the rock, (Fig.2.21). Most of the particles are completely obliterated into fine to medium crystalline sparry calcite masses with deformed structures .

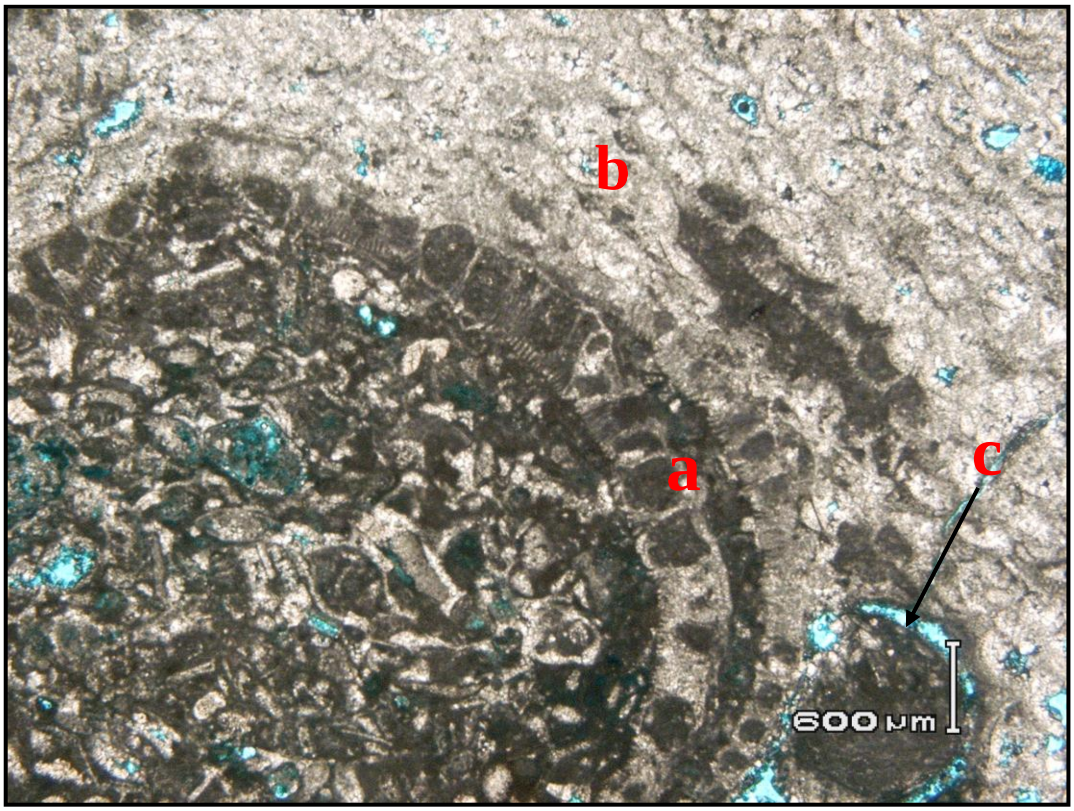


Fig. (2.21) Photomicrograph of Al Jaghbub Formation. (unit 2) it shows packstone to grainstone texture with Bryozoa colony (a), calcite cement (b), interskeletal porosity (c).(sample #5) PPL.

2.3.1.5.3Upper Jaghbub unit (III)

Lithologically, it represented by skeletal limestone, medium hard to hard, massive, with large sized pelecypods (*Pecten .sp*).

Petrographically, it is characterized by wackstone texture with micritic matrix, glauconite and rare phosphate remains , the allochems include: pelloides, *Quinqueloculina sp* ostracods, and echinoids fragment (Fig.2.22).

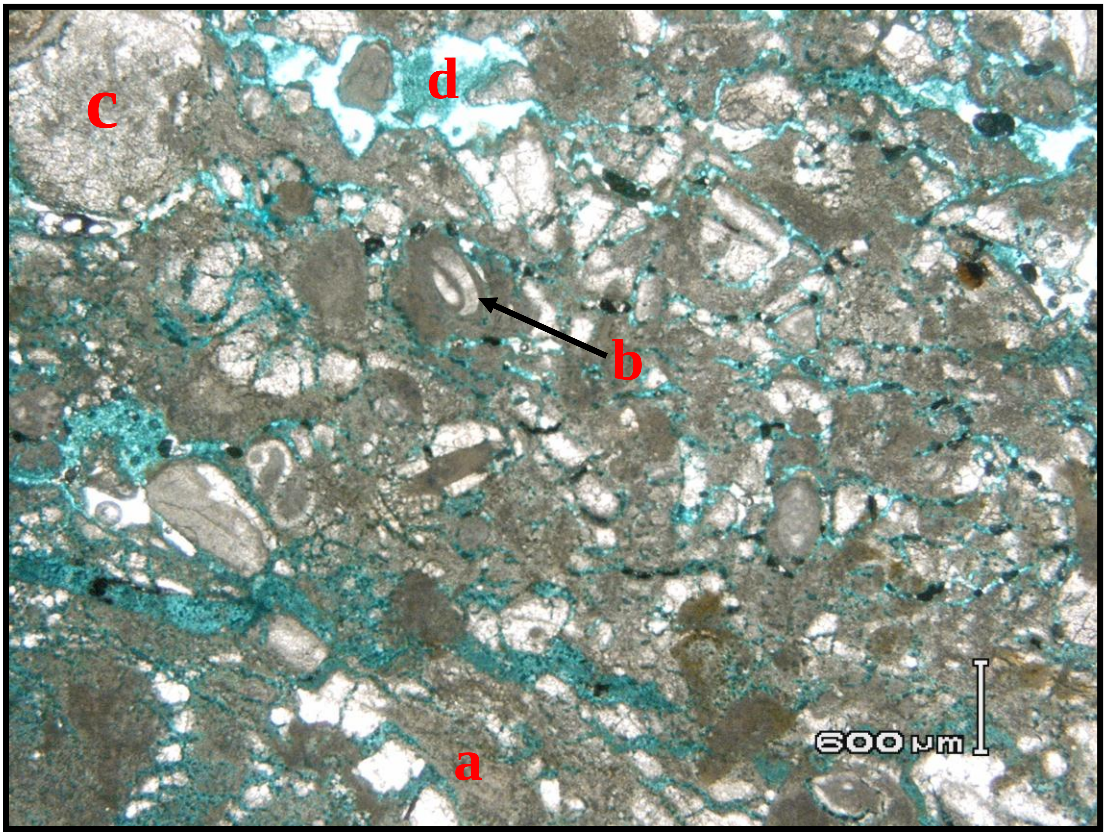


Fig.(2.22) Photomicrograph of Al Jaghbub Formation,(unit 3), shows some Algal peloids (a), *Quinqueloculina sp* (b), echinoid plate(c) and (d) intergranular porosity,(sample #2). PPL.

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2.3.1.5.4 Upper Jaghbub unit (IV)

Lithologically, it consist of limestone, cream, hard it exhibits large scale cross bedding , oolitic in places with high concentration of shell fragments and bryozoans. Porosity is fair and of moldic type.

Petrographically, this unit is characterized by packestone grading to grainstone in places ,containing bryozoans ,*Miogypsinoides* ,*complanatus* as bioclast floating within the lime mud matrix, isopach cement is observed as a diagenetic elements around bioclast grains (Fig.2.23).

Based on the reported foraminiferal by other workers ;El Deftar and Issawi (1977); Muftah et al.(2017) and this work . Al Jaghbub Formation in Al Burdia area is an Early Miocene (Burdigalian) Middle Miocene (Langhian to Tortonian) where, *Borelis melo Amphistegina cf. radiata ,Miogypsina sp., complanatus .,and few miliolids*. Are indicative elements to this age.

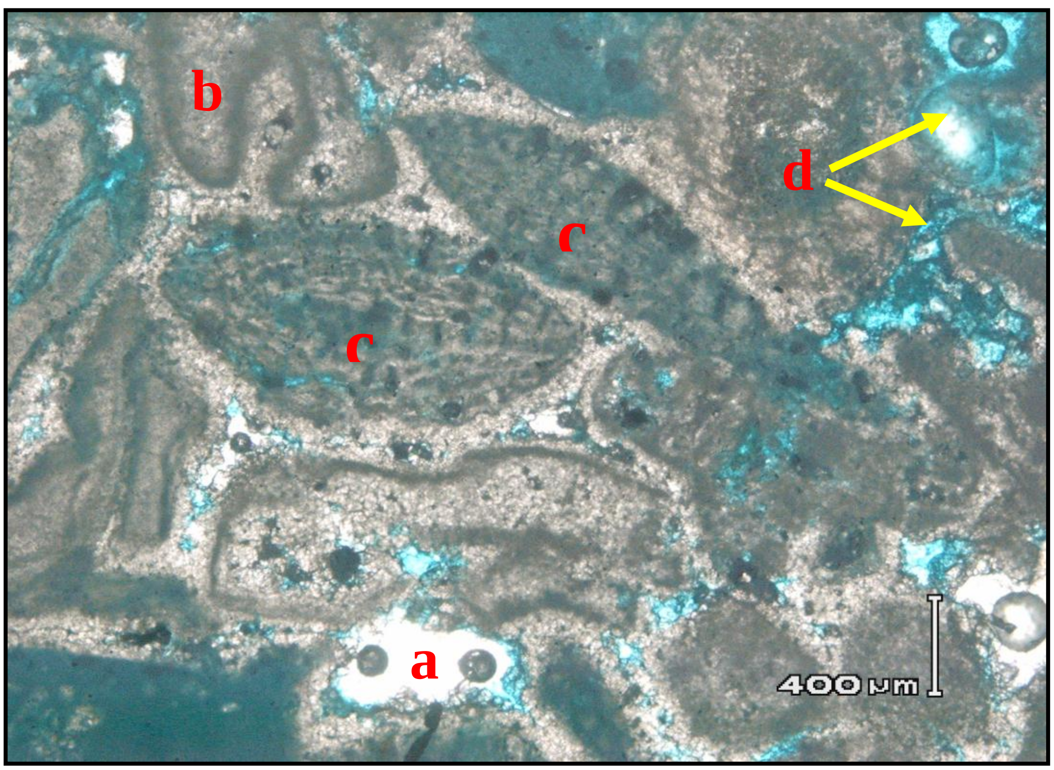


Fig. (2.23) Photomicrograph of the Al Jaghbub Formation. (unit 4) shows packstone to grainstone texture with isopacheous cement (a), peloidal grains (b) *Miogypsinoides, complanatus* (c) and intragranular porosity (d). (sample # 1) PPL.

2.3.2 Subsurface Stratigraphy:

Subsurface data provided by AGOCO in (area 60) which include four wells; (B1-33, C1-33, A1-LP7C and B1-LP7C). B1-33 , A1-LP7C and B1-LP7C wells are located on Marmarica Uplift in the north; while C1-33 well is located on the Marmarica Terrace in the south (Fig.2.24). The four wells well be carefully checked and studied using their composite logs, and the main reference for the description of the cores data is the final geological reports (TDL).

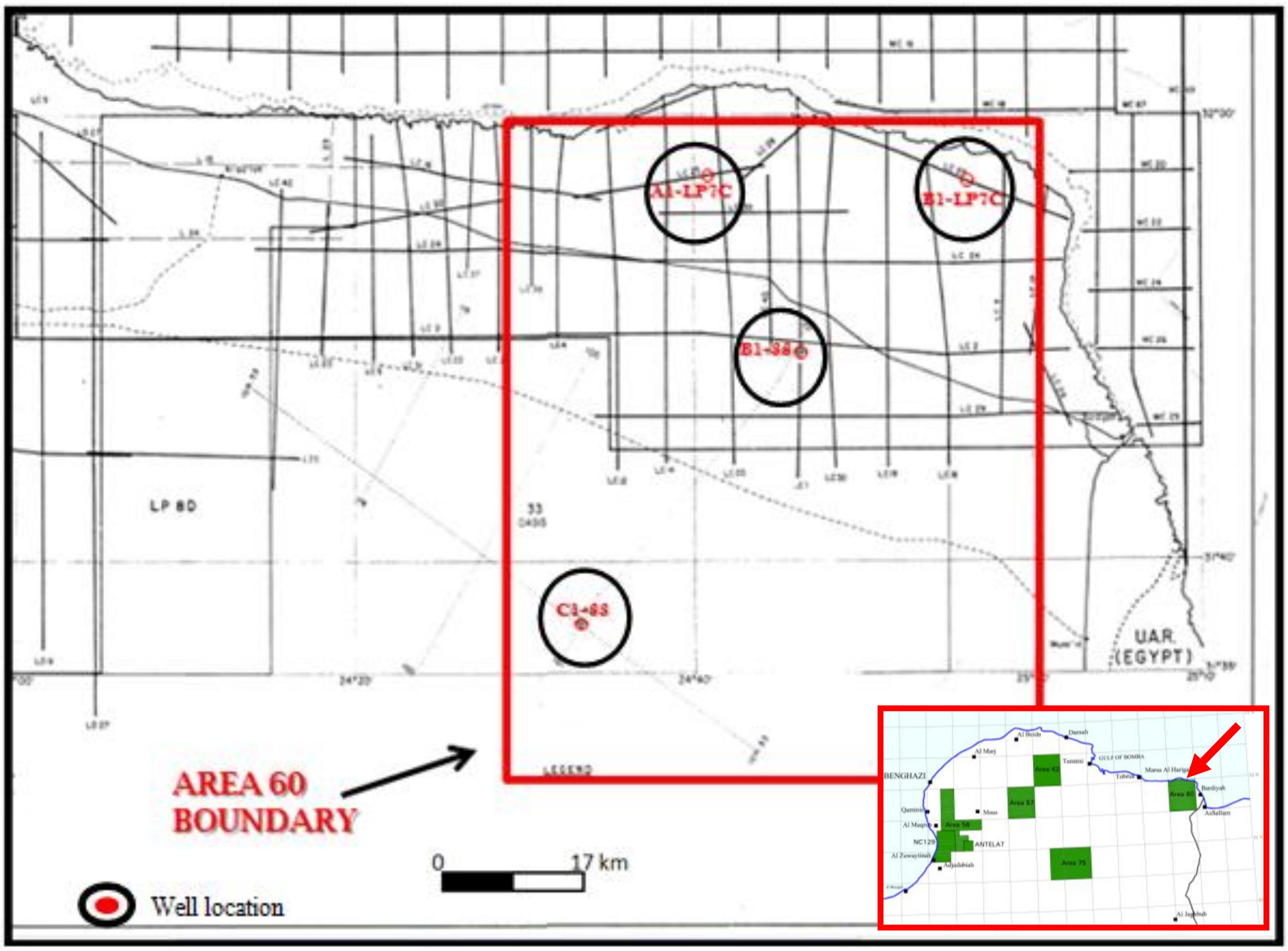


Fig . (2.24) Index map shows AGOCO Concessions of Cyrenaica region, with enlarged studied wells in area 60 seismic base map (after AGOCO,2009).

2.3.2.1 well B1-33

1-Drilling History

The B1-33 drilled by Oasis Oil Company to total depth of 13,672’, (Fig 2.25).

2-Stratigraphy

Miocene (From surface –390'): It consists of mainly limestone /dolomitic limestone, calcarenite, coarse grained, with good intergranular porosity, good-excellent moldic porosity in the dolomitic part.

Middle Eocene (390’-436') :It consists of mainly limestone, calcarenitic faceis, coarse grained, with abundant of nummulites porosity is good–very good intergranular it decreases with depth in the limestone.

Lower Eocene(792’-1040') :It consists of limestone with abundant of Nummulites fragments ,some cherts occured of this interval. Porosity is very poor to nil.

Paleocene (1040'-1134'): It consists of nummulitic limestone, with no visible porosity.

Upper Cretaceous (1134'-3550'):The uppermost part of this interval consists of continuous carbonate rocks, cryptocrystalline, occasionally to finely - medium crystalline textures with chert .Porosity is very poor to nil. The faceies changed down ward @2000' to mainly dolostone. This dolomite has fair – good moldic porosity, which by depth becomes poor.

Turonian: this section started at 2910 with limestone interbedded with shale facies, porosity is fair to good.

Cenomanian (3140'-3550'): it consists of mainly, sandstone interbedded with shales, with few limestone inter beds. The limestone is calcilutite, chalky, and tight. The sandstone beds are yielding excellent porosity of inter-intra granular types.

Albian (3550'-5850'). The interval is mainly composed of sandstone with shale interbeds. However, the limestone and dolomite intercalation are also present at the middle and lower part of the interval. The sandstone in general has good –very good porosities.

Aptian (5850'-8050'): It consists of limestone interbedded with shale down wards with rare dolostone beds locally. The carbonates facies has poor to nil porosities.

The lower part of Aptian (7200' -8050') is composed of sandstone interbedded with shale , Occurrence of highly argillaceous limestone beds.

Barremian (8050'-11580'): Started with tight limestone down to 10650' with no visible – very poor porosity .The porosity slightly improved and getting better downward.

Interval from (10650'- 10800') : dolomitic crystalline with good- excellent porosities .
(10800-11580): Oolitic limestone of shallower marine condition.

Upper Jurassic (11580'-12220'): This interval is composed mainly of limestone with few layers of Sandstone and shale interbedded .The sands and shale percentages are increasing downward.

Middle Jurassic (12220'- 12760') : It composes of dolostone and limestone with shale interbeds at the middle part.

Lower Jurassic (12760'-13672'TD): It composes of mainly limestone and sandstone interbeds with thin shale streaks. the porosity is nil.

Addaloush e.t.all (2008), studded the lithofacies and palaeoenvironment of Jurassic Sequences in NE Libya, in these wells. They concluded that the best potential for porosity within the Jurassic sequences in this area is provided by Oolitic shoals and intertidal deposits, particularly those that are dolomitized, along an E-W trending coastal belt. The carbonate porosity is mainly intercrystalline with an oomoldic component.

2.3.2.2 Well C1-33

1-Drilling History

It is drilled by Oasis Oil Company to total depth of 11,193' Fig (2.25)

2-Stratigraphy

The penetrated successions From Miocene down to Upper Cretaceous, consist of continuous carbonate facies of nummulitc Limestone with rare dolomitic intercalation.

Upper Cretaceous (2035'- 2550') :The litholgy of this part of Upper Cretaceous is similar to that in B1-33 Well. However, interval from (2550'-3852') the section changed into argillaceous limestone and dolomite with very thin intercalation of Anhydritic bed. This section is generally poor in porosity.

Cenomanian(3852'-4385'): It consists of limestone interbedded with shale facies,with calcarenitic limestone facies in the middle part displays fair porosity.

Lower Cretaceous:

Albian- Aptian: (4385'-8140') this interval consists of limestone, sandstone and shale interbeds, and occasional dolomites ,The sandstone units are generally nil-poor in porosity, but at some horizons it is fair to poor.

Triassic - Jurassic: (8490'-10150'): The Jurassic section from top to bottom consist of sandstone and shale interbeds. The upper part of Jurassic down to 8960' containing thin streaks of coal, which was not detected in B1-33 Well to the north. The sandstones of Jurassic in the upper part yield poor porosities, but in the lower part of Triassic exhibit good porosity with local unconsolidated sand–to friable sandstone.

Paleozoic:

Permian: (10150'-10265') The Permian section consists mainly of sandstone interbedded with thin shale .The sandstone at the upper part has fair – good inter-granular porosities.

Permo-Carboniferous (10265'-11193' TD): the section consist of dolomite, limestone with Shale interbeds.

2.3.2.3 Well A1-LP7C

1-Drilling History

This well was drilled in the early 1970s .It is drilled in 1971 in NOC/SE (L) L Joint venture block LP-7C in NE Cyrenaica, Libya. It was drilled by Shell Exploration to a total depth of 12,025 ft. Fig (2.25).

2-Stratigraphy.

Lower – Middle Miocene: Miocene consists of dolomitic limestone with good vuggy Porosities.

Upper Cretaceous:

Early Campanian –Maastrichian is missing in this well, however the interval (350 - 1420') of **Cenomanian- Early Campanian** consists of dolomite at the upper part with poor porosity and is changed to dolomitic limestone- sandy with depth and good reservoir rocks. Cenomanian has a good intra-sequence sealing system at the interval 1420'– 2270' of **Albian–Cenomanian**. This sequence consists of good to excellent porosities preserved in sandy oolitic lime grainstone facies. The porosities are well connected.

Lower Cretaceous:

(Aptian – Middle Albian) from 2270' to 5200' This interval consists of Shale interbedded with Limestone .The Limestone is Poor –fair porosity.

(Barremian–Lower Aptian) from 5200'to 8839'.it made of shale ,limestone and sandstone section. Both limestone and sandstone have poor porosity.

(Lower Berriasian–Lower Barremian) from 8839'to10680'It consists of mainly limestone grainstone-packstone texture intercalated with fine –coarse grained sandstone, and local organic rich shale streaks within limestone.

Middle- Upper Jurassic:

(Callovian – Lower Berriasian) From 10680' to12000'.This interval consists of medium – coarsely crystalline dolostone with exhibiting poor – very poor porosity.

2.3.2.4 Well B1-LP7C

1-Drilling History

This well was drilled in the early 1970s ,It is drilled in1972 in NOC/SE (L) L Joint venture block LP-7C in NE Cyrenaica, Libya .It is drilled by Shell Exploration to a total depth of 10, 056 ft.

2-Stratigraphy.

Tertiary: Only **Paleocene –Early Eocene** sections is present 0 -1290'with no description due to no available sample.

Upper Cretaceous :

(Lower Campanian – Santonian) :1290'-2030'.This interval consists of limestone, oolitic, grianstone becoming dolomitic in the upper part ,the porosity is good to fair.

(Middle Albian – Cenomanian): 2030'-3855'.This interval consists of sandstone with fair porosity .

Lower Cretaceous :

(Aptian – Middle Albian) 3855' –7810'.This interval consists of limestone intercalated with Sandstone. The sandstone and limestone are yielded good porous sections.

(Lower Berriasian –Lower Barremian) from 7810' to 9025' This interval consists of Limestone intercalated with Sandstone. Both yielded poor porosity.

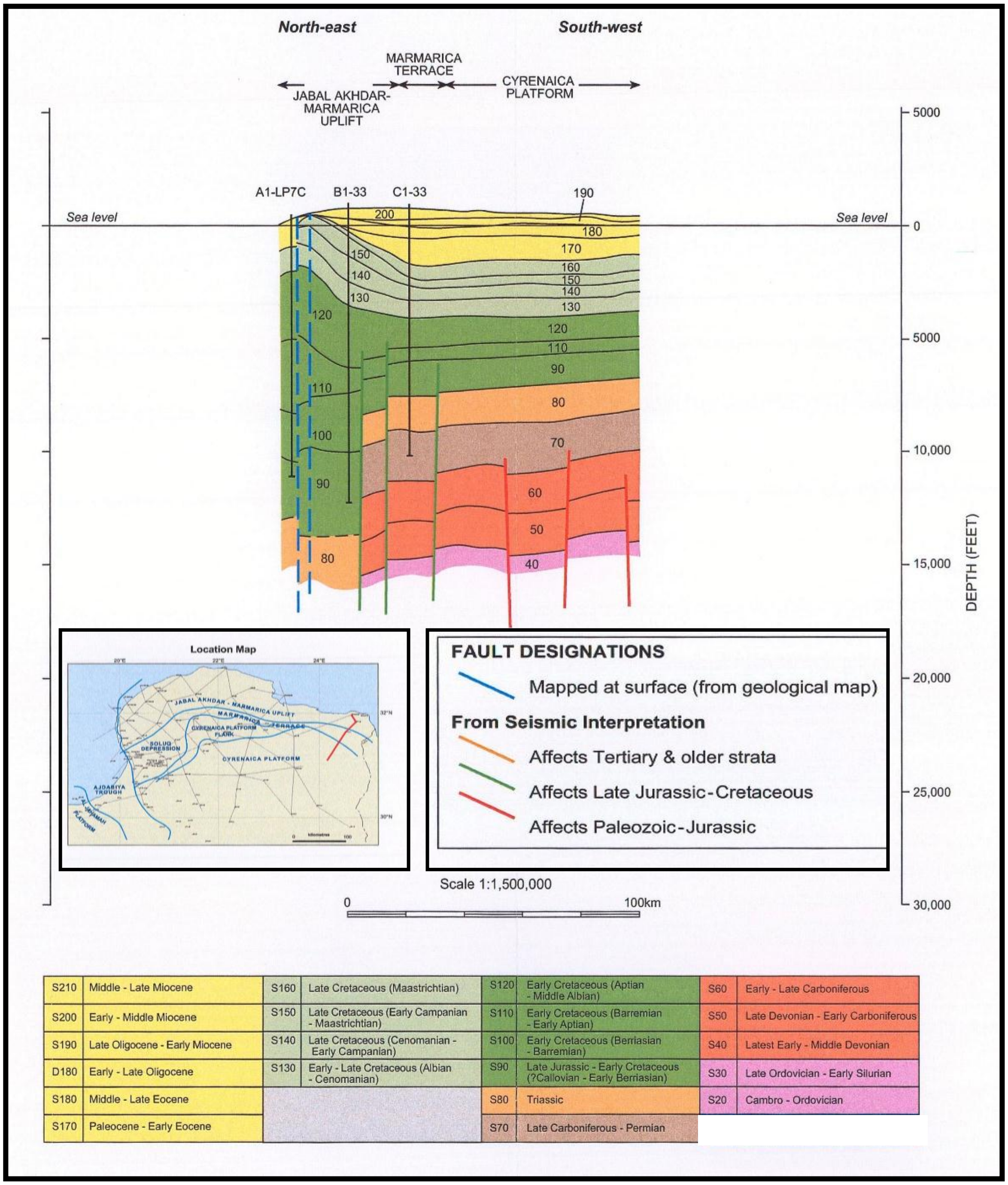


Fig. (2.25) Structural correlation between wells A1-LP7C, B1-33and C1-33. In corner of NE Libya (as indicated by red line on the location map) after ECL,2004.

Also many Stratigraphic units are repeated within each well with normal thickness variations result from regional changes in depositional patterns. First I try to make well tops starting from upper part and then to the basal part of the well tops (Table. 2.1) and correlate the logs with each other.

The chronostratigraphic correlation (Fig. 2.26) in this study is made by petrel software based upon the stratigraphic information data obtained from selected exploration boreholes to illustrate the stratigraphic relation-ships in terms of change in lithofacies, thickness variation, continuity (lateral). On the correlation only the well C1-33 record a complete sequence start at the base with Paleozoic section that represented by brown color and finishing up with Tertiary Miocene sequences at the top.

Table 2.1 Shows the well tops data and measuring depth (MD) of the four wells.

	Well identifier	Surface	X	Y	Z	MD
11	A1-LP7C	Miocene	1631000.01	675000.00	308.00	0.00
2	A1-LP7C	CAMPANIAN AL MA	1631000.01	675000.00	-42.00	350.00
31	A1-LP7C	(U.Cretaceous	1631000.01	675000.00	-42.00	350.00
36	A1-LP7C	Early Cretaceous	1631000.01	675000.00	-1098.00	1406.00
15	A1-LP7C	Albian - Cenomani	1631000.01	675000.00	-1098.00	1406.00
25	A1-LP7C	APTIAN	1631000.01	675000.00	-1962.00	2270.00
3	A1-LP7C	Barremian-Aptian	1631000.01	675000.00	-4892.00	5200.00
4	A1-LP7C	Berriasian- Barrem	1631000.01	675000.00	-8531.00	8839.00
19	A1-LP7C	Middle - L. Jurassi	1631000.01	675000.00	-10372.00	10680.00
23	A1-LP7C	TD	1631000.01	675000.00	-11717.00	12025.00
10	B1-33	Miocene	1640000.01	660000.00	677.00	0.00
1	B1-33	Late Eocene	1640000.01	660000.00	287.00	390.00
12	B1-33	PALEOCENE	1640000.01	660000.00	-307.00	984.00
13	B1-33	(U.Cretaceous	1640000.01	660000.00	-457.00	1134.00
30	B1-33	Turonian	1640000.01	660000.00	-2233.00	2910.00
37	B1-33	Early Cretaceous	1640000.01	660000.00	-2463.00	3140.00
8	B1-33	Albian - Cenomani	1640000.01	660000.00	-2463.00	3140.00
29	B1-33	Barremian-Aptian	1640000.01	660000.00	-5173.00	5850.00
18	B1-33	Middle - L. Jurassi	1640000.01	660000.00	-10903.00	11580.00
27	B1-33	TD	1640000.01	660000.00	-12995.00	13672.00
28	B1-LP7C	PALEOCENE	1653000.01	677000.00	43.00	0.00
14	B1-LP7C	CAMPANIAN AL MA	1653000.01	677000.00	-1247.00	1290.00
32	B1-LP7C	(U.Cretaceous	1653000.01	677000.00	-1247.00	1290.00
38	B1-LP7C	Early Cretaceous	1653000.01	677000.00	-1987.00	2030.00
5	B1-LP7C	Albian - Cenomani	1653000.01	677000.00	-1987.00	2030.00
6	B1-LP7C	APTIAN	1653000.01	677000.00	-3812.00	3855.00
7	B1-LP7C	Berriasian- Barrem	1653000.01	677000.00	-8982.00	9025.00
20	B1-LP7C	TD	1653000.01	677000.00	-10013.00	10056.00
21	C1-33	Miocene	1621000.01	638000.00	674.00	0.00
33	C1-33	Late Eocene	1621000.01	638000.00	189.00	485.00
34	C1-33	PALEOCENE	1621000.01	638000.00	-226.00	900.00
22	C1-33	(U.Cretaceous	1621000.01	638000.00	-1361.00	2035.00
35	C1-33	Turonian	1621000.01	638000.00	-1876.00	2550.00
39	C1-33	Early Cretaceous	1621000.01	638000.00	-3178.00	3852.00
9	C1-33	Albian - Cenomani	1621000.01	638000.00	-3178.00	3852.00
26	C1-33	APTIAN	1621000.01	638000.00	-7466.00	8140.00
17	C1-33	Traissic -Jurassic	1621000.01	638000.00	-7816.00	8490.00
16	C1-33	PERMIAN	1621000.01	638000.00	-9481.00	10155.00
40	C1-33	Permo-Carbonifer	1621000.01	638000.00	-9581.00	10255.00
24	C1-33	TD	1621000.01	638000.00	-10519.00	11193.00

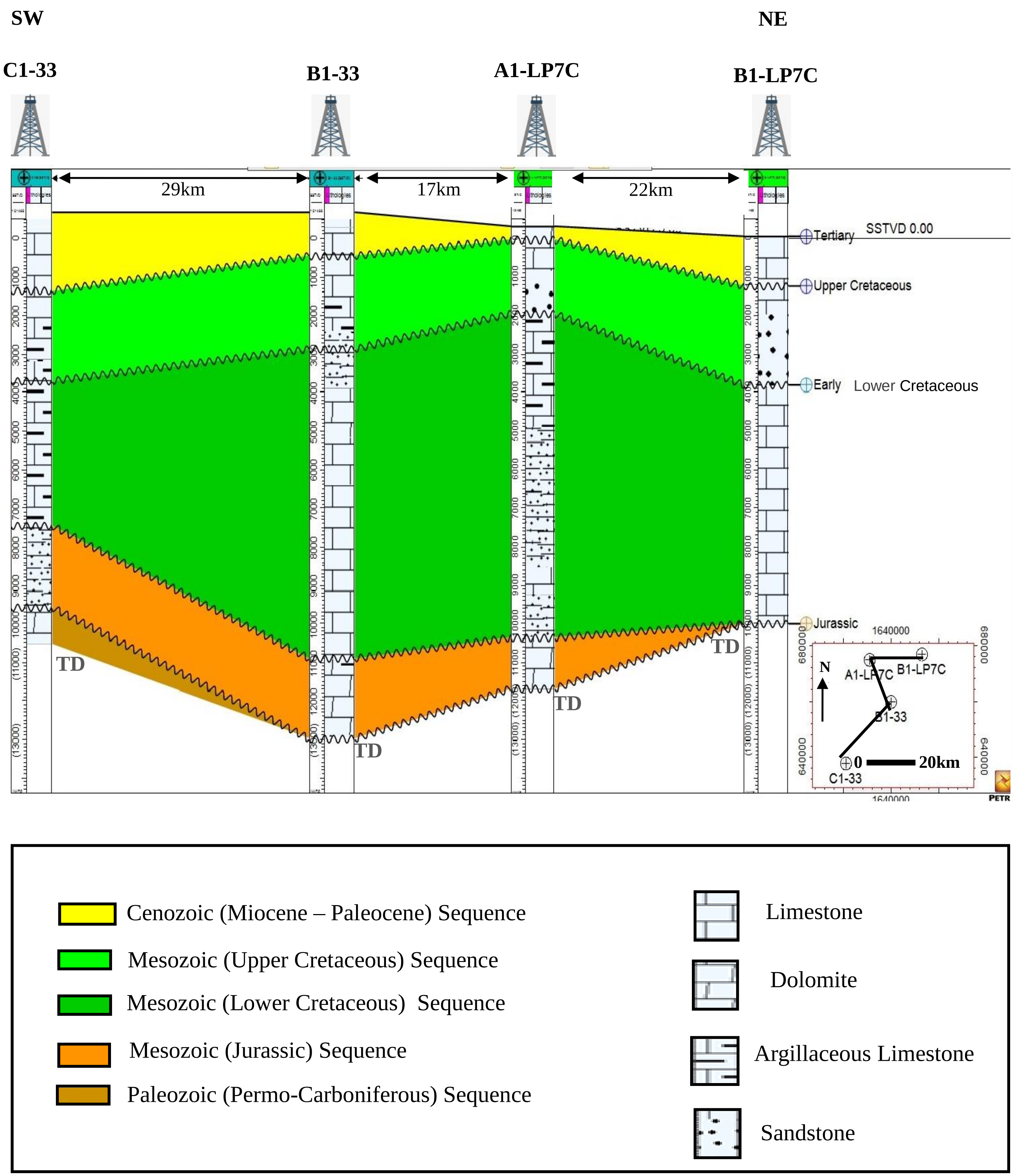


Fig. (2.26) Chronostratigraphic Correlation with lithostratigraphy of the penetrated sedimentary sequences of the four wells ; the datum is mean sea level.

Chapter Three
Structural Setting And Analysis

3.1 Introduction

Al Jabal al Akhdar -Marmarica uplift was a part of the northern African-Arabian active margin that had been evolved following the opening of the Neotethys. Age-dating assigned for the Tethyian oceanic crust suggests that this opening was during Jurrasic-Early Cretaceous (Laubscher and Berbouli 1977, Biju-Duval et al 1979, Dercourt et al 1986, Robertson and Dixon 1984, and Klitzsch 1986).Triassic marine sediments recorded eastward in northern Egypt explained an earlier opening of the Neotethys (Hanter 1990) Accordingly, the activity in the African-Arabian margin is attributed to the Alpine movement in which Africa has been moved westwards relative to Eurasia in Late Cretaceous - Late Eocene times (Smith 1971, Fairhead and Green 1989). Marmarica uplift involves the study area and extends probably, eastwards, beyond the Libyan border into the northern part of Western Desert of Egypt (Fig.3.1). It is characterized by thick upper Jurassic/lower Cretaceous syn-rift sediments of the North Cyrenaica Rift, which were deformed and uplifted during the Late Cretaceous/Early Tertiary (i.e. Syrian Arc Orogeny; (El-Arnauti et.al. 2008).

From the structural point of view, Röhlich (1974 and 1980) considered initially the central part of Al Jabal Al Akhdar as main Upper Cretaceous rocks exposed in the ENE-WSW trending brachyanticlinal cores of Jardas Al Ahrar and Majahir inliers and flanked by extensive exposures of Tertiary sediments. He added these inliers are bounded with ENE-WSW oriented down-faulting zones and developed through three structural stages thus forming a large ENE-WSW complex arch emerged, as an island, the central part of which was deeply eroded. According to him, the climax event of ENE-WSW folding was in intra-Senonian (Santonian). Despite this, a contradictory is taken on Röhlich arguments where all fault trends (Faults that parallel or make acute angles with the main Santonian folding axes, in particular) are considered normal faults and, consequently, their analysis with the folds is kinematically away from the basic concepts of shears or Alpine tectonic regime.

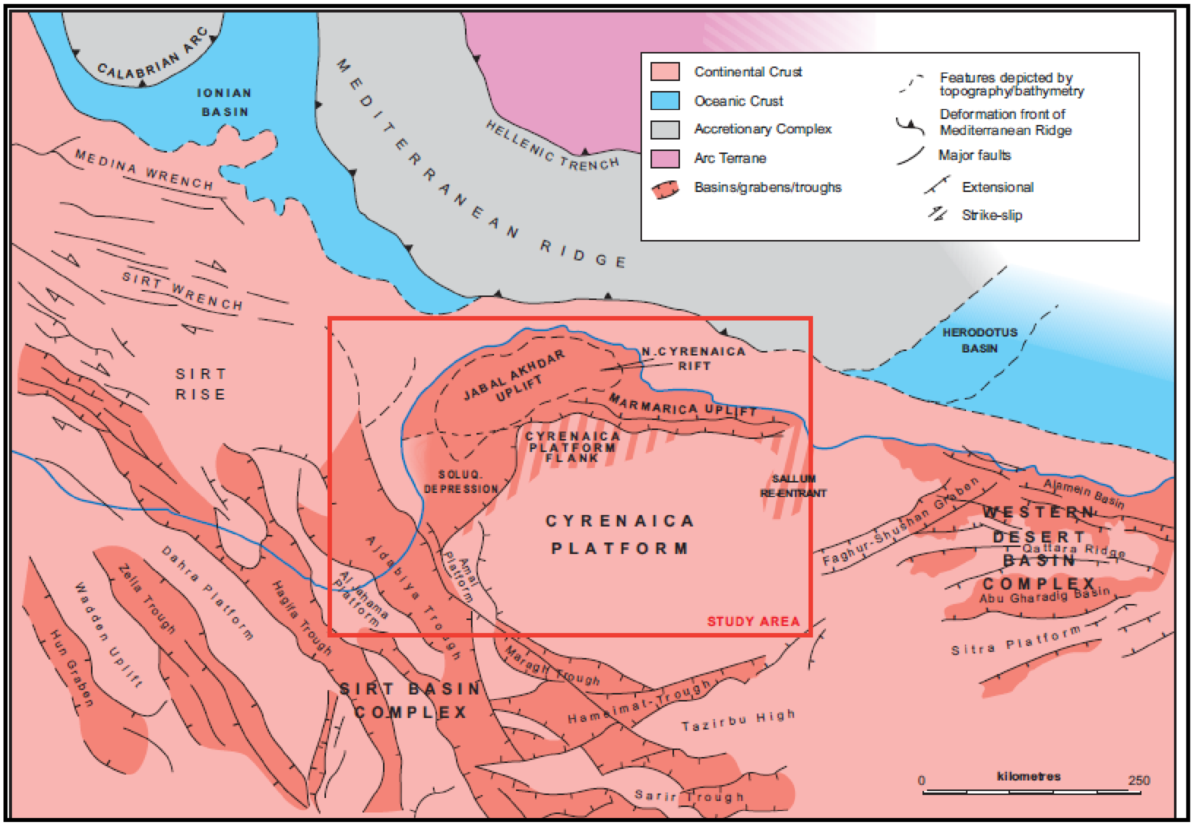


Fig. (3.1) Tectonic elements of the north east Libya (after Ecl,2004)

The present study involves the structural setting in the eastern part of Al Jabal Al Akhdar-Marmarica uplift with more detailed on the structural characteristics and analysis of Al Burdia area. Herein, the field measurements are taken as the dip amounts and directions changes within each formation to follow the sequence of different structural levels, deformational phases and unconformities.

In general, the dip of beds in Late Cretaceous and Tertiary attains an average (10-20^{o}) but sometimes become steep and overturned (50-70^{0} SW direction) especially in Early Oligocene bed rocks (Fig. 3.2).

3.2 Structural characteristics and Division

This section begins with a description of structural style observed in outcrop then proceeds to describe a series of cross sections and accompanying seismic lines. Explanation of geometrical constraints and important features are given in the following:

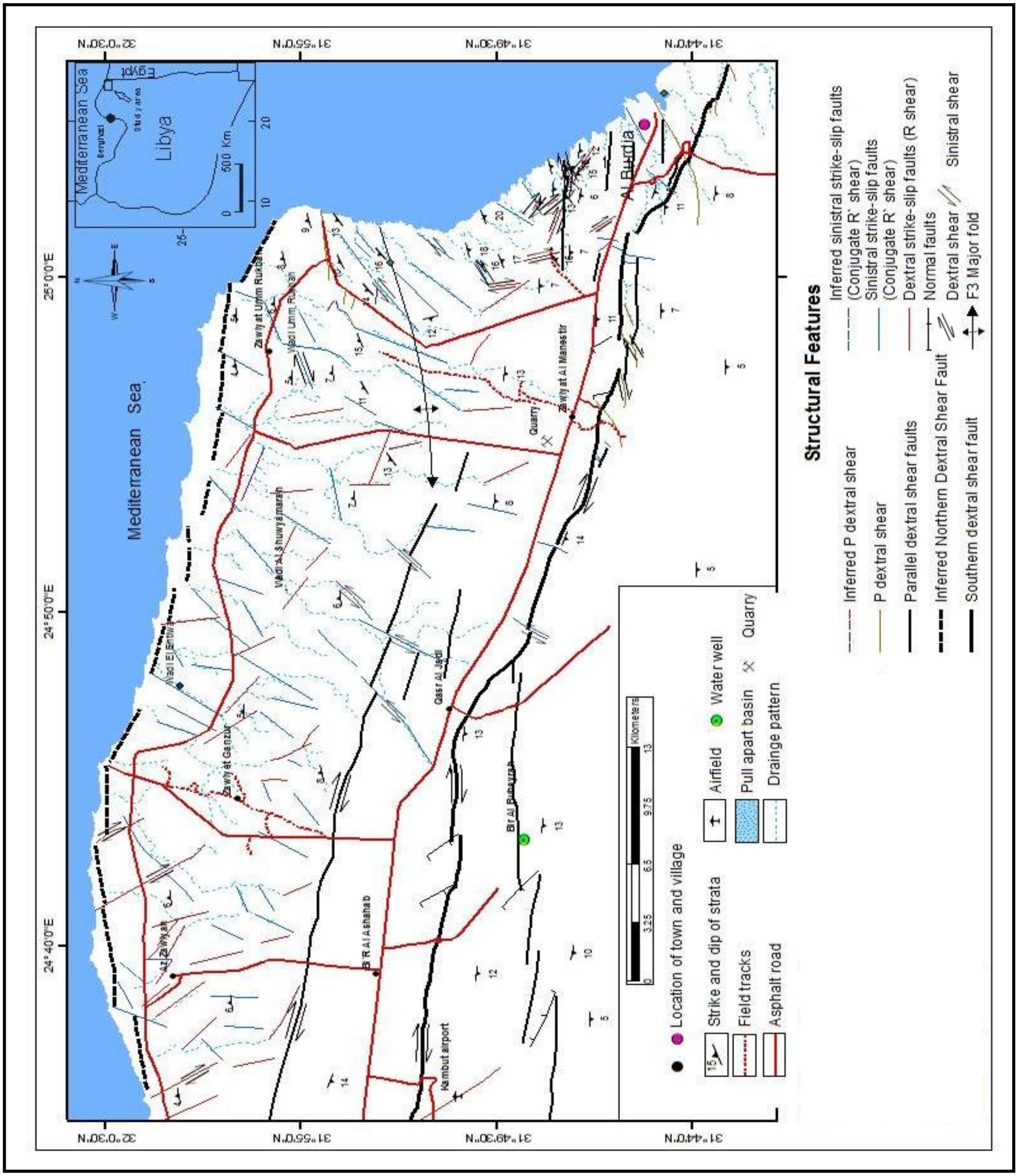


Fig. (3.2) Structural map of the study area.

3.2.1 Folds

Folds result from compressional stress and are either broad flexures (bending) in which rock units are hundreds of meters thick have been slightly warped (Van der Pluijm, 2004).

On the outcrops, folds are very rare in Late Cretaceous but markedly shown in Oligocene and Miocene beds. They range from centimeters to km scales. On the basis of intensity and styles of folding during the sequence of tectonic events, the folds of the present area are classified into three phases of folding (F_1, F_2, and F_3).

F_3 fold is a major and seen on the structural map (Fig. 3.2), while the other two phases of folding (F_1 and F_2) have minor scale and are plotted in the detailed geological map of Wadi Al Raheb affecting Al Majahir, Al Bayda and Al Abraq formations (Fig. 3.3).

F_1 phase of folding is the oldest and affects Al Majahir and Al Bayda formations (Figs. 3.3). The fold is recognized as overturned anticline oriented approximately ENE-WSW. Its axis extends for about 2km and is plunged gently WSW (Fig. 3.4). Along the northwestern limb of the fold, Al Majahir and overlying Al Bayda sediments are displaced eastwards in a sense of dextral movement along E-W strike-slip fault. On this limb, amount of dips are gentle to moderate (10^o-20^o), which are coupled with steeper ones (50^o-70^o) on the opposite limb leading to overturning and vergency of the fold in the SSE direction. Most probably, the SSE overturning and displacement by the E-W fault resulted in exposing the Late Cretaceous Majahir Formation along the northwestern limb, which is missing in the core and southeastern limb of this fold (Fig. 3.4). In the southeastern part of F_1 fold, algal limestone facies occupies the core of the overturned part then followed upward with well-bedded limestone facies of Al Bayda Formation, which is displaced sinisterly by a NE-SW strike-slip fault (Fig. 3.3).

On the stereonet plots, the field measurements in the northwestern limb showed the value of $\beta 1$ gives a general dipping 30^o N32^oW and $\beta 2$ in the southeastern limb attains dipping 46^o S15^oE. The intersection of $\beta 1$ and $\beta 2$ plots exhibits plunging S65^oW / 7^o (Fig. 3.4b). Close to the closure of the fold, the southeastern limb becomes vertical and overturned where the older dolomitic limestone facies are ridding obliquely in the opposite side under the younger well-bedded limestone facies of Al Bayda Formation.

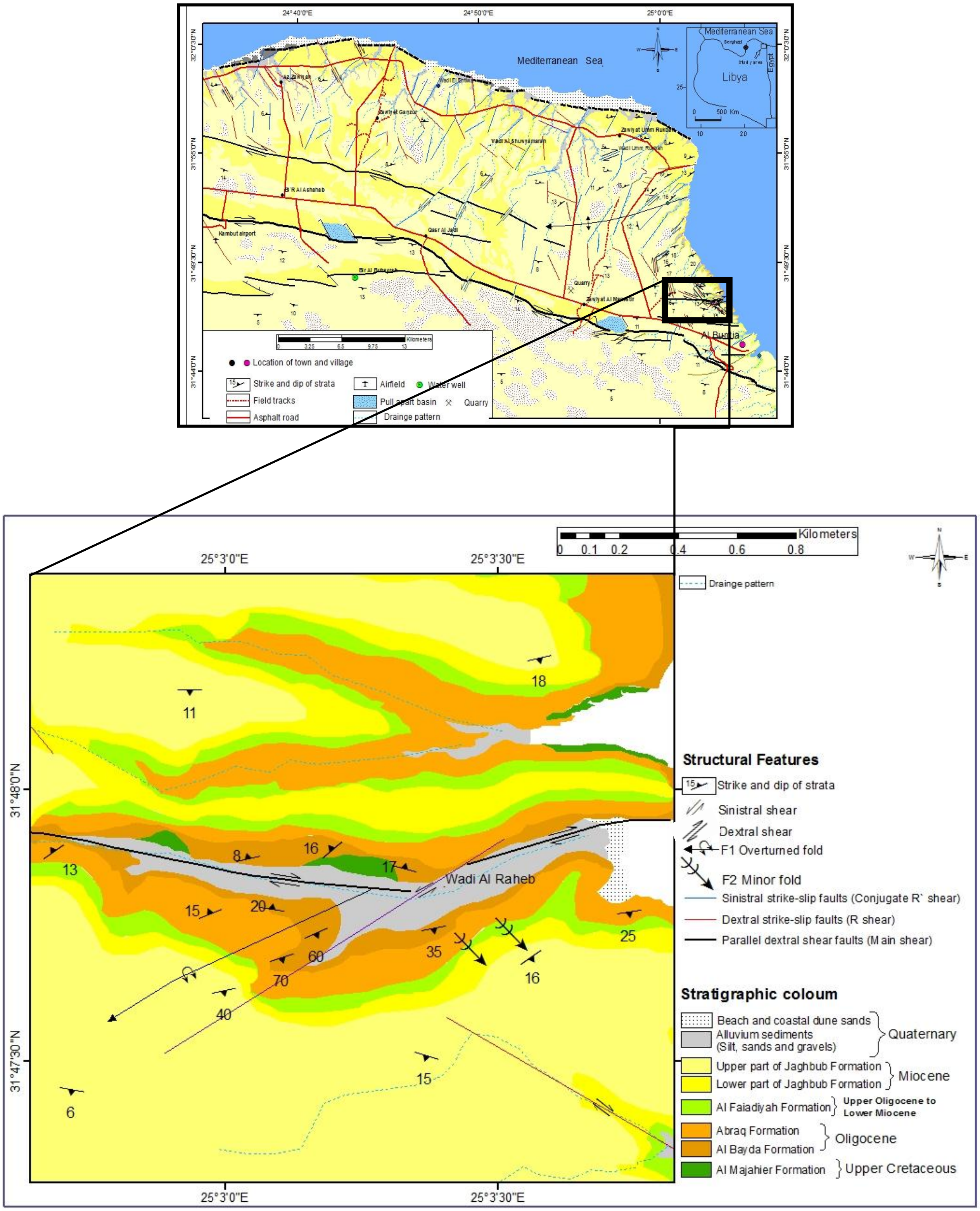
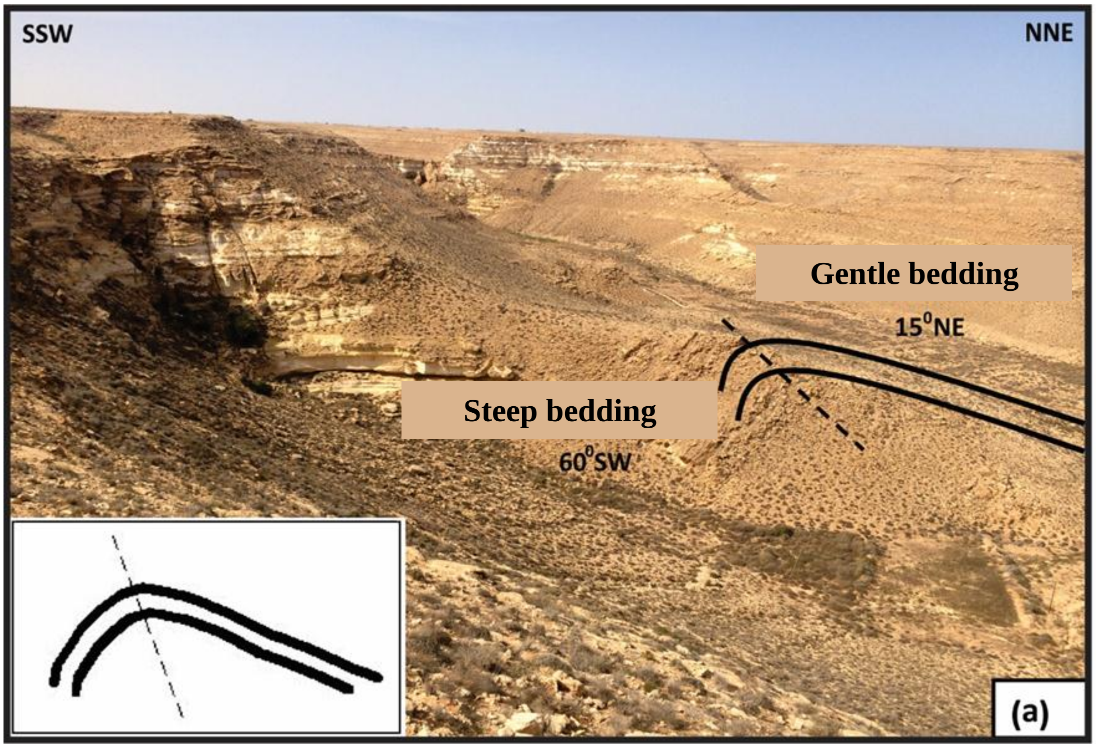


Fig. (3.3) Detailed geological map of Wadi Al Raheb showing the development of F_1 and F_2 minor folds in Al Majahir, Al Bayda and Al Abraq formations.



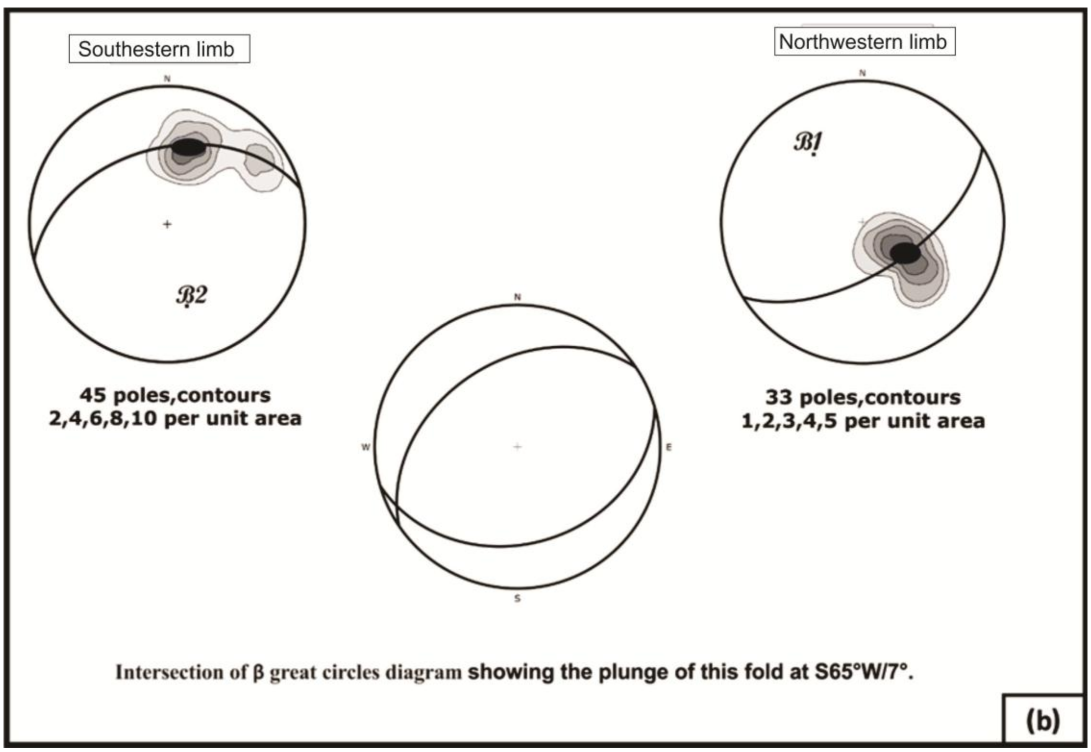
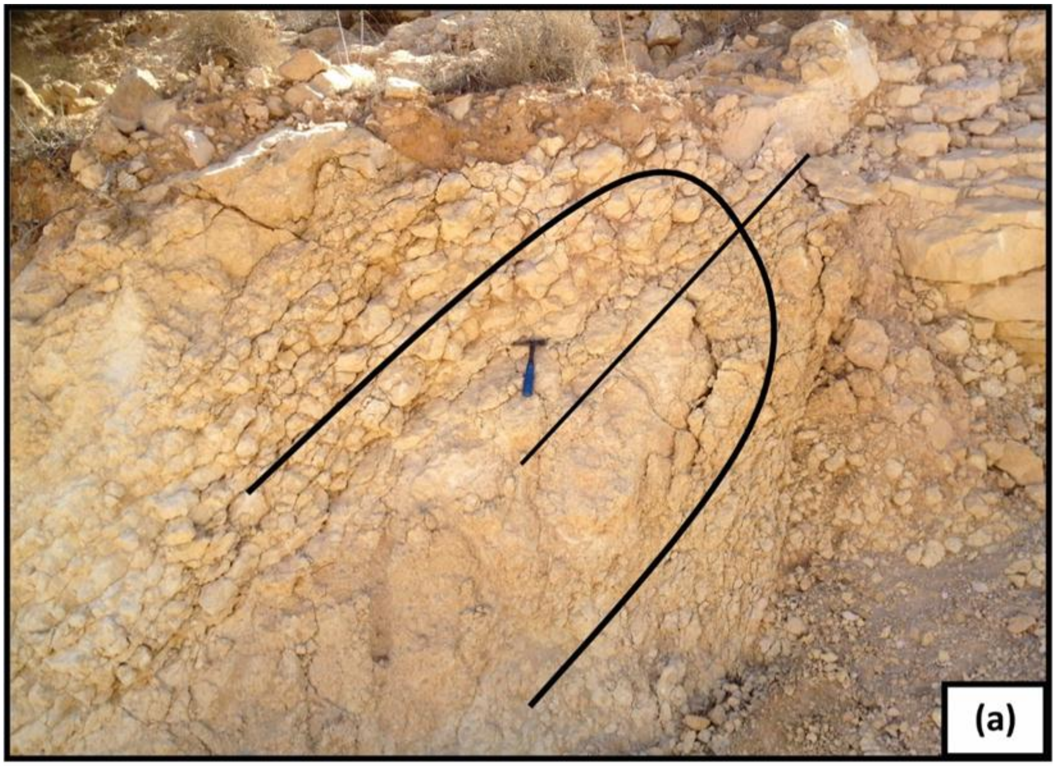


Fig. (3.4) (a) General view showing F_1 overturned plunging anticline fold in Wadi Al Raheb; Photo looking NE. (b) Equal area lower hemisphere projection of the field measurements.

F_2 folds are developed at a minor scale on the southern flank of Wadi Al Raheb affecting marly and glauconitic limestone beds of Al Faidiyah Formation (Figs. 3.3 and 3.5-3.6). These folds are striking NE-SW with a vergence towards the SSE direction. Their styles are tight, overturned, open and asymmetric (Figs. 3.5a and 3.6a).

On the stereonet diagrams, the field measurements on the northeastern limb showed that β_1 determined from the poles of beddings attains plunging 32^o on a bearing $N40^oE$, whereas the measurements along the southwestern shows plunging of β_2 at 64^o and a bearing $S27^oW$. The intersection of β_1 and β_2 plots exhibits plunging $S55^oE$ / 8^o (Fig. 3.5b). Elsewhere, other systems of F_2 folds are open to asymmetric and trending ENE-WSW and present in Al Faidiyah Formation of Wadi Al Raheb (Fig. 3.6a). On plots, the field measurements in the northeastern limb showed the value of β_1 gives a general dipping 34^o / $N25^oE$, while on the southwestern limb β_2 gives plunging 69^o / $S48^oW$. The intersection of β_1 and β_2 plots exhibits plunging $N42^oW$ / 12^o (Fig. 3.6b).

F_3 phase of folding is a major and affects in the overlying Oligocene and Miocene formations representing the final phase of folding and plunges in the SW. It is ended by the present morphology of gentle and elongated folding during Oligocene to Miocene ages. This means that Al Burdia area is kinematically evolved during successive structural substages initiated by overturned and tight folding in Upper Cretaceous to Oligocene, then open in late Oligocene - Early Miocene and gentle folding in the Middle Miocene. In other words, F_1 to F_3 folds represent sequence phases of folding generations within and before outlining the final shape of Al Burdia area. Moreover, the approximate alignment of the folding orientation from F_1, F_2 to F_3 precludes a continuous and perpendicular principle stress (i.e. acted roughly along NNW-SSE). The dip directions on the flanks of F_3 fold are seen on the map inside the northwestern and southeastern parts are cored by low lying Miocene rock units that extend underlying the Quaternary from Zawiyt umm Rukbah in the north to Zawiyt al Manestir in the south (Figs. 2.1 and 3.2).



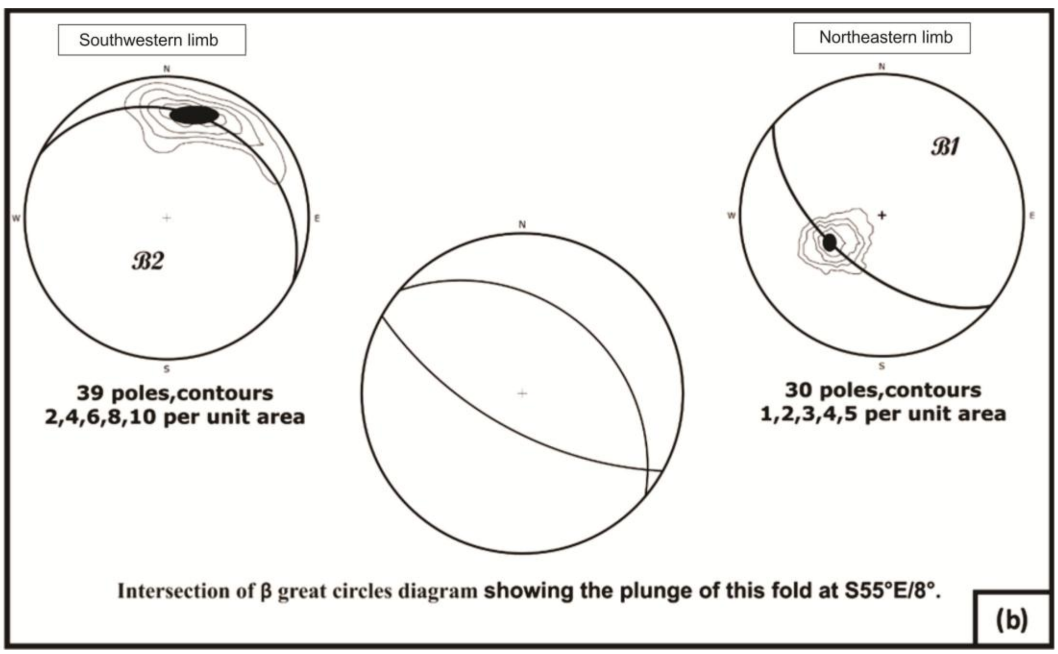


Fig (3.5) (a) F_2 tight overturned fold in Al Faidiyah Formation in Wadi Al Raheb; Photo looking NE. (b) Equal area lower hemisphere projection of the field measurements.

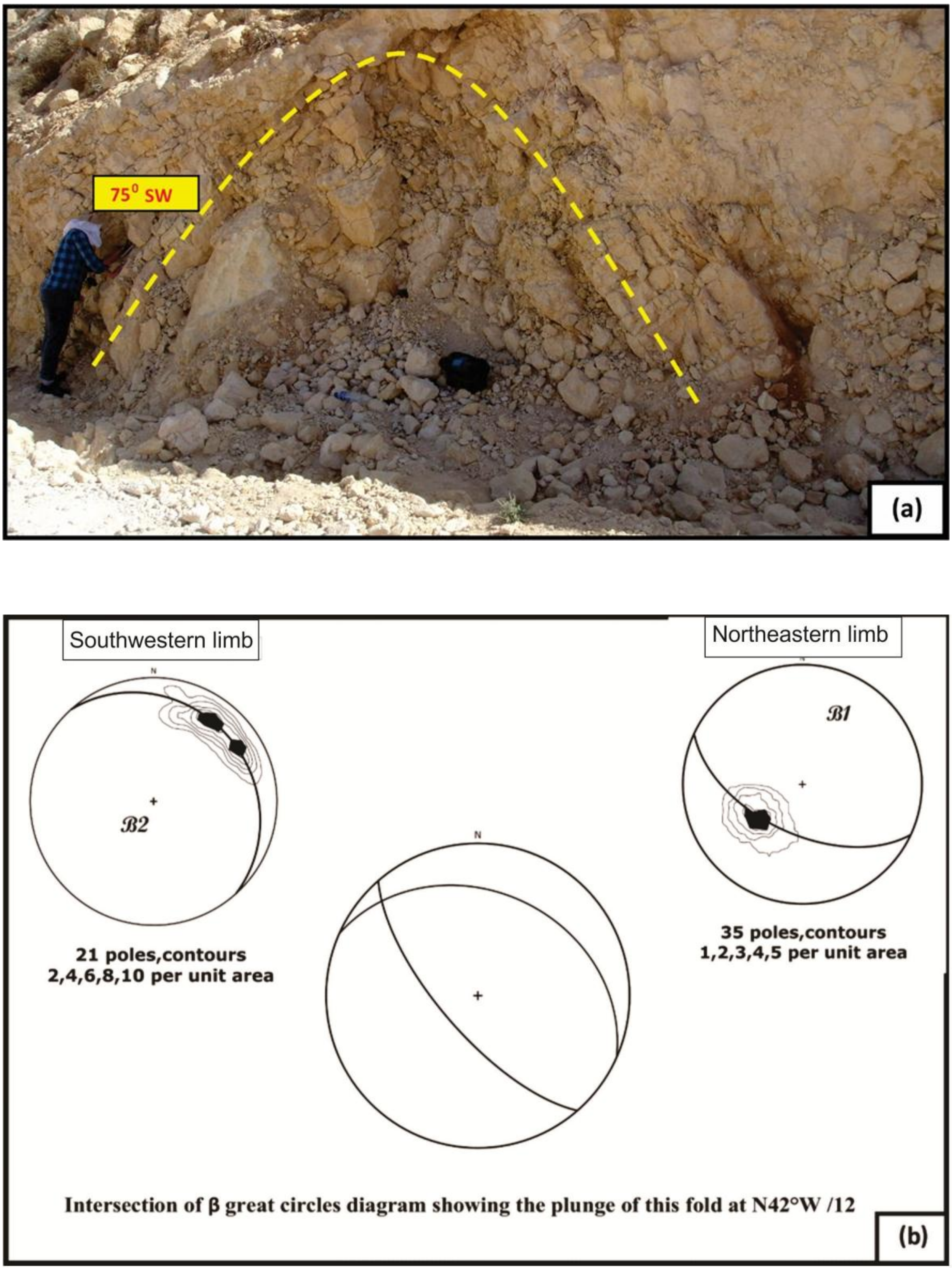


Fig. (3.6) a. F_2 Open asymmetric fold in Al Faidiyah Formation of Wadi Al Raheb; Photo looking NE. (b) Equal area lower hemisphere projection of the field measurements.

3.2.2 Faults

Faults represent the most prominent geological features in the study area. The major faults systems were defined very clearly based on the satellite image and field observations. Most of the lineaments measured on remote sensing imagery are linear segments of stream valleys or other geomorphological alignments. These alignments are assumed to have formed as a result of differential erosion along lines of weakness (fracture zones) in the crust and produced by numerous tectonic episodes. Figures (3.2 and 3.7) show the distribution and strike of the abundant faults.

Al Burdia area represents about 20km wide of E-W to WNW-ESE dextral displacement zone. This structure is confined by distinguished pair of major E-W to WNW-ESE inferred and confirmed dextral shear faults in the north and south. Both faults are dissected by NNW-SSE normal faults and other secondary arrays of N-S to NNE-SSW, NW-SE sinistral and dextral strike-slip faults, which are linked with the major shear faults forming intricate structural pattern. In comparison, these trends reflect an intimate relationship with the trend of joints. Kinematic indicators along these faults are documented in the field on the slickensides, flower structures, small scale of dextral and sinistral displacement, and pop up structures. In the following is the description and characteristics of the main fault trends and secondary faults.

3.2.2.1 Northern Dextral Shear Fault (NDSF)

The NDSF is a major inferred E-W to WNW-ESE fault trend that delimits the northern boundary of the study area and exhibits a sense of dextral shear and well-demonstrated at a moderate relief (elevation up to 110m). It defines the northern boundary of Marmarica uplift and its strike swings along N70^{o}E to N85^{o}E and sometimes N75^o–85^{o}W. This fault boundary extends for about 50 km and terminates west of Wadi Umm Rukbah (Figs. 3.1 and 3.2).

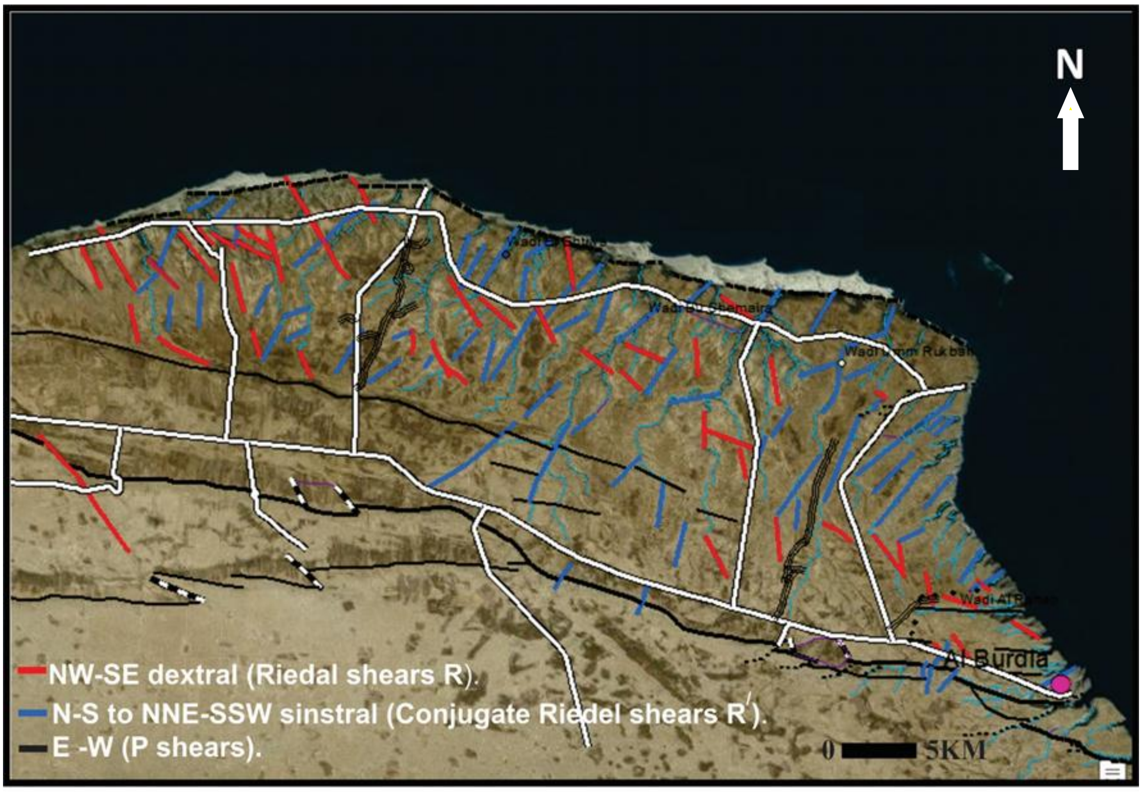


Fig. (3.7) Satellite imagery showing a combination of the N-S to NNE-SSW , NW-SE and E-W trending of strike slip faults of the study area .

Fig. (3.8) Shows one of the approximately E-W dextral strike-slip fault in the northern part of Al Burdia area; (looking NW).

3.2.2.2 Southern Dextral Shear Fault (SDSF)

The SDSF defines the southern boundary of the displacement deformation zone and runs along the WNW-ESE trend. It cuts across Al Jaghbub Formation in the south at elevation 110m. In this locality, Al Jaghbub Formation exhibits the association of well-developed NNW-SSE normal faults and pull apart basins that are associated with tensional joints and well-developed shear joints (Figs.3.2). On the outcrops, small eroded scarps along this fault can be recognized. Therewith, fault scarps are replaced by fault- line scarps and are located along or near the trace of a fault. Topographically, they are marked by a high to moderate relief that reflects differential resistance to erosion of the rocks at the contact of the fault (Georgy and Stephen1996).

The dip of the plane of the present shear fault ranges between 75^o and 80^o towards the north and north northeast. The movement along this shear fault is dextral and characterized with restraining parts (dominated by compression) in the southwest and releasing parts (dominated by tension or at least relaxation of the strata) in the south to southeast. Admittedly, the restraining motion is characterized by ridges or small scaled-high land, while the releasing motion emphasizes local depression or sag ponds (temporary and permanent lakes) to rhombo-shaped pull-apart basins (Fig 3.9) similar as shown by Dewey et al. 1998, McClay and Bonora 2001, Holdsworth et al. 2002 and El Amawy et al. 2010).

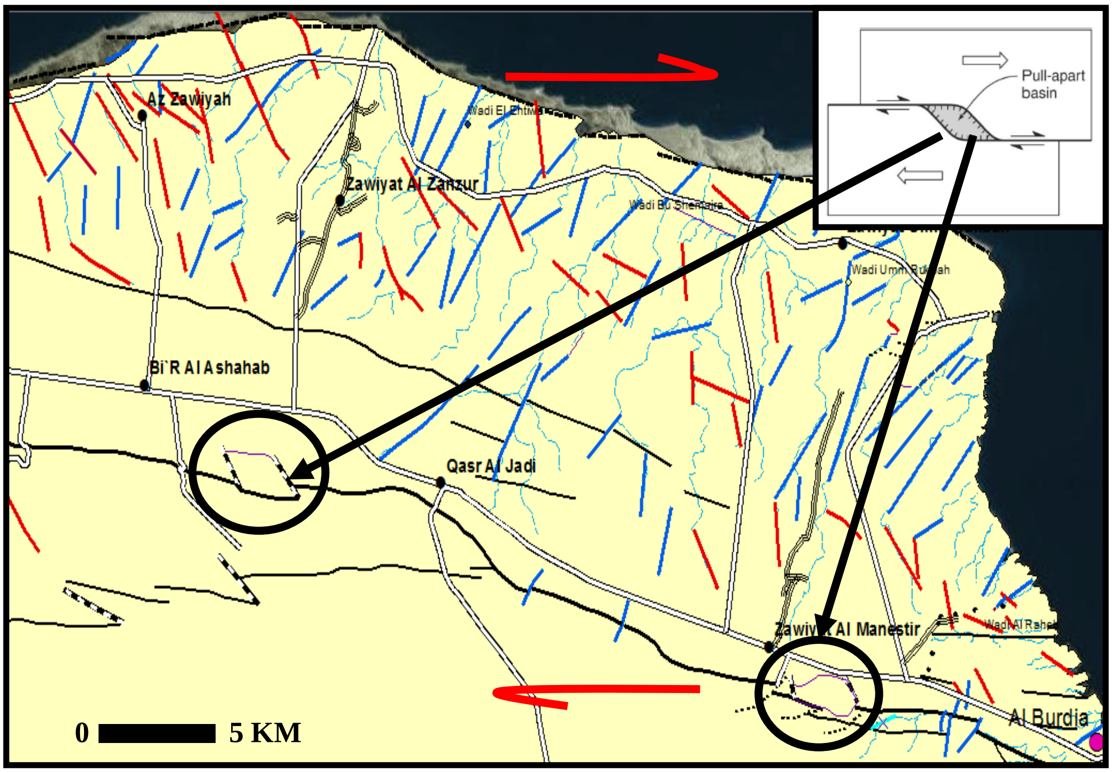


Fig. (3.9) showing the development of the rhombo-shaped pull apart basins along the southern major shear fault.

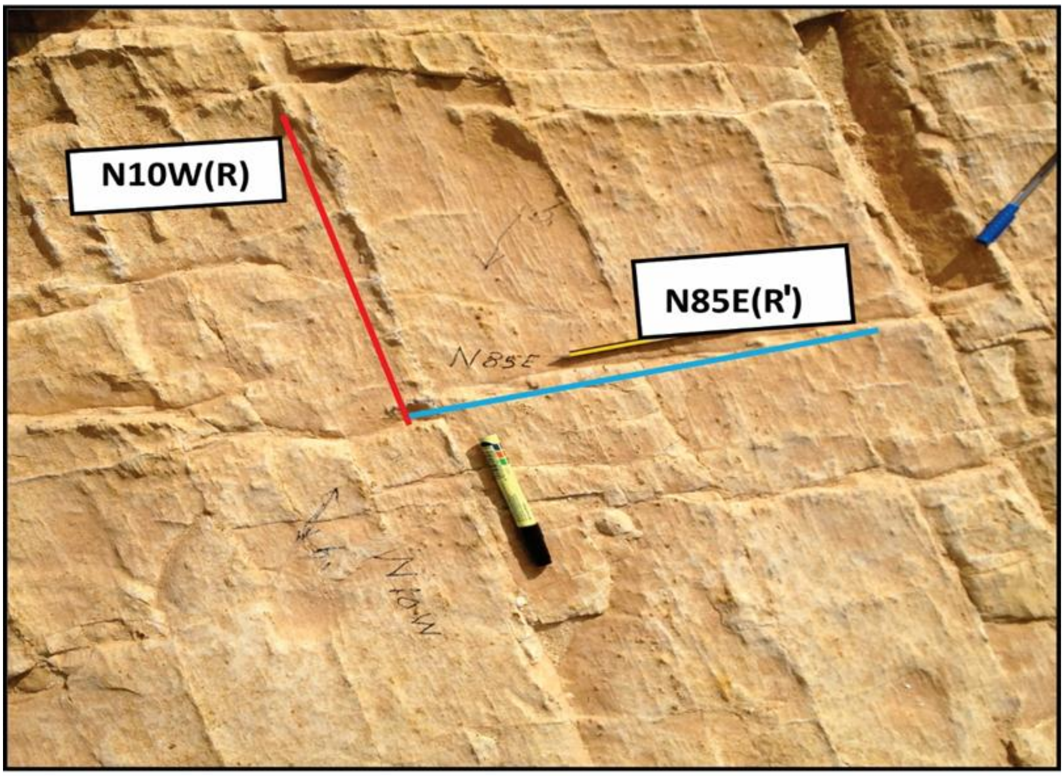


Fig. (3.10) Shows the intersection between two sets of shear joints (i.e. equivalent to the Riedel (R) and conjugate Riedel (R`) shears) in Al Majahir Formation at Wadi Al Rahib; (looking NW).

The secondary category of faults extends at meters to km scales and is developed due to the movement along the major faults and elsewhere dislocates them as in the following:

3.2.2.3 N- S to NNE-SSW strike-slip fault trends

This fault category represents the most trend in the study area and is distinctive in the center and cover all parts of the study area. They can be interpreted as pattern of conjugate Riedel shears (R̀)according to the classical simple-shear models (e.g. Tchalenko 1970). The conjugate Riedel shears or R' shears, are antithetic shear fractures that are oriented at high angles to the fault (roughly 70° to 80°) and have a shear sense opposite to that of the main fault (Twiss and Moores 2007); (Fig. 3.10). In Table (3.1) the strike of this category is aligned between N15-25E and the dip ranges between 75^o and 80^o towards the west and north northwest. These faults are cutting across Al Majahir, Al Bayda, Al Abraq, Al Faidiayh and Al Jaghbub formations (Figs. 2.1 and 3.2). On the outcrops, small eroded scarps along this fault can be recognized. The length of these fault trends varies from 200 m to 1 km. On the outcrops, these faults dissect the different rock units in a sinstral sense of movement that ranges between a few centimeters and 1.25 m. On some outcrops, shear joints are accompanied with these faults indicating the same sense of sinistral displacements that vary between a few millimeters and 25 cm (Fig. 3.11).

3.2.2.4 NW-SE strike-slip fault trends

Traces of these faults range in length from 1 to 2 km and along their planes the different rock units and folding axes are horizontally displaced with a few meters to 1.2 km. They dislocate the NDSF and SDSF in a sense of dextral shear but, in places, display inconsistent crosscutting relationship with the other N-S to NNE-SSW sinistral strike-slip faults. The faults of this category are will dominant in the center and northwestern part. In Al Majahir and Al Bayda formations, the effect of all these faults is markedly shown by the development of their shear joints which are visually the most spectacular features on the outcrops. Table (3.2) shows the strike of this category is aligned between N30-50W and the dip ranges between 75^o and 85^o towards the east and north northeast.

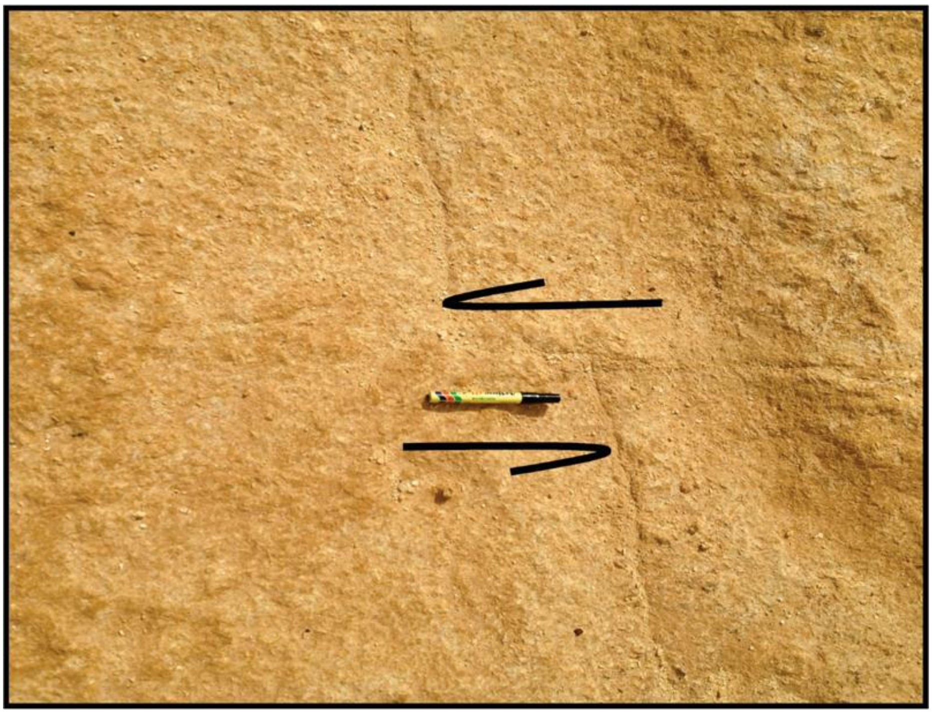


Fig. (3.11) Sinistral displacement in Al Bayda Formation of E-W shear joint recognized along sinistral strike-slip faults.

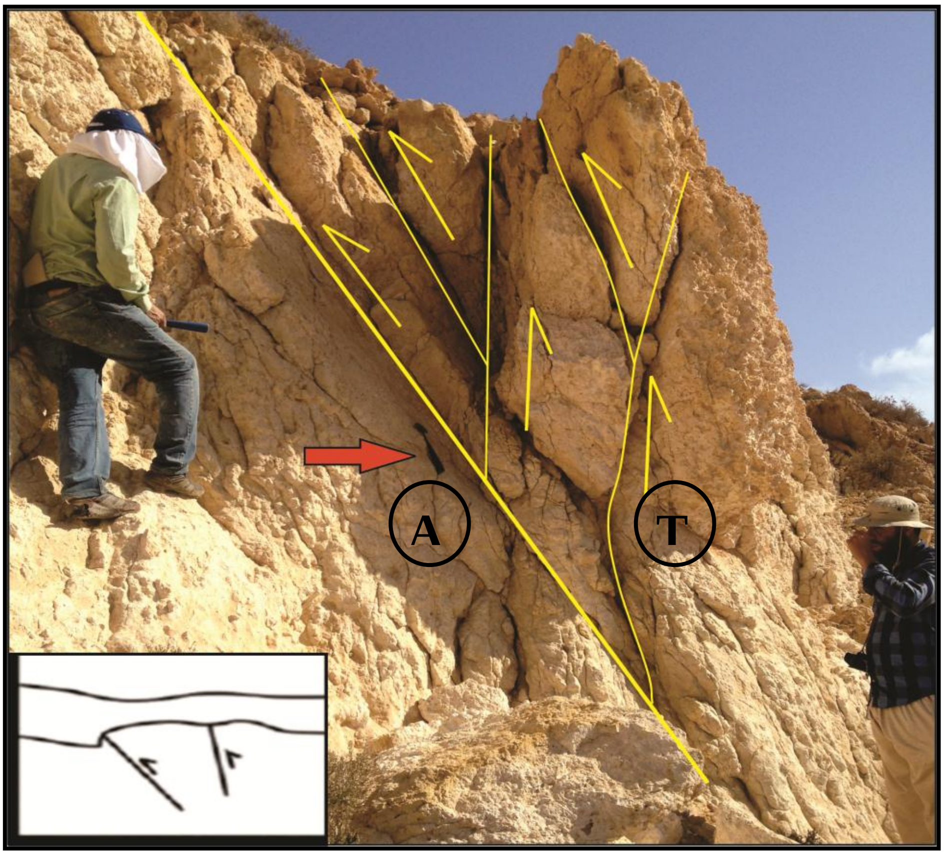


Fig. (3.12) Positive flower or pop up structure along the E-W dextral strike-slip fault within Al Majahir Formation of Wadi Al Raheb. Red arrow refers to a slickenside along which blocks of Al Majahir rocks are moved in a way up structure: (looking NE).

(Table 3.1) Measurements of the dip and strike of the Conjugate Shears (R`) faults

	Strike	Dip		Strike	Dip
1	N20E	70NW	36	N40E	80NW
2	N15E	80NW	37	N45E	77NW
3	N25E	80NW	38	N40E	80NW
4	N60E	75NW	39	N50E	75NW
5	N18E	80NW	40	N37E	85NW
6	N20E	80NW	41	N30E	75NW
7	N30E	70NW	42	N22E	80NW
8	N15E	85NW	43	N10E	80NW
9	N30E	70NW	44	N18E	75NW
10	N25E	65NW	45	N25E	85NW
11	N20E	80NW	46	N20E	70NW
12	N40E	86NW	47	N25E	85NW
13	N50E	80NW	48	N15E	85NW
14	N15E	85NW	49	N20E	70NW
15	N20E	70NW	50	N30E	75NW
16	N25E	75NW	51	N25E	80NW
17	N15E	70NW	52	N18E	75NW
18	N18E	80NW	53	N25E	85NW
19	N25E	75NW	54	N19E	80NW
20	N15E	70NW	55	N16E	70NW
21	N10E	80NW	56	N25E	80NW
22	N35E	70NW	57	N30E	85NW
23	N18E	88NW	58	N45E	85NW
24	N22E	81NW	59	N15E	81NW
25	N20E	75NW	60	N35E	80NW
20	N20E	70NW	61	N70E	70NW
21	N30E	80NW	62	N60E	80NW
22	N15E	75NW	63	N40E	65NW
23	N15E	70NW	64	N45E	60NW
24	N20E	80NW	65	N15E	85NW
25	N35E	85NW	66	N35E	80NW
26	N30E	88NW	67	N40E	70NW
27	N15E	81NW	68	N45E	81NW
28	N20E	75NW	69	N15E	75NW
29	N30E	70NW	70	N35E	70NW
30	N55E	80NW	71	N70E	80NW
31	N15E	85NW	72	N60E	75NW
32	N20E	88NW	73	N40E	80NW
33	N35E	81NW	74	N45E	80NW
34	N22E	75NW	75	N15E	75NW
35	N18E	75NW	76	N35E	70NW

(Table 3.2) Measurements of the dip and strike of the Riedel Shears (R) faults

	Strike	Dip		Strike	Dip
1	N40W	70NE	**25**	N40W	80NE
2	N35W	80NE	**26**	N45W	77NE
3	N30W	80NE	**27**	N40W	80NE
4	N45W	77NE	**28**	N50W	75NE
5	N45W	75NE	**29**	N37W	85NE
6	N45W	70NE	**30**	N30W	75NE
7	N30W	80NE	**31**	N55W	80SE
8	N25W	85NE	**32**	N45W	80NE
9	N35W	70NE	**33**	N60W	75NE
10	N25W	75NE	**34**	N55W	85NE
11	N20W	85NE	**35**	N60W	70NE
12	N40W	86NE	**36**	N55W	85NE
13	N50W	75NE	**37**	N60W	85NE
14	N40W	85NE	**38**	N55W	70NE
15	N45W	80NE	**39**	N65W	75NE
16	N40W	80NE	**40**	N50W	75NE
17	N55W	70NE	**41**	N45W	75NE
18	N60W	80NE	**42**	N45W	85NE
19	N25W	75NE	**43**	N35W	75NE
20	N45W	70NE	**44**	N55W	70NE
21	N40W	80NE	**45**	N50W	75NE
22	N35W	70NE	**46**	N45W	85NE
23	N55W	88NE		N50W	75NE
24	N50W	75NE	**47**	N55W	78NE

3.2.2.5 E-W to WNW-ESE strike-slip fault trends

These faults parallel to the main NDSF and SDSF and, therefore, are characterized by dextral shear. They are fewer in number and range in length from 4 to 8 kilometers. Occasionally, some of these faults attain the ENE-WSW trend and reflect the same style of dextral displacement. Table (3.3) shows the trend of these faults represent as P shear of the E-W fault trends and, therefore, it is characteristic to the P shear trends in wrenching zones (Abdel Khalek et al.1989, Dewey et al. 1998, Holdsworth et al. 2002, Marques and Coelho 2003). Inside Wadi Al Rahib, these faults are more intensive and the horizontal dextral movement is accompanied with subvertical movement or thrust component and formation of positive flower or pop-up structures (Fig. 3.12). In this case, the E–W to WNW–ESE strike-slip shearing planes are behaved as thrust planes on which the individual imbricate rock masses (i.e. hanging wall) are pushed up in response to the acted principal stress (synthetic movement).

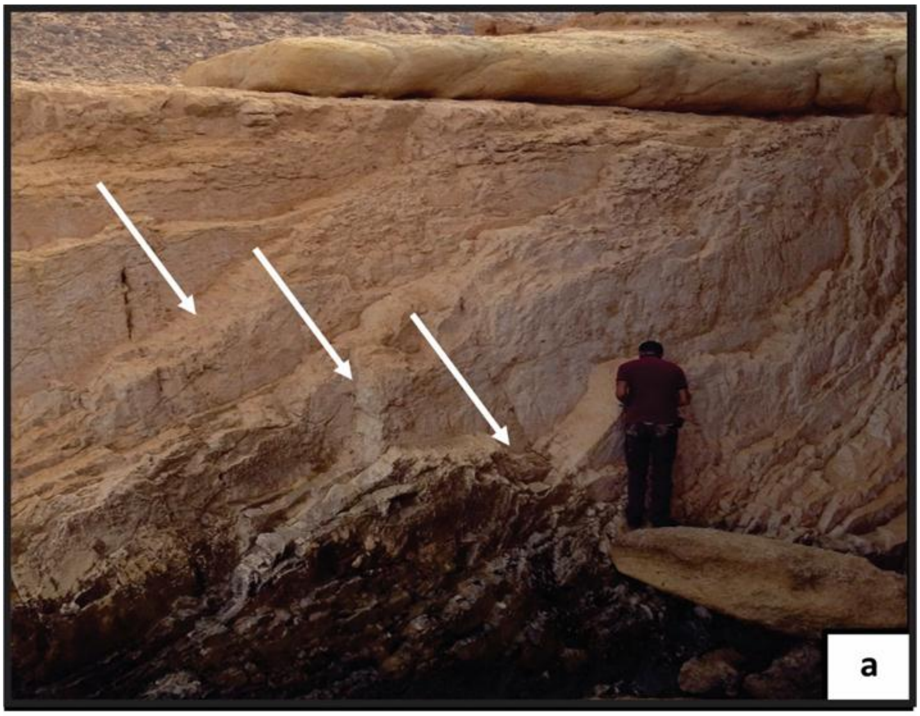
A close up view of slickenside in the Cretaceous bed rocks at the cliff sea of Wadi Al Shaqqah to the northwest of Wadi Al Rahib frictional sliding processes are developed describing the entire horizontal movement on the surface of these faults. The slickenside surfaces are commonly steeped with parallel sides indicating the direction of dextral motion (Hatcher 1990 and Girty 2009); (Fig, 3.13).

3.2.2.6 NNW-SSE normal faults

These fault trends are rare in the study area and characterized by down throw to the SW and, sometimes, NE. They coexist with the other strike-slip faults and form
across the SDSF rhomboid shape of pull apart basin (Fig. 3.2). Elsewhere, open or tensional joints are associated with the trend of these faults.

(Table 3.3) Measurements of the dip and strike of the P shear E-W fault trends

No	Strike	Dip		Strike	Dip
1	N75W	70NE	18	N70E	80NW
2	N80W	80NE	19	N75E	75NW
3	N75W	80NE	20	N80E	70NW
4	N60W	77NE	21	N85E	80NW
5	N75W	75NE	22	N75E	85NW
6	N60W	70NE	23	N70E	88NW
7	N80W	80NE	24	N85E	81NW
8	N80W	85NE	25	N80E	75NW
9	N85W	70NE	26	N77E	70NW
10	N75W	75NE	27	N85E	80NW
11	N65W	85NE	28	N75E	85NW
12	N55W	86NE	29	N80E	88NW
13	N60W	75NE	30	N85E	81NW
14	N75W	85NE	31	N80E	75NW
15	N80W	80NE	32	N80E	75NW
16	N75W	80NE	33	N85E	85NW
17	N80W	70NE	34	N75E	88NW



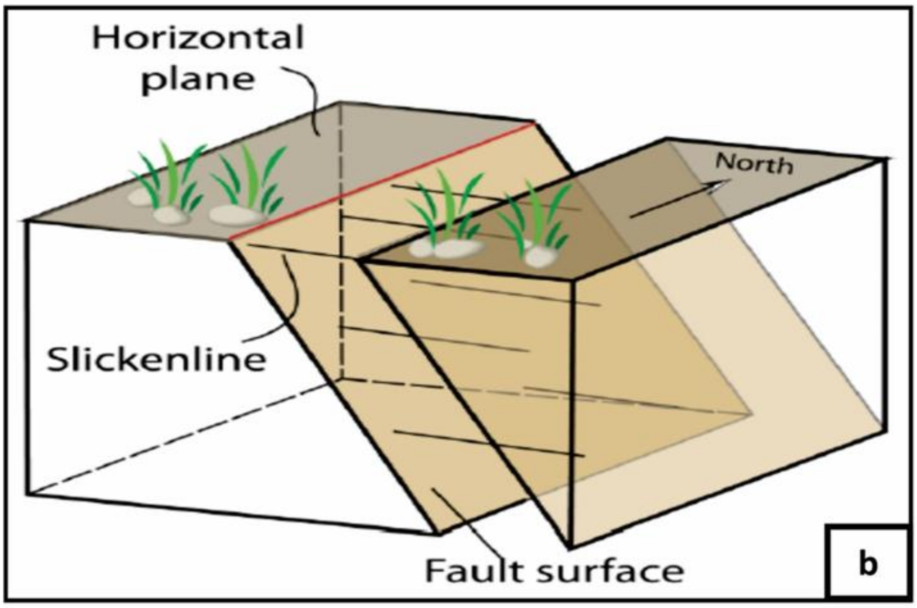


Fig. (3.13) (a) Slickenside surfaces at Wadi Al shaqqah indicating dextral movement along parallel E-W to WNW-ESE the dextral strike-slip faults; Photo looking SW, (b) Block diagram illustrating the mechanism of horizontal movement on the slickenside of the strike-slip faults (after Girty, 2009).

3.2.3 Joints

Joints patterns exposed on both horizontal and vertical outcrops are mostly used to infer the paleostress orientations and, thus, give evidence of the tectonic history of a region (Dyer 1988 and Bahat 1999). Thereby, investigation of the different joint patterns requires consideration of the tectonic events and stratigraphy, which altogether produce variations in both the style and orientation of these joints (Fig. 3.14).

In the present area, the joints are regular and, sometimes, irregular and along their planes there are little or no displacements. On the outcrops, some of joints (the shear joints, in particular) form conjugate arrays and are infilled with crushed rock fragments and remobilized. minerals (calcite and quartz). Sometimes, some surface markings on tensional joints are represented by plumose marks.

In the study area, as the joint patterns are only outcrop features and change horizontally and vertically with the stratigraphic sequence variation, their investigation will deal with in each formation as follows:

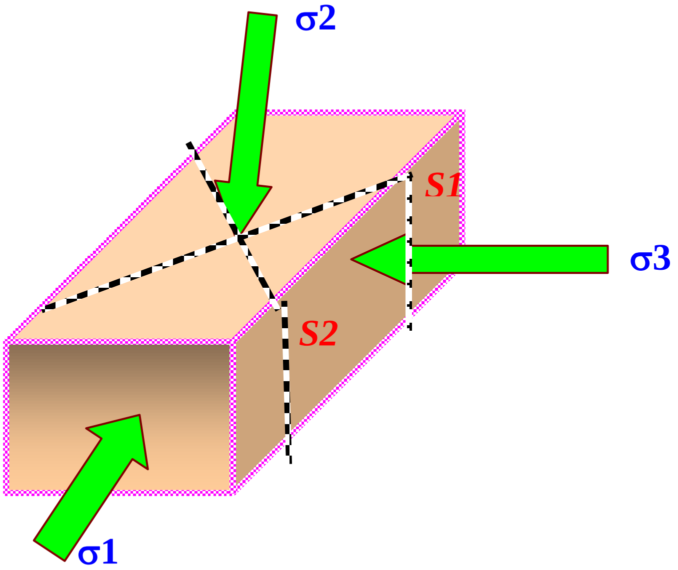


Fig. (3.14) Explanatory sketch from joint analysis showing S1and S2 shear planes related to the effect of strike slip faulting.

In Al Majahir Formation, the joints are dense and well-developed (Fig. 3.15a,b). They are straight and mainly represented by two sets; NNE-SSW and WNW-ESE joints. Most of these joints are closed except some joints, which follow the NNW-SSE trend are open with spacing 15-50 cm. Spacing changes are locally due to differences in rock type and bed thickness. In some thin limestone beds, the spacing is 5 m or less. The vertical dimension of fractures is much less than their horizontal extent. There are some lateral displacements are noticed as dextral and sinistral movements along the WNW-ESE and NNE-SSW joints respectively. No vertical slip occurs obviously on the tensional joints.

In Al Bayda Formation, the main directions of joints are striking NW-SE and NNE-SSW with minor trends along the ENE-WSW and NE-SW faults (Fig. 3.15c), while in Al Abraq Formation, they are subordinate and mainly striking WNW-ESE, ENE-WSW, NW-SE and NNE-SSW. Most joints noted in Al Bayda Formation are mostly tensional joints and striking NNW-SSE. On the outcrops, the length of the joints ranges from 1m to 5m.

In Al-Jaghbub Formation, the joints are represented by two sets; NNE-SSW and WNW-ESE joints. Many extensional fractures are branched into a number of centimeter-scale joints forming small-scale flower structure (Fig. 3.15d), related to the effect by the NW-SE dextral strike-slip faults. These structures are clearly observed in Al-Jaghbub Formation.

Rose diagrams conducted for all the linear features in the study area are interpreted as one of the most informative ways of representing orientation data.

A majority of the surface linear features in the region from these rose diagrams have two preferred orientations in Cretaceous rocks (N10-20E and N30-40W), three preferred orientations in Oligocene rocks(N10-20E, N75-85E and N40-50W) and two preferred orientations in the Miocene rocks(N40-50E and N40-60W); (Fig. 3.16).

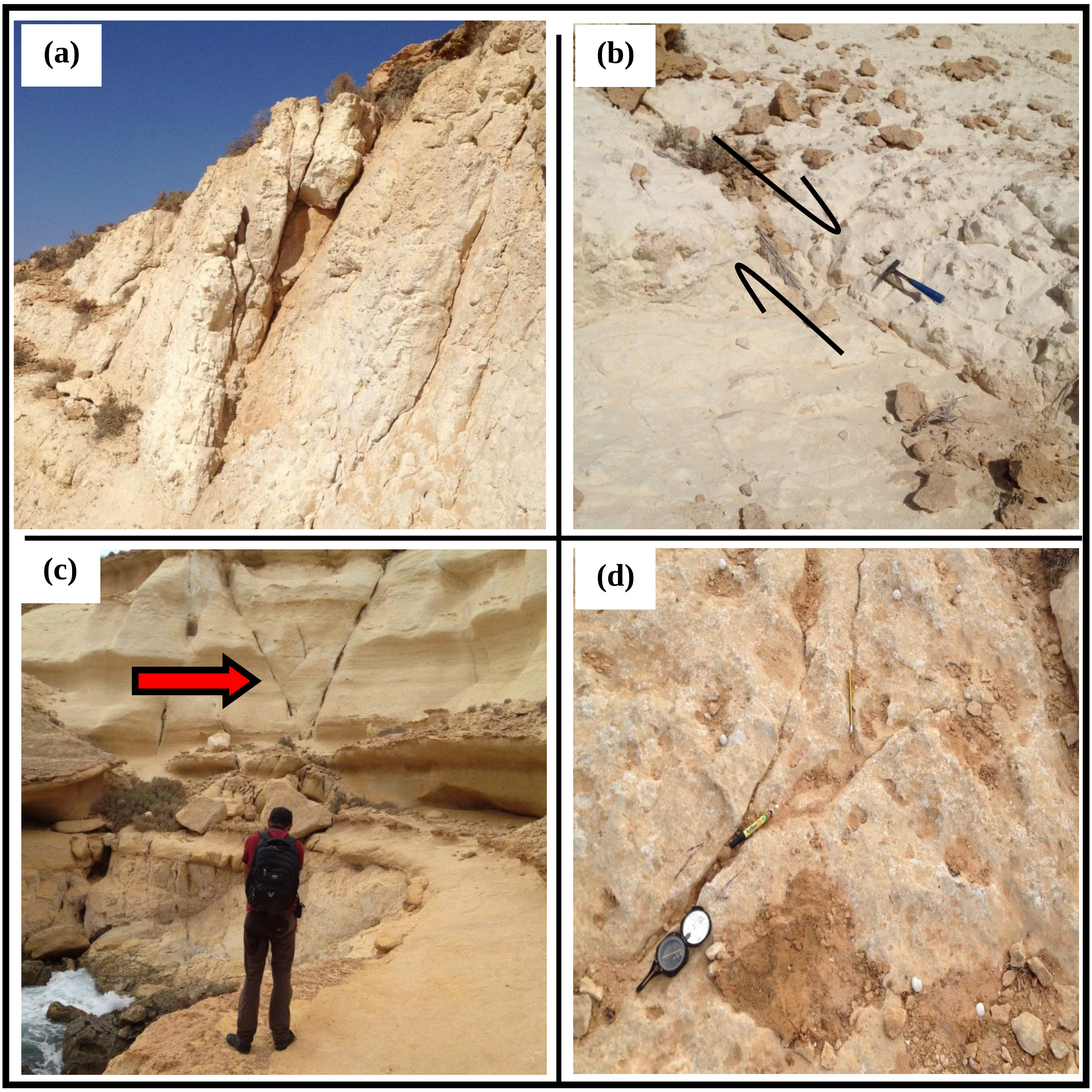


Fig. (3.15) Different joints patterns in Al Burdia area. (a) Shear joints developed along E-W dextral strike-slip fault trend in dolomitic limestone beds of Al Majahir formation. Photo looking NE. (b) Two shear joints in the Al Majahir Formation showing dextral displacement along one of them to the other in Wadi Al-Raheb; Photo looking ENE. (c) Red arrow refers to conjugate shear joints in the Al Byada Formation at Wadi Friq Al-Raheb. (d) Joint branching into a number of joints forming a centimeter-scale flower structure in Al-Jaghbub Formation; Photo looking E.

(Table 3.4) Measurements of the strike readings of the joints in Late Createceous rocks.

No	Strike	Strike	No	Strike	Strike
1	N65E	N25E	18	N30E	N10E
2	N15E	N55E	19	N330W	N30E
3	N315W	N270W	20	N340W	N275W
4	N295W	N310W	21	N270W	N310W
5	N10E	N295W	22	N15E	N340W
6	N15E	N30E	23	N25E	N35E
7	N20E	N315W	24	N55E	N300W
8	N30E	N30E	25	N35E	N60E
9	N25E	N315W	26	N45E	N295W
10	N40E	N310W	27	N40E	N315W
11	N45E	N25E	28	N35E	N45E
12	N55E	N30E	29	N55E	N35E
13	N60E	N25E	30	N55E	N315W
14	N75E	N45E	31	N75E	N65E
15	N50E	N345W	32	N65E	N350W
16	N25E	N330W	33	N20E	N310W
17	N300W	N45E	34	N330W	N20E

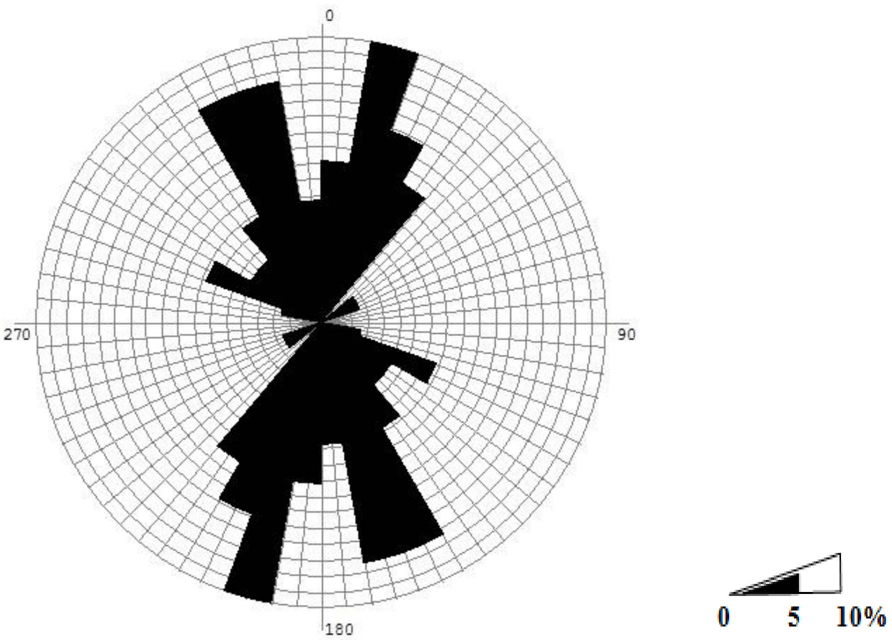


Fig. (3.16) Rose diagram of joint measurements in Al Majahir Formation.

(Table 3.5) Measurements of the strike readings of the joints in Oligocene rocks.

No	Strike	Strike	No	Strike	Strike
1	N12E	N25E	18	N05E	N45E
2	N325W	N55E	19	N270W	N30E
3	N65E	N15E	20	N315W	N345W
4	N25E	N30E	21	N275W	N290W
5	N310W	N295W	22	N15E	N340W
6	N15E	N30E	23	N25E	N35E
7	E-W	N35E	24	N55E	N300W
8	N290W	N10E	25	N35E	N60E
9	N310W	N75E	26	N45E	N295W
10	N330W	E-W	27	N40E	N315W
11	N315W	N25E	28	N35E	N45E
12	N300W	E-W	29	N55E	N35E
13	N60E	N25E	30	N55E	N315W
14	N25E	N45E	31	N25E	N65E
15	N20E	N90E	32	N65E	N350W
16	N25E	N80E	33	N20E	N310W
17	N310W	N60E	34	N22E	N30E

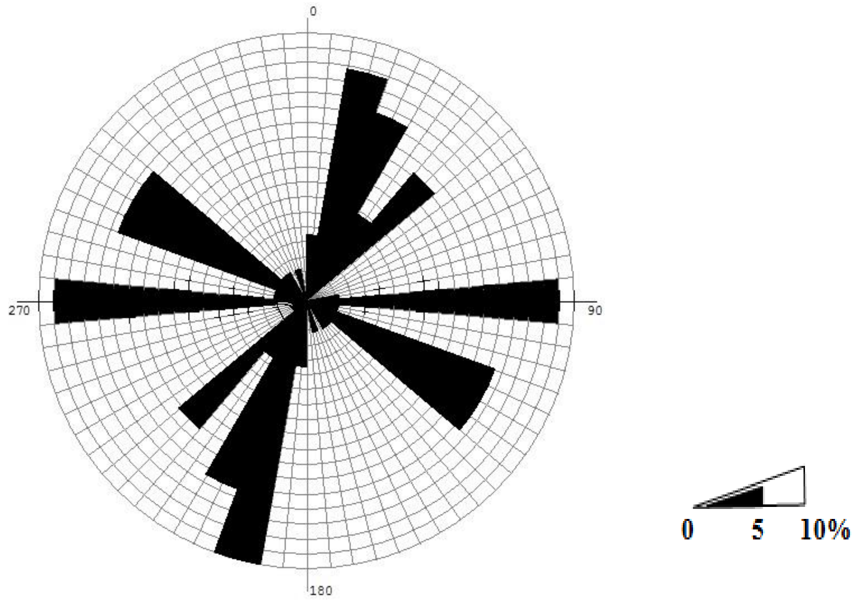


Fig. (3.17) Rose diagram of joint measurements in Al Byada and Al Abraq formations.

(Table 3.6) Measurements of the strike readings of the joints in Miocene rocks.

No	Strike	Strike	No	Strike	Strike
1	N45E	N20E	18	N340W	N25E
2	N275W	N55E	19	N330W	N30E
3	N35E	N270W	20	N340W	N275W
4	N45E	N310W	21	N270W	N310W
5	N295W	N295W	22	N15E	N340W
6	N55E	N30E	23	N25E	N35E
7	N20E	N315W	24	N55E	N300W
8	N30E	N30E	25	N35E	N60E
9	N25E	N310W	26	N35E	N295W
10	N40E	N320W	27	N40E	N315W
11	N45E	N55E	28	N65E	N45E
12	N55E	N60E	29	N55E	N35E
13	N60E	N25E	30	N55E	N315W
14	N75E	N45E	31	N75E	N65E
15	N50E	N345W	32	N65E	N315W
16	N25E	N40E	33	N20E	N330W
17	N300W	N45E	34	N340W	N310W

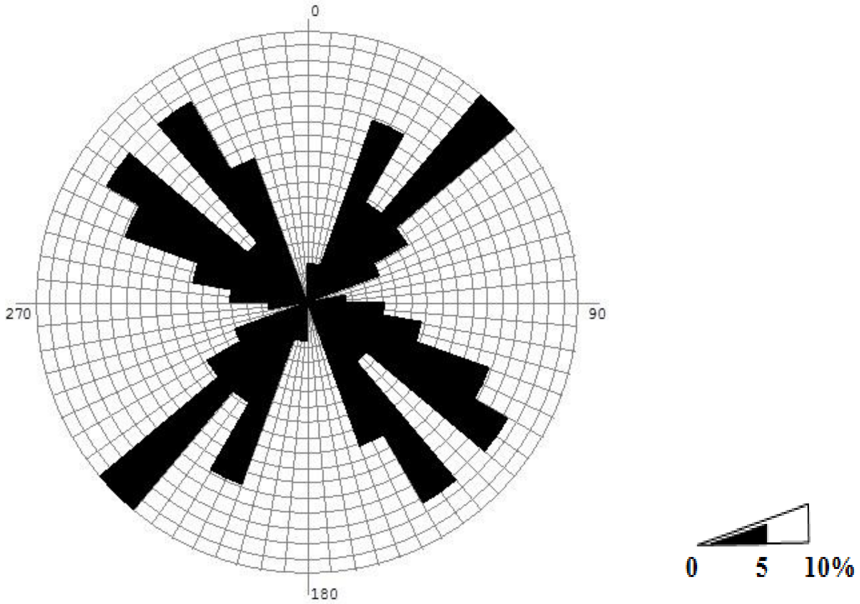


Fig. (3.18) Rose diagram of joint measurements in Al Jaghbub Formation.

3.2.4 Unconformities

Unconformities are surfaces of erosion or non-deposition that separates younger strata from older rocks (Van der Pluijm, 2004). An unconformity surface that separates parallel sedimentary layers is recognized as disconformities, however angular unconformity is present as the erosional surface separates between two successions of different dips (Fig. 3.19). In the study area there are several cycles of sedimentation, which are separated by two types of unconformities surfaces. These surfaces reflect the tectonic events during the uplifts.

Unconformity surfaces in the study area are recognized by:

- Angular unconformity surface between Al Majahir and Al bayda formations (Algal limestone Member) Fig (3.20).
- Disconformity surface between Al bayda and Al Abraq formations. Fig (3.21).
- Disconformity surface between Al Abraq and Al Faidyah formations .
- Disconformity surface between Al Faidyah and Al jaghbub formations.

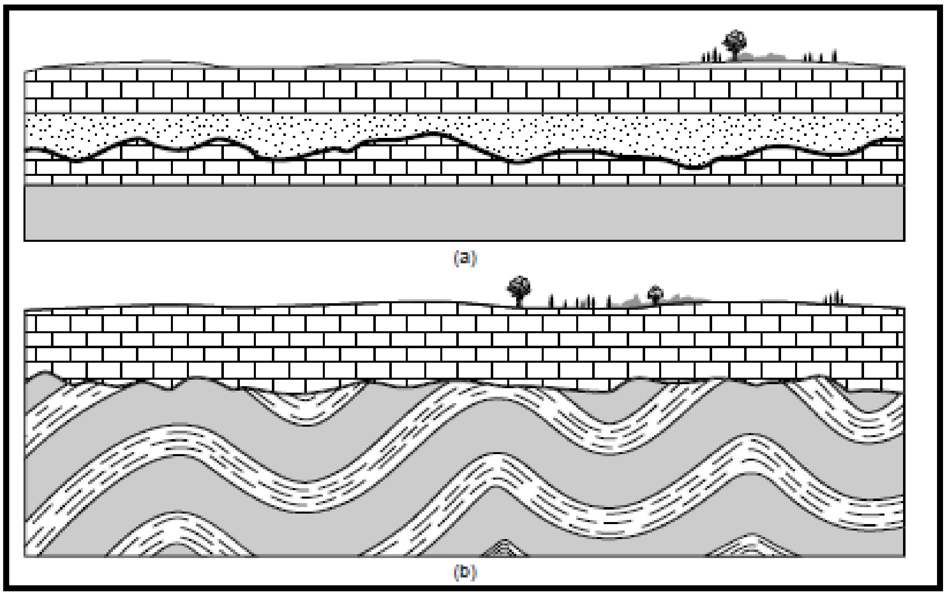


Fig. (3.19) Shows the two main kinds of unconformity (a) Disconformity surface (b) Angular unconformity (after Ben A. van der Pluijm,2004.)

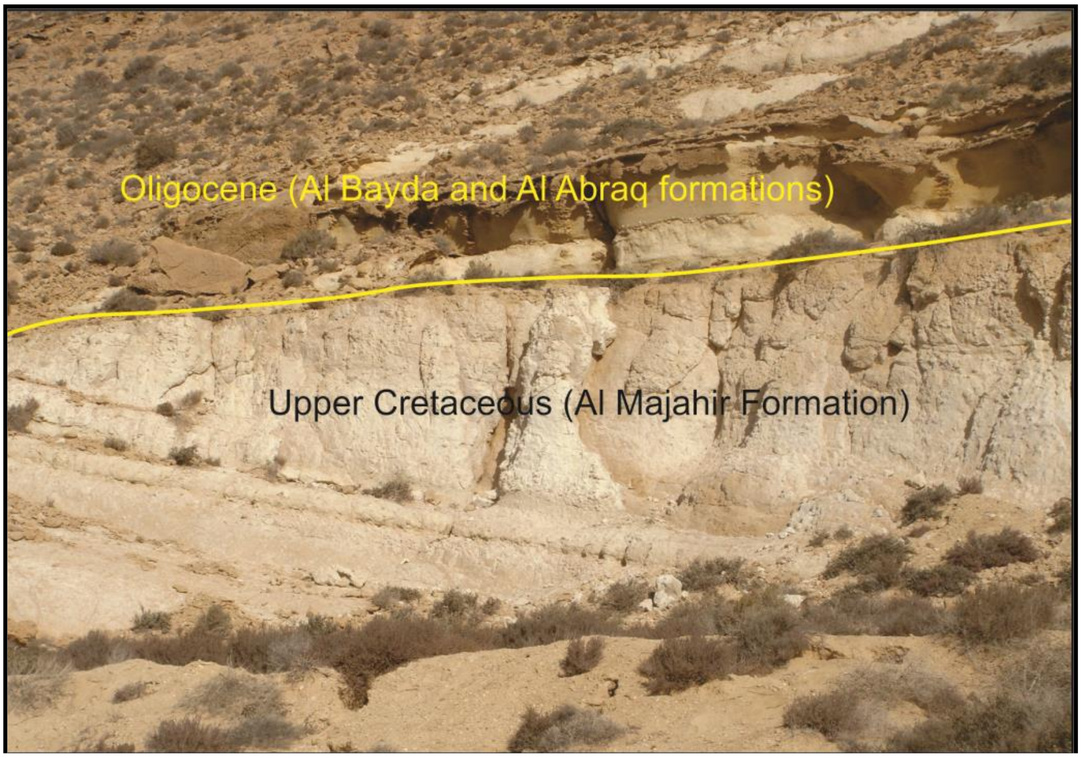


Fig. (3.20) Field photograph showing angular unconformity between the Upper Cretaceous and Oligocene in Wadi Al Raheb; (looking NE).

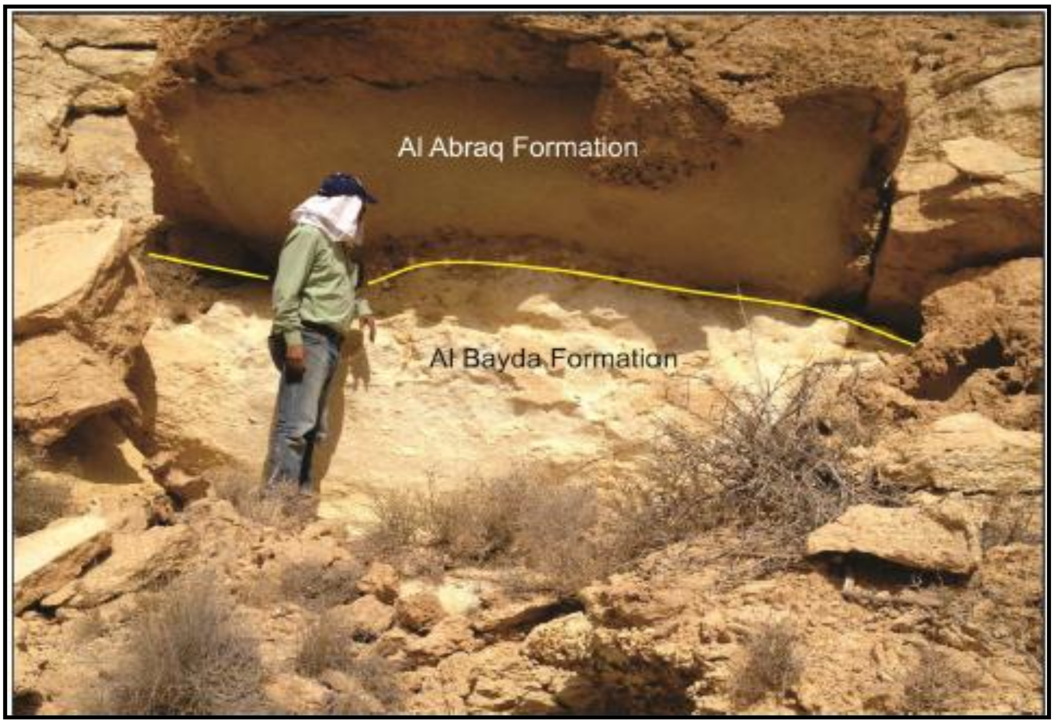


Fig. (3. 21) Field photograph showing a disconformity surface between Al Bayda and Al Abraq formations in Wadi Al Raheb; (looking N).

3.3 Subsurface Structural Analysis

The main objective of this part was to integrate the existing 2D seismic data interpretation with surface geology and satellite image to define potential structural corridors at depth.

The subsurface structural analysis in this study was carried out with only two seismic lines 2D , bouguer gravity map, and depth structure map are also provided for this study. (Fig. 3.22). The seismic lines were compared with cross sections based upon well control, and used as a general guide for structural analysis. Cyrenaica comprises whole BANEL (Basin Analysis North East Libya) study which has limited, mostly vintage 2D coverage and no 3D data. Most of the 2D seismic is of a vintage & processing which does not allow for detailed analysis, The data set had also poor resolution. Therefore only manual picking method was employed.

3.3.1 Fault interpretation

On 2D seismic sections, faults appear as diffuse zones of discontinuous horizon reflectors. Abrupt vertical displacement of several reflectors along a distinct line (faults plane) is the best indicator for the presence of faults (Marillier et al.,2006). Fault interpretation was done in the same way as horizon interpretation by identifying and defining the major fault patterns observable on the seismic sections.

Three reflectors were picked in this study which represent only the age, not the name of formations, and shows a fair to good continuity, they are:

• First reflector represents base of Upper Cretaceous.

• Second reflector represents Lower Cretaceous .

• Third reflector represents Jurassic- Cretaceous boundary.

seismic line # LC27 :

The seismic line was located in NE part of Area 60. The section is oriented NW-SE passing through well B1-LP7C (Fig. 3.22).The reflection quality of seismic horizons associated with Basel - Cretaceous lower Cretaceous and Jurassic – Cretaceous boundary are fair to good .

The line shows a huge anticlinal structure in the center where B1-LP7C was drilled, with large displacements of all interpreted reflectors at the south east . On the surface field observation and measurements confirm this anticline with a gentle style and plunging towards the SW (Figs. 3.2 and 3.23) . Listric normal faults with small antithetic, synthetic and flower structures are also clearly noticed on the section .

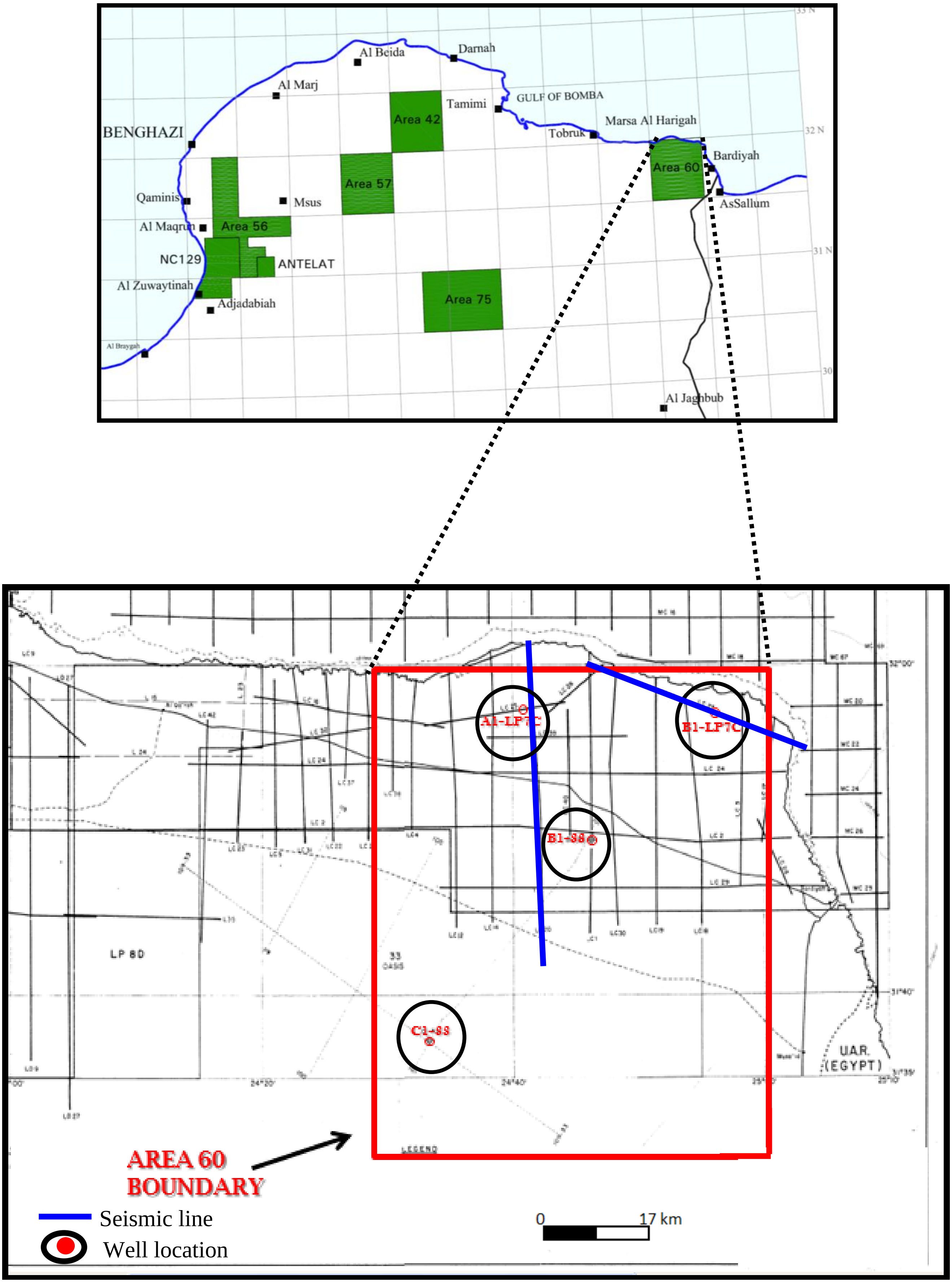


Fig. (3.22) Shows the location of the drilled wells and the seismic lines of the study area ,source from (AGOCO, 2009).

seismic line # LC20 :

The seismic line was located in the central part of Area 60. The section is oriented N-S trend, with the same reflection indicating some thinning of the Lower Cretaceous section towards the south (Fig. 3.22). This may indicated tilting of the basin during the deposition of this unit. The section also shows normal faults and small antithetic faults cutting the strata from Jurassic to Lower Cretaceous as shown with normal dip-slip movement and down throw to the south with about 50 m/sec (1000").

At the base of Upper Cretaceous the down throw is disappeared and the strata on both sides of the fault are located at the same depth indicating inversion during Upper Cretaceous, with style of strike-slip motion. This movement was continued with the same sense of movement, later on, upward in younger successions (Fig. 3.24).

Based on interpretation of picked reflectors and thickness in the wells, the orogenic movements of the interpreted faults can be divided as follows:

1-Stage of listric normal fault:

This stage was markedly shown during Jurassic to Lower Cretaceous and the type of normal faults was attributed to the northward relaxation in North Africa during the opening of Neotethys. Enhancement of this relaxation may be developed due to increase in weight (thickness) of sediments which are variety at the head of the hanging wall comparing with thickness at foot wall where it almost constant and thinner (Lowell, 2003).

2 -Stage of compression and development of strike-slip tectonics:

This stage represents structural inversion during Late Cretaceous to Miocene times in response to a right lateral compressional shear. The result was rotation northern and southern Cyrenica region within E-W to WNW-ESE dextral displacement zone and development of releasing and restraining zones and formation of negative and positive flower structures .The result of this effect led to inversion of the Marmarica basin.

3.3.2 Depth Structure maps

The depth map in seismic reflection method is reflection of the subsurface picture to time map. Thus, the depth maps also show the same picture of the studied wells, but the difference lies in the closures dimensions, number of contour interval between these maps, faults displacements and difference in number of minor faults located in the area.

The depth contour map (Fig 3.25) shows interval of the Lower Cretaceous ranges from (1600 – 2700 ft) with contour interval equals to 100m .

The map shows structure trends dominated by a NW-SE trend. Also shows sum anomalies that are controlled by normal (tilted faults) were well B1-LP7C has been drilled in this closure.

Figures (3.26 and 3.27) represent the depth maps with contour interval (500 ft.) was generated by (ECL project work in 2004 of Cyrenaica) for the studied wells. The maps show effect of some Early to Late Cretaceous faults have a trends dominated by a NW-SE trend.

3.3.3 Gravity Anomaly Map

The contour lines in bouguer gravity anomaly map (Fig 3.28) shows some positive and negative anomalies especially in the north eastern part, which are related to structure tectonic of the area. The bouguer gravity map presented in Cyrenica is only moderately reliable due to the vintage of the data set. Numerous problems exist in establishing the boundaries of the distinct geotectonic provinces, their own internal structure and depth to basement.

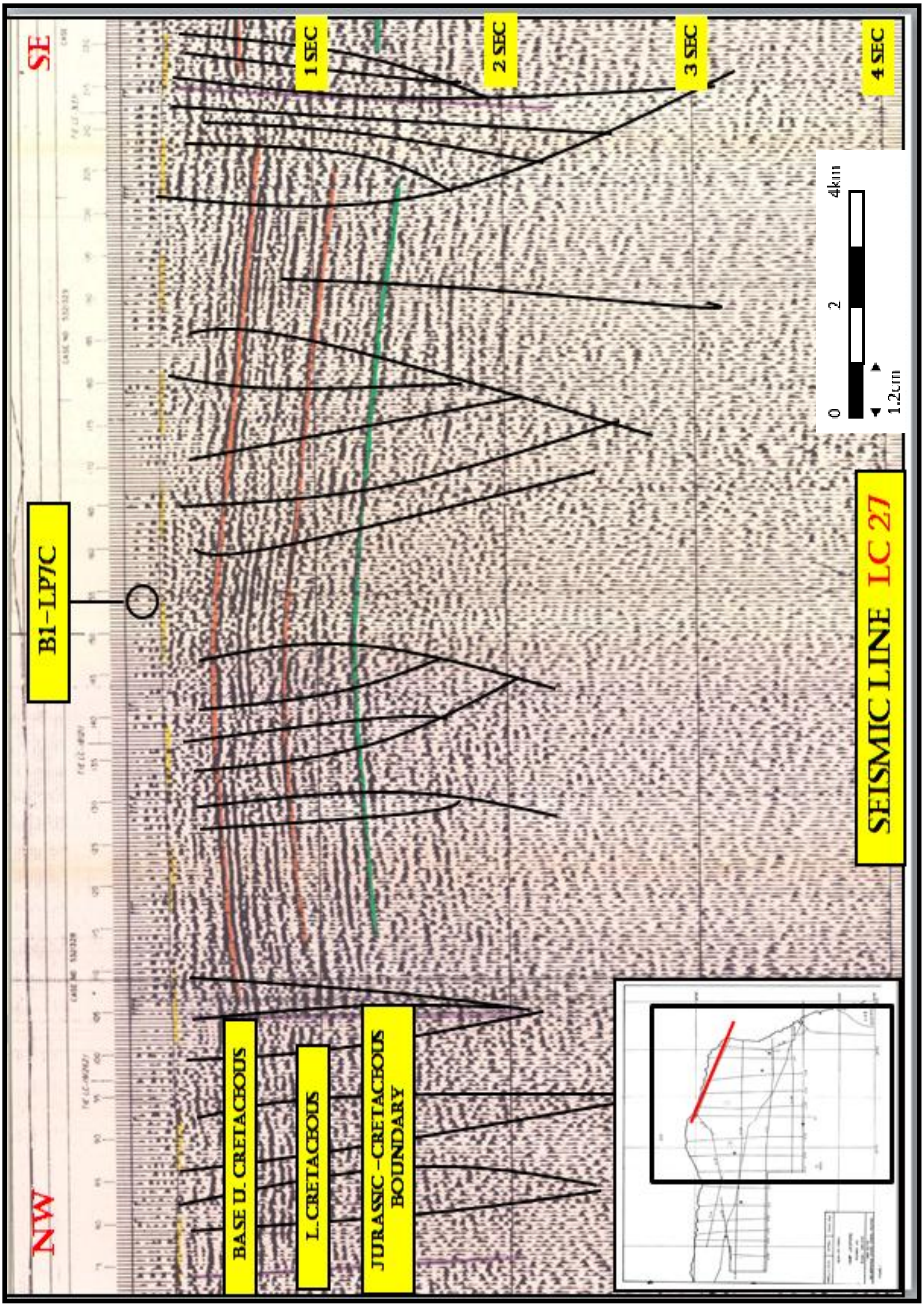


Fig. (3.23) Shows the first seismic section line LC 27 ,crossing from the NW to SE.

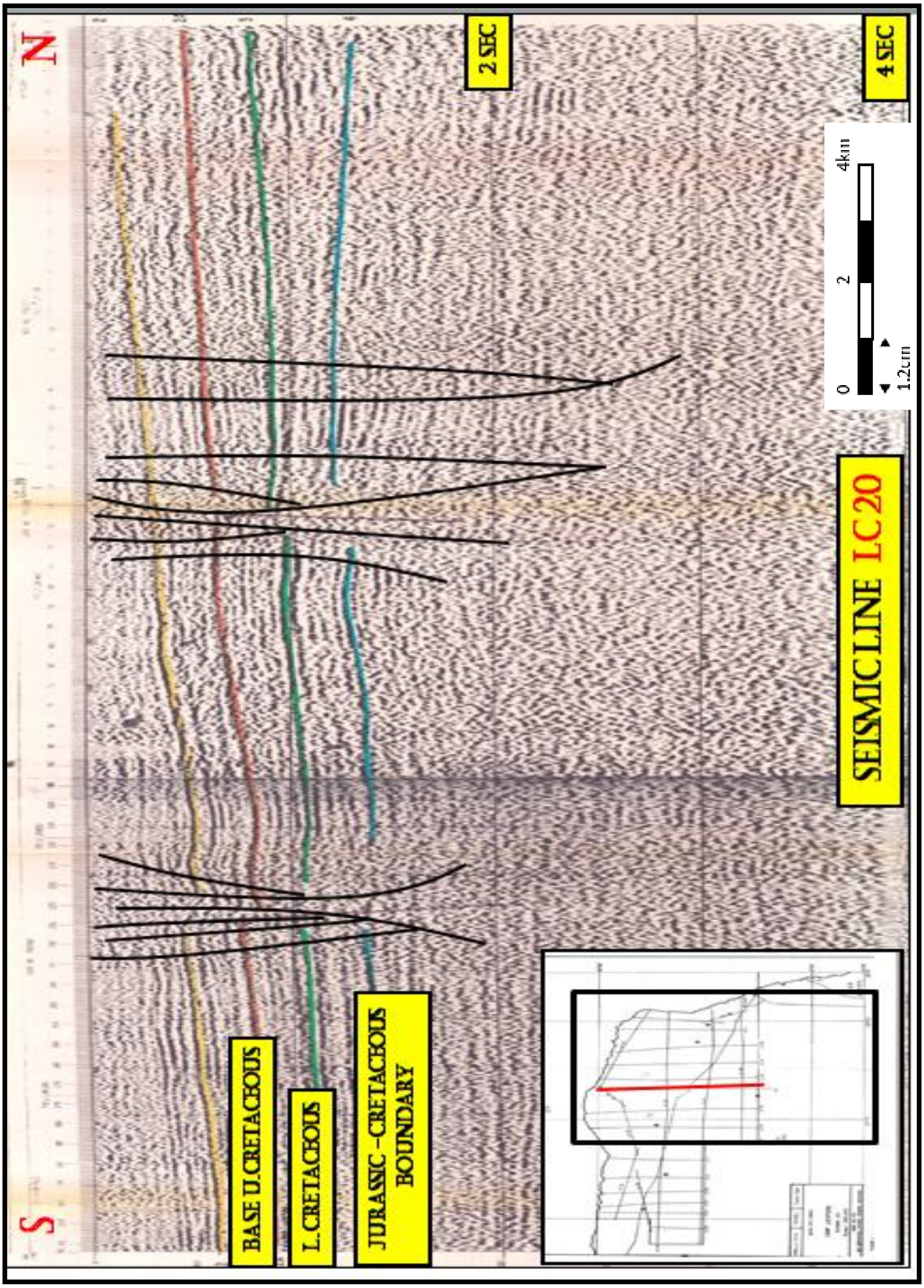


Fig. (3.24) Shows the second seismic section line LC 20 ,crossing from the S to N.

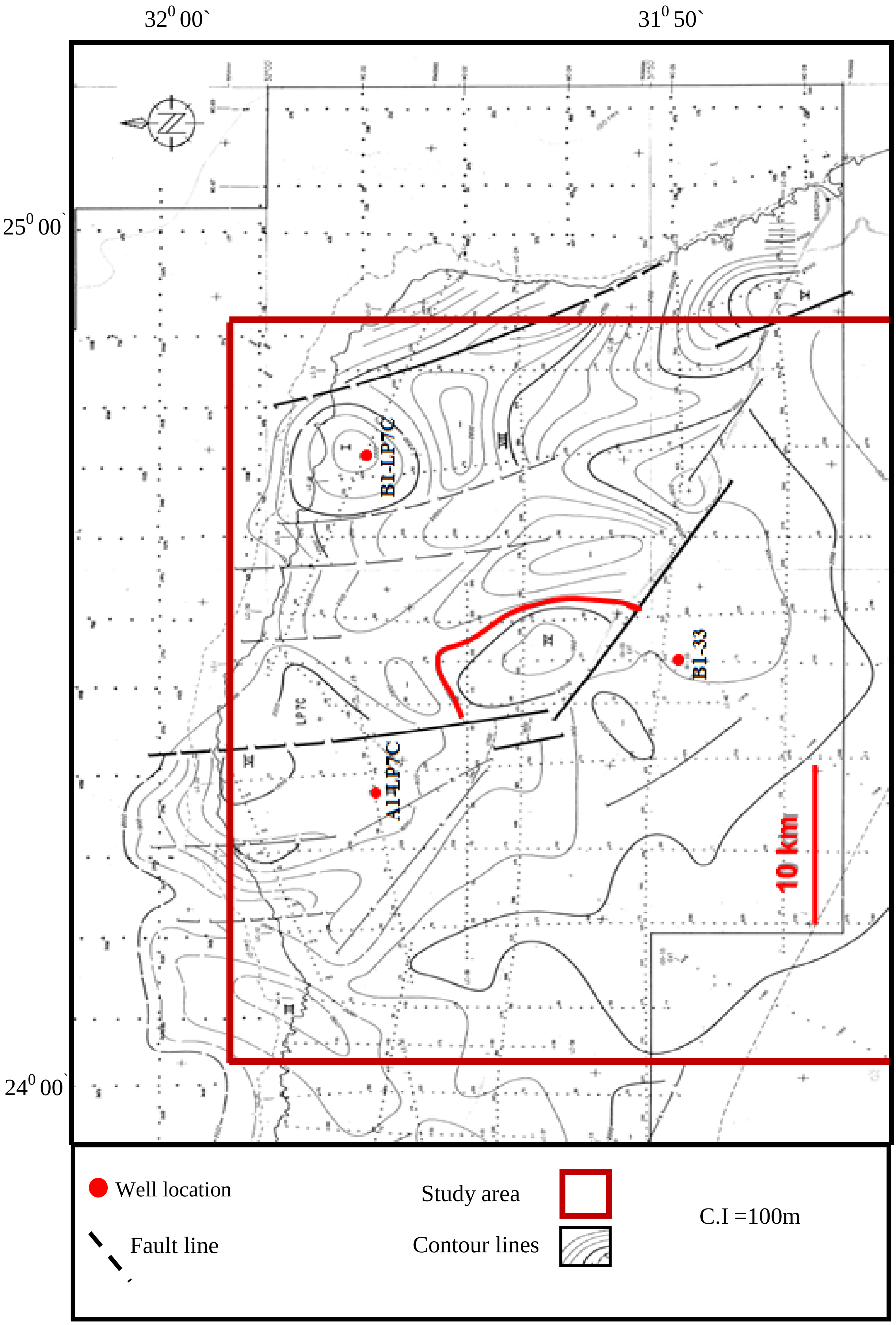


Fig. (3.25) Depth map of lower cretaceous after, AGOCO.2009.

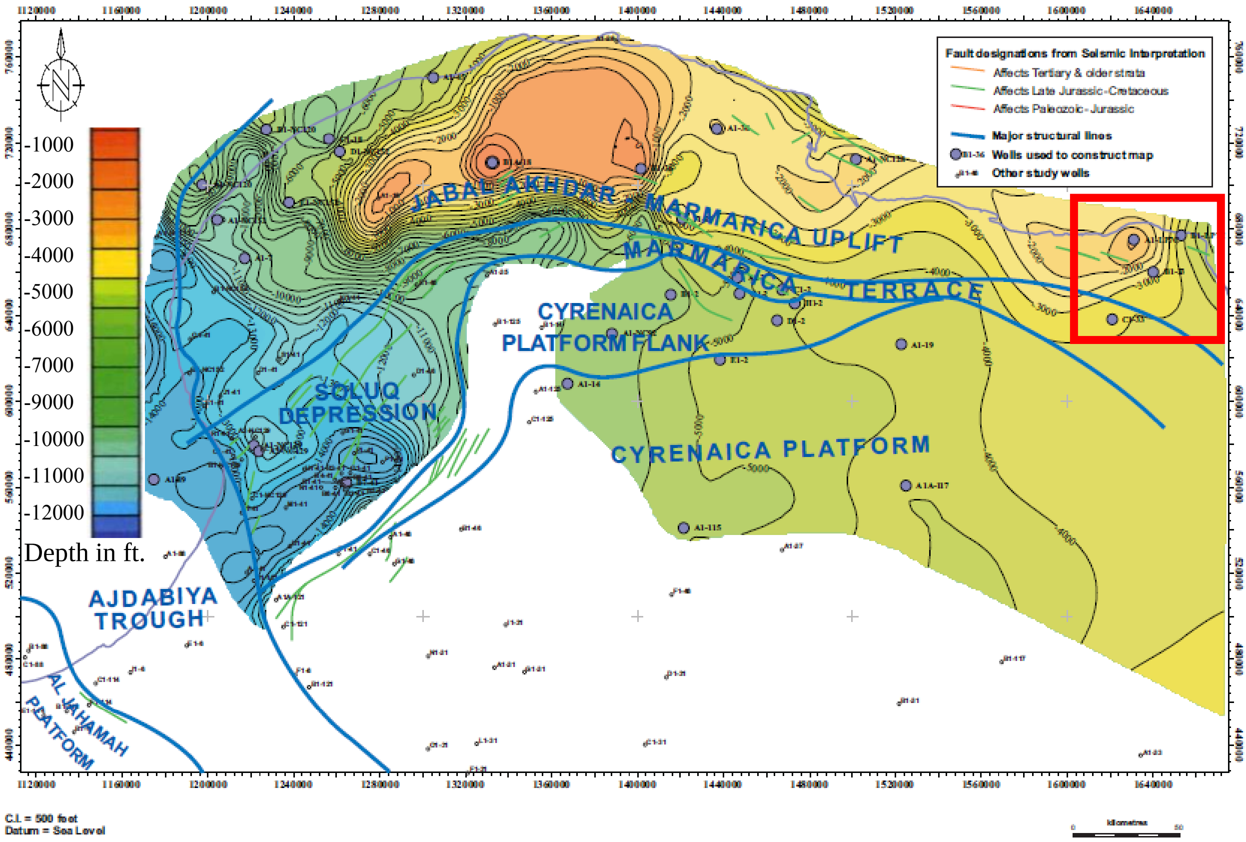


Fig. (3.26) Depth structure map of Early - Late Cretaceous (Albian - Cenomanian) after, ECL2004.

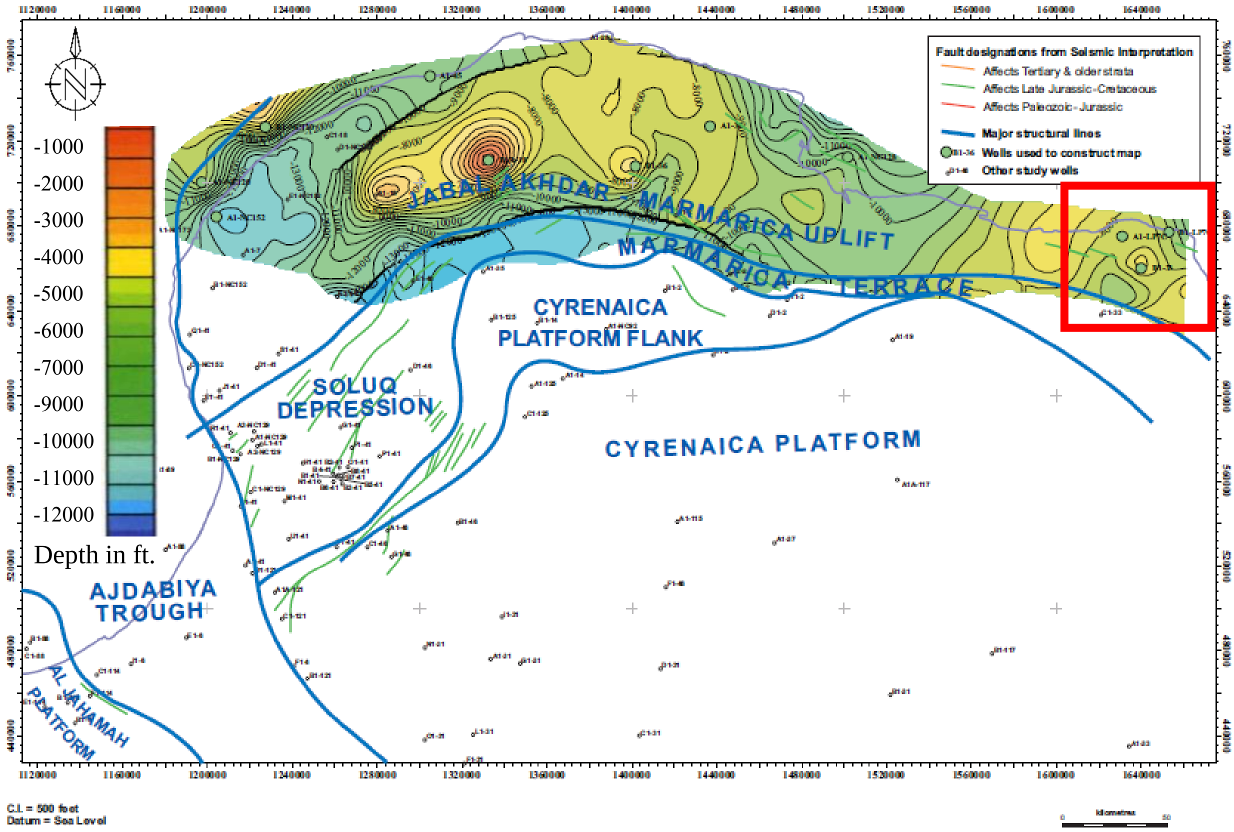


Fig. (3.27) Depth structure map of Early Cretaceous (Berriasian- Barremian) after, ECL2004.

Fig. (3.28) Bouguer Gravity Anomaly Map after, AGOCO.2009

Structural cross-section across the available boreholes, A1-LP7C and B1-33.which represent Marmarica uplift and C1-33 which represent Marmarica Terrace is illustrate the structural picture of the area as it is shown in (Fig.3.29).From the structural cross-section we can see the thickness of Late Cretaceous (pale green color) is increased toward the north of the study area ,which is confirmed the surface geological mapping of the study area ,and decreased toward the south ,This may be due to tectonic force that was effect on the area at the Late Cretaceous stage.

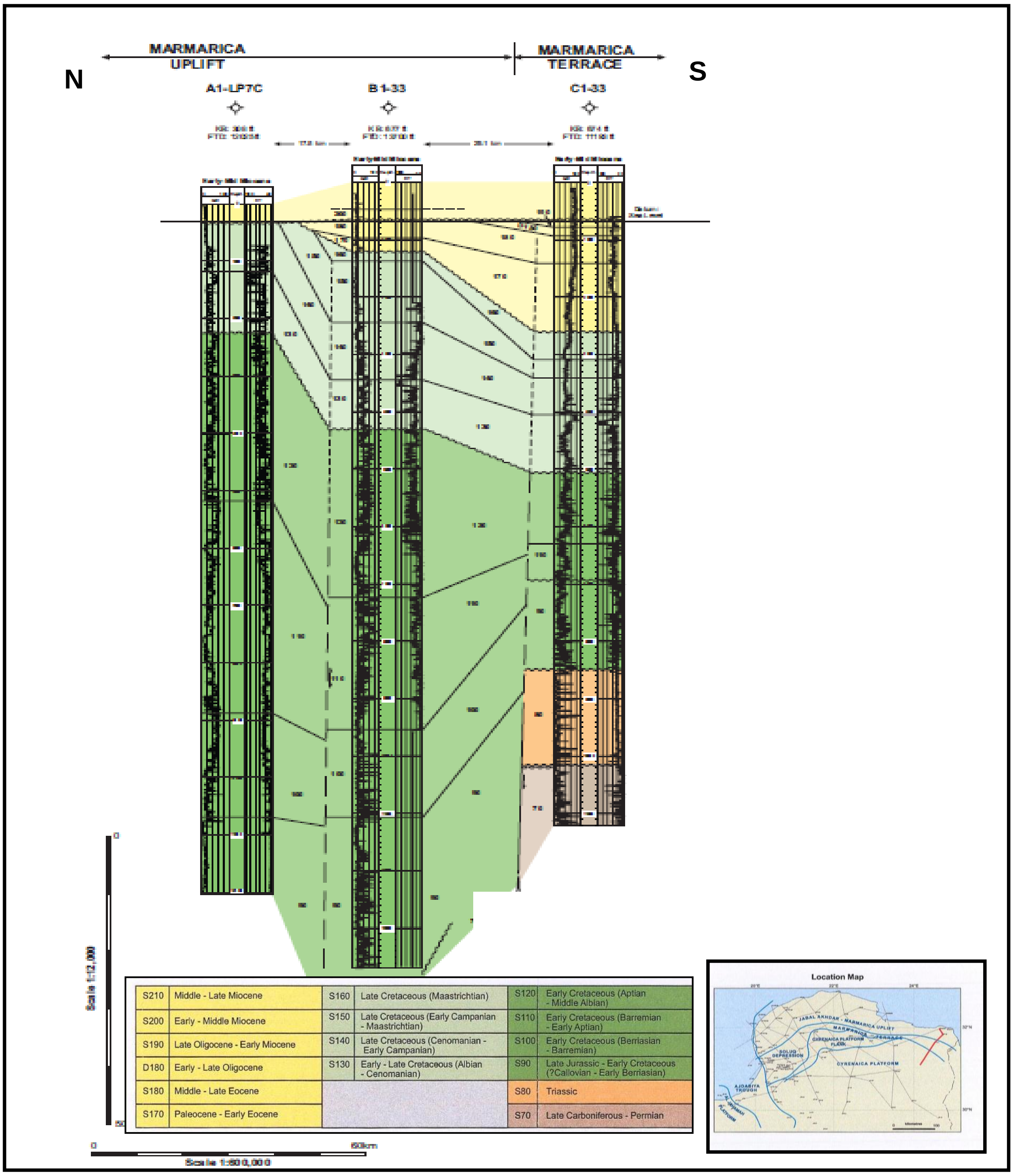
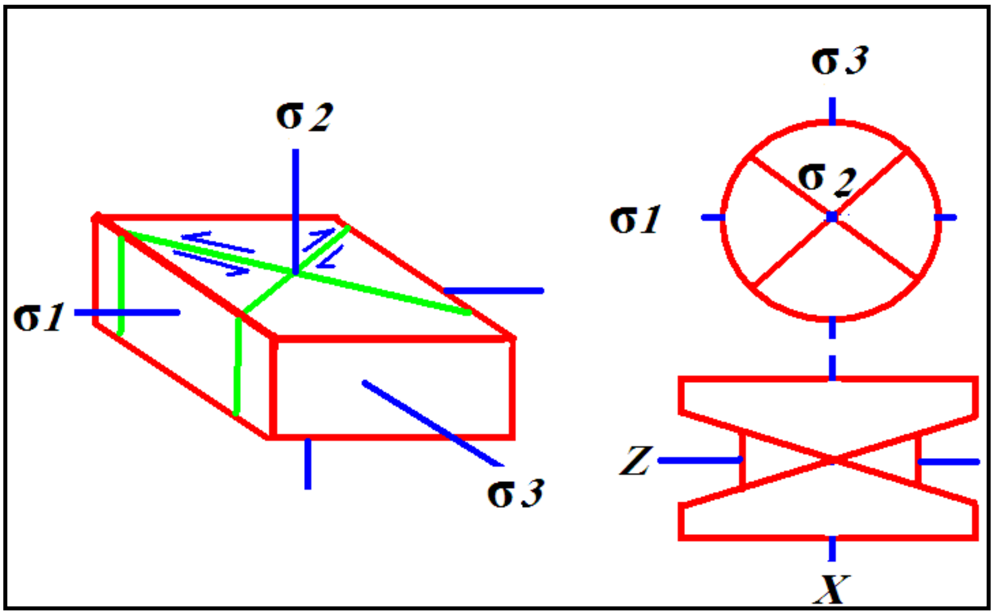


Fig. (3.29) Structural cross section, along Marmarica Uplift and Marmarica Terrace, (as indicated by red line on the location map). after ECL,2004.

3.4 Geometrical Analysis and Stress Model

For geometrical analysis, the strike and dip of both faults and joints are measured in the field then plotted on the lower hemisphere projections .As the faults and joints represent the response to applied stresses, the pole plots, on the stereonets, are taken to estimate the nature of the paleostresses involved or at least to place broad limits on the possible orientations of those stresses. This estimation is carried out as the present structural features have been formed under similar stress conditions and where each set within the faults and joints exhibits inconsistent cross-cutting relationship with the other sets. The result is that each pole plot reflects the main conjugate and contemporaneous structural sets.

Therefore, each pole plot displays two conjugate great circles. Using Bucher's method (Phillips 1960) or Dihedral method (Leyshon and Lisle 1996), the intersection of conjugated great circles on the pole diagram represents the orientation of the intermediate stress σ_2, whereas the principle and least stresses σ_1 and σ_3 are coincident with the directions of acute and obtuse bisectors between these circles respectively (Fig. 3.30).



(Fig, 3.30) showing the fault orientation in relation to principal stress and strain axes.

In the study area, the analysis is accomplished once for whole faults and joints, and then carried out for the joints present in each or group of formations. Geometrically, the strike and dip of about 130 faults are measured in the field by using satellite image then plotted on the lower hemisphere projection by the Win-Tensor software was utilized to determine the principle stress axes of faults in the study area. This program is free source program developed originally in DOS by Delvaux (1993) and then modified for Windows by Devaux and Sperner (2003). The graphical output of the stress inversion by the Win-Tensor program depicts the projection of the principal stress axes in a lower hemisphere equal-area projection and allows evaluating the overall quality of the result (Delvaux and Barth, 2010).

The direction of the greatest principle stress that is applied to the faults in the study area was represented in (Fig. 3.31). In this figure, the three principal stress axes are represented by a red dot surrounded by a circle for σ1, a triangle for σ2, and a square for σ3. The related horizontal stress axes are represented by large blue arrow outside the stereogram for maximum horizontal stress axis (SH) and red arrow for the minimum horizontal stress axis (Sh). The small circle on the upper left corner of each panel shows the direction and type of the horizontal stress axes.

The histograms to the lower left corner of the stereograms depict the distribution of the misfit angle F5 in the Win-Tensor program weighted arithmetically according to the magnitude for each case. The red arrow refers to the extensional tectonic movements.

On the plot diagram (Fig. 3.31a), it is found that the prominent and conjugated fault trends are striking N45^{o}W and N25^{o}E and dipping commonly 70^{o}NNE and 75^{o}WNW respectively. The attitude of principal stress axes, which is represented by the plunge angle and plunge direction, of the faults are σ1=S13°E (N13°W) /12°, σ2=N 4°W /78°and σ3=S80°W/03°.

On joint plot diagram about 780 joints within the study area are projected (Fig. 3.31b). On this figure, the two main sets of joints are striking N60^{o}W and N18^{o}E and dipping 75^{o}NNE and 80^{o}WNW respectively. The principle stress (σ_1) strikes S22^{o}E (N22^{o}W) and plunges S22^{o}E/18^o, the least stress (σ_3) strikes N70^{o}E and plunges N70^{o}E/4^o , whereas the intermediate stress (σ_2) strikes N20^{o}W and plunges N20^{o}W/72^o.

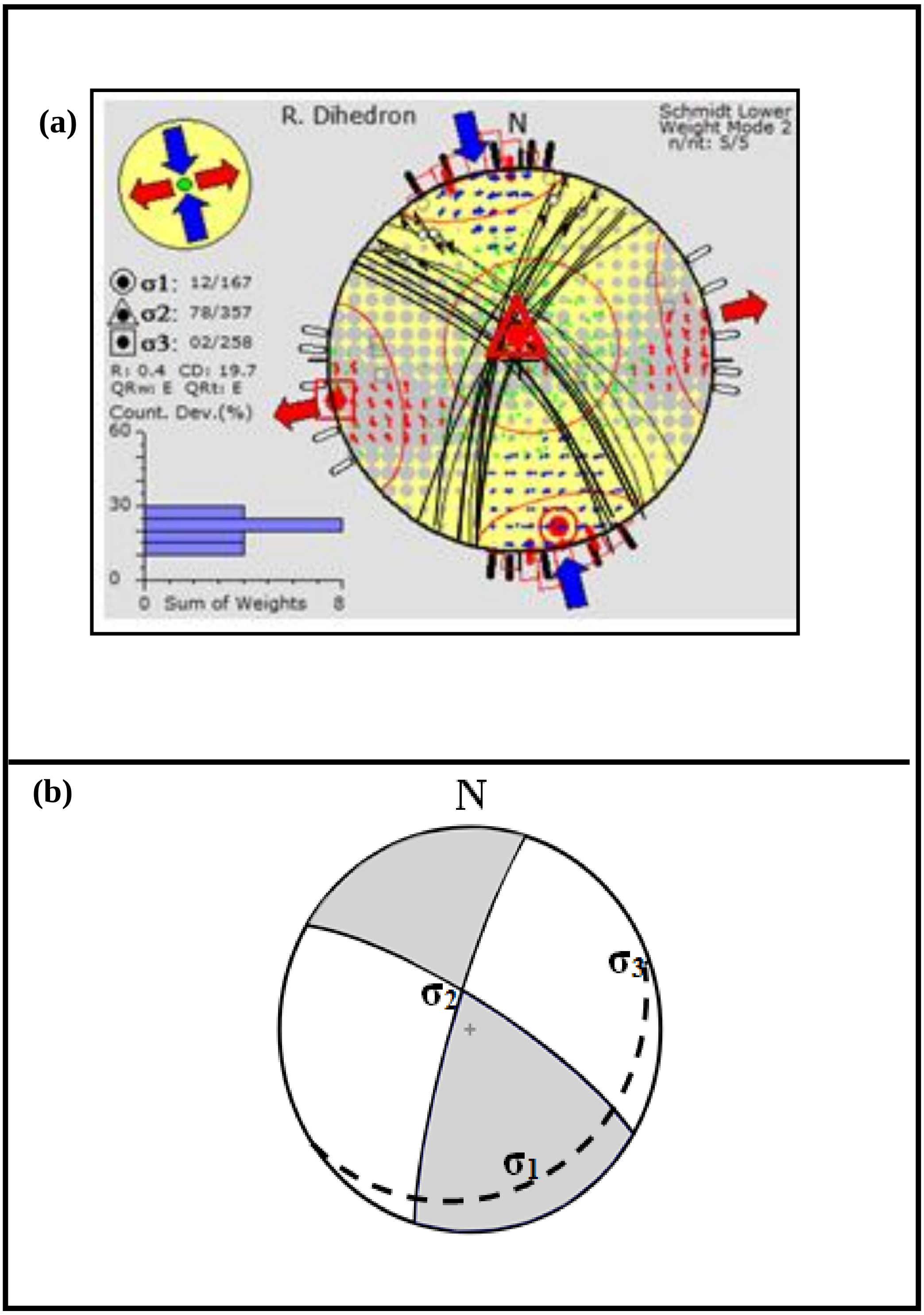


Fig. (3.31) Stereographic projections showing the orientation and stress analysis of (a) NW-SE and NNE-SSW fault subsets and corresponding stress tensor.(b) NW-SE and NNE-SSW joint trends of the study area. In fig (b) The axis of σ_1 lies in the shaded parts.

Similarly, the joint plot diagram in Al Majahir Formation showed that the principle stress (σ_1) trends S15°E (N15°W) and plunges S15°E/20°, the least stress (σ_3) orients S70°W (N70°E) and plunges S70°W/4°, while the intermediate stress (σ_2) is acting along N32°W and plunges N32°W/70° (Fig. 3.32). In Al Bayda and Al Abraq formations, the principle stress (σ_1) strikes S15°E (N15°W) and plunges S15°E/25°, the least stress (σ_3) orients S75°W (N75°E) and plunges S75°W /7° and the intermediate stress (σ_2) is acting along N12°W and plunges N12°W/65° (Fig. 3.32). On the other hand, in Al Jaghbub Formation, the three principle stresses σ_1, σ_2 and σ_3 give the same attitudes in Al Bayda and Al Abraq formations (Fig. 3.32). This is due to the stress analysis of Al Abraq Formation is carried out on two major sets of joints which are approximately coincident with those in Al Bayda and Al Abraq formations. Accordingly, the Oligocene principle stresses are continued with their attitudes during the Miocene time and thus with the same major trend of joints. The difference in the accompanied sets of joints in the Oligocene is most probably attributed to the rheology of the Oligocene rock units.

To sum up, the associations of the strike slip, thrust and normal faults, pop up structures, shear and tensional joints with folds are developed due to the movement along the NE-SW shear zones and assume style of dextral wrenching regime.

The approximate locations and orientations of stresses in faults and joints with the trend of folds promote exclusively the existence of simple shear rather than pure shear mechanism in this regime. This encouraged us to propose stress model accommodated with the association of these structural elements as such explained by some authors (i.e. Abdel Khalek et al 1989, Dewey et al. 1998, Holdsworth et al. 2002, Marques and Coelho 2003, and El Amawy et al. 2011).

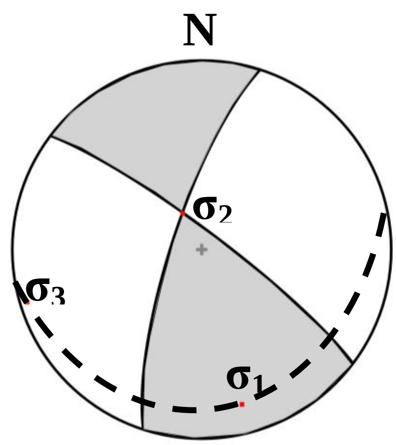
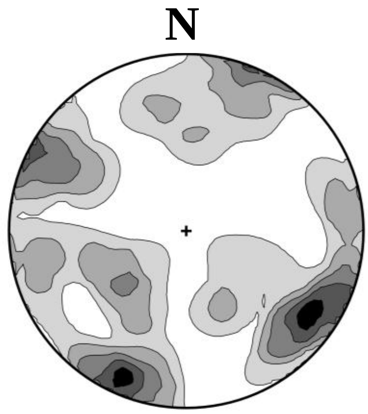
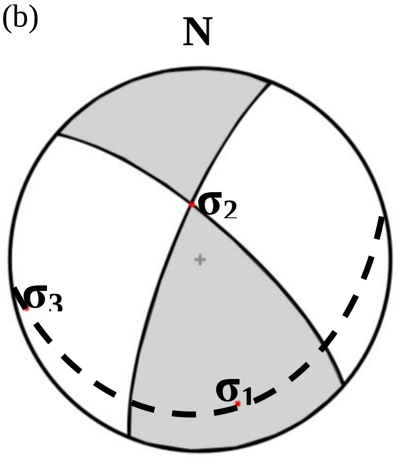
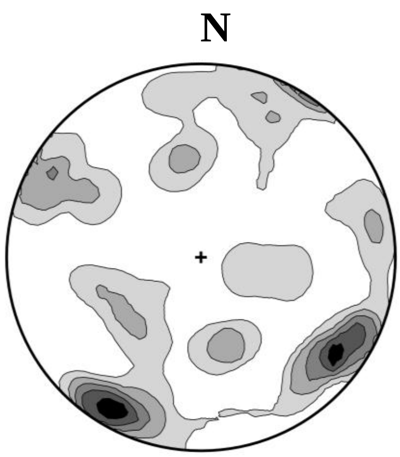
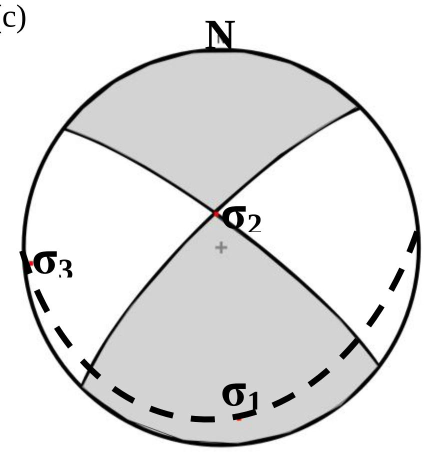
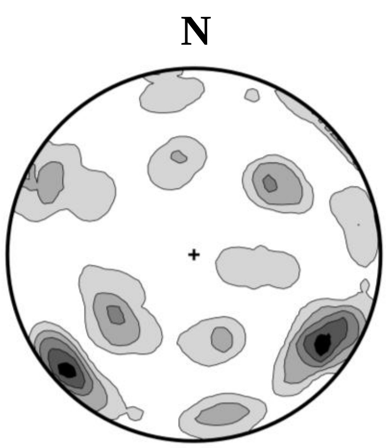
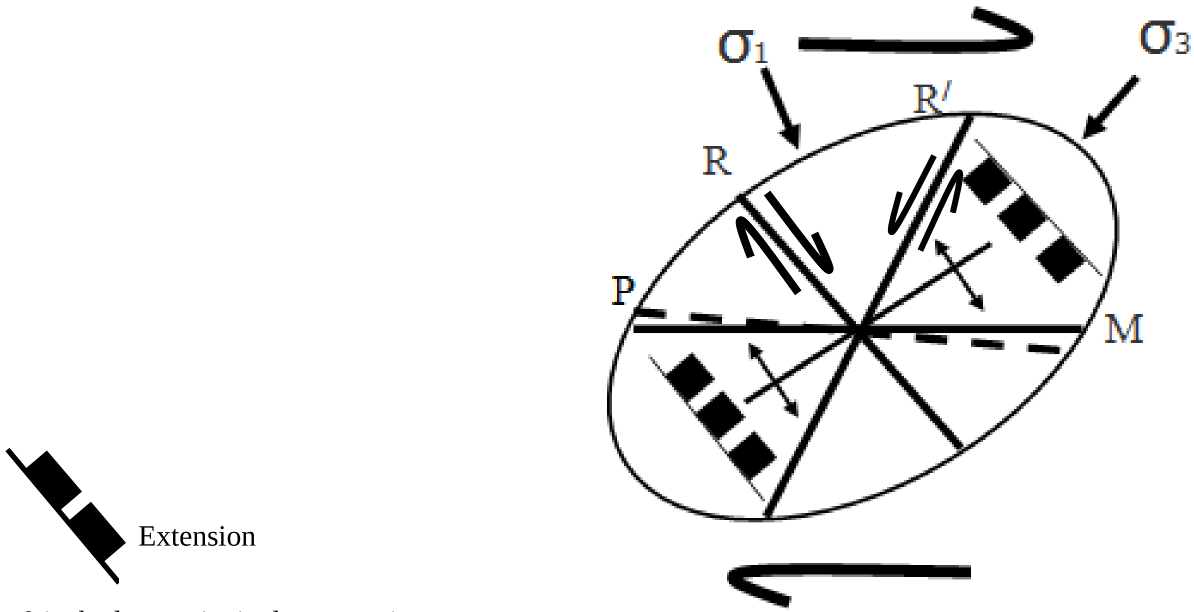
Formation	Stress analysis	Equal area lower hemisphere projections
Al Majahir	(a) 	 229 poles, contours 0, 1, 2, 3, 4 per unit area
Al Abraq and Al Bayda	(b) 	 345 poles, contours, 1, 2, 3, 4,5,6 per unit area
Al Jaghbub	(c) 	 206 poles, contours 2, 4, 6, 8 per unit area

Fig. (3.32) Equal area lower hemisphere projections showing the orientation and stress analysis of NW-SE and NNE-SSW joint trends in (a) Al Majahir Formation. (b) Al Bayda and Al Abraq formations. (c) Al Jaghbub Formation. The axis of σ_1 lies in the shaded parts.

On the ellipse diagram (Fig. 3.33), the NW-SE dextral strike slip fault trends are kinematically coincident with the Riedel shears (R), while the approximate N-S to NNE-SSW sinistral strike slip fault trends are the main system of conjugated Riedel shears ($R^{/}$). Both shear trends intersect at acute angles with the trend of the main shear zones. The WNW-ESE fault segments represent P shears as they developed on and parallel to the E-W fault trends. The main shearing (M), on the other hand, represents the E-W trend of the main shear zones.



σ3 is the least principal stress axis

σ1 is the greatest principal stress axis

R= Riedel shear = N45^{o}W

$R^{/}$ = Conjugated Riedel shear = N25E

M = Main shear = E-W

P = parallel shear to the Main shear.

Fig. (3.33) Proposed stress model illustrating the structural patterns in the study area.

Chapter Four

Tectonic Evolution

4.1 Introduction

The Upper Cretaceous–Tertiary successions cover commonly the northern part of Libya. The Cyrenaica region in northeastern Libya has a long geologic history ranging from the Paleozoic to Late Miocene. Structurally, it is divided in two major parts separated by the Cyrenaican fault system; Cyrenaica platform to south and Cyrenaica uplift in the north, El Hawat and Abdulsamad (2004). The first covers the central and southern parts of Cyrenaica region, while the second subdivision involves Al Jabal Al Akhdar - Marmarica uplifts in northern Cyrenaica. In Cyrenaica platform, the Paleozoic sediments represent the main succession in the geologic column relative to the Mesozoic and Tertiary cover, Röhlich (1980) . However, in the Cyrenaica uplift an almost complete column of Mesozoic and Tertiary is documented. Confirmation is added, in this latter respect, where the Paleozoic has not been penetrated by the existing wells. As already stated before, the inversion in Al Jabal Al Akhdar and Marmarica uplifts (Cyrenaica inverted basin) is a phenomenon of Alpine orogeny and related to the convergence between the African and European plates during Late Cretaceous-Miocene. Thereby, several tectonic phases have been created during this convergence and were responsible for the formation and evolution of the different structural elements in Al Jabal Al Akhdar- Marmarica uplifts, El Arnauti et al. (2008).

To establish an understanding evolutionary scenario on the tectonics of the study area, it is essential to refer to and discuss the previous tectonic studies in Al Jabal Al Akhdar- Marmarica areas and other concept on the tectonics as follows:

4.2 Previous tectonic studies

Röhlich (1974 and 1980) has subdivided the exposed pre-Quaternary sediments in Al Jabal Al Akhdar into three structural stages. The limits between them are separated by unconformities.

1. The lower structural stage is represented by Qasr Al Abid and Al Baniyah formations (Cenomanian - Coniacian). This stage may also include the Lower Cretaceous sediments, which are encountered in the study area by deep drillings. During this stage, both formations were affected by the intra-Senonian orogeny as recorded by the NE-SW to ENE-WSW trending intense Santonian folding episode in the central part of Al Jabal

Akhdar. Jardas Al Abid fold considers an example in this part. The Santonian folding was enough high to a degree the erosional truncated beds of Al Baniyah Formation are recorded as the main tectonic event of this stage.

2. The middle structural stage is represented by Al Majahir, Wadi Dukhan and Al Uwayliah formations (Campanian - Landenian). The formations, during this stage, are slightly deformed as compared with the lower ones. However, the cycle of sedimentation was ended at the beginning of the Eocene. In general, the folding during this stage was slight but affected a larger area as compared to the Santonian folding episode. Extension the folding to Landenian age (Al Uwayliah Formation) led to the emergence beyond the central part of Al Jabal Al Akhdar. In this concern, Röhlich (1980) added a large area in NE Libya was emerged and the strata of the preceding sedimentary cycle were eroded from the highest parts of the NE-SW trending tectonic arch. The uparching led to subsequent erosion and thus produced a regional unconformity between the Late Cretaceous and the overlying Tertiary rocks. Herein, Röhlich (op.cit.) attributed the lacking of the Palaeocene strata to this erosion. Despite this, the fieldwork in the present area showed that the paucity and even missing of the Maastrichtian (Wadi Dukhan Formation, Palaeocene (Al Uwayliah Formation) and Early to Middle Eocene (Apollonia and Darnah formations) over the Late Cretaceous exposures is most probably related to the Late Cretaceous uplift and not completely to the erosion. Hence, by the end of Late Cretaceous, the uplift resulted in undulated topography by which the subsequent deposition was controlled by lows and highs; thick sediments in lows, lacking and missing on the highs. Moreover, the basins along the northern Africa-Arabia plate recorded strong subsidence during Palaeocene-Early Eocene times (Chatellier and Slevin 1998). In the present area, angular unconformity is markedly noted with the Late Cretaceous / Oligocene boundary, where the moderately dipping beds of Al Majahir Formation are overlain by the gently dipping Al Bayda Formation.

3. The upper structural stage comprises all remaining younger formations (Middle Eocene-Middle Miocene) and largely covers Al Jabal Al Akhdar and Marmarica.

In general, the sediments of the later stage form a very flat NE-SW arch and are subdivided into subsidiary lows and highs (basins and domes) and hence the shape of the structure corresponds roughly to the present morphology without taking into the account the wadis and escarpments. Based on the subdivision of the whole structure into lows and highs, Röhlich (1974) recognized all fault trends in Al Jabal Al Akhdar as normal faults without investigation and analysis of the kinematic indicators along their planes (Fig. 4.1).

El Hawat and Abdulsamad (2004), on the other hand, extended their view to consider the southern limit of Al Jabal Al Akhdar as down faulted to the north forming the coastal plain along the Mediterranean coast.

Following studies by some authors (e.g. El Werfalli et al. 2000, El Hawat and Abdulsamad 2004) related the tectonic inversion of Al Jabal Al Akhdar to compressive forces generated from the convergence between the African and European plates during the Alpine orogeny. The impact of this inversion is reflected on the stratigraphic record of northern Cyrenaica and evidenced by repeated syn-depositional mass movements, unconformities and post-depositional deformation structures. They added the timing of northern Cyrenaica tectonic events is gleaned from surface and subsurface data, where the subsidence along the Cyrenaica fault was initiated during the Triassic and when the Pangaea started to break up. This subsidence is then accelerated during middle Jurassic - Early Cretaceous time and with the opening of the Tethys. Late Cretaceous time is themed with the Alpine orogeny during which the downwards movement of Cyrenaica basin (located north Cyrenaica fault) was terminated and reversed in response to the accelerated compressional influence of this orogeny. This inversion is followed by tectonic pulses during the Santonian, Paleocene, Early-Middle Eocene, Oligocene and finally at the end of Miocene. In this context, the mentioned authors showed that Al Jabal Al Akhdar is tectonically developed during two main phases. The first phase was started by compressive forces, which induced right-lateral wrenching, during Late Cretaceous-Miocene and formed style of NE-SW to ENE-WSW trending folds accompanied with the alignment trends of major normal faults. The second tectonic phase was started at the end of Miocene by the vertical uplifting and overprinting the earlier wrench tectonic signature in response to the increased influence of the Mediterranean ridge.

The result is the configuration of this structure is conformable with Röhlich (1974 and 1980) but the difference is the current authors assigned the structural features to right-lateral wrenching of the Alpine orogeny instead of pure block-faulting mechanism. Despite this, a contradictory is taken on the arguments of El Werfalli et al. (2000), El Hawat and Abdulsamad (2004) where the alignment of normal faults with the fold trends is kinematically away from the basic concepts of shears in right-lateral wrench tectonics. Other discrepancies, El Hawat and Abdulsamad (2004) extends their views to consider the northern limit of Al Jabal Al Akhdar as down- faulted boundary separated from the Mediterranean ridge further north into the offshore by narrow and steep continental margin. In contrast, the published swath bathymetry and seismic reflection data from

Hugan and Mascle (2001) considered this boundary as over thrust boundary between the Cyrenaican continental slope in the south and the Mediterranean ridge in the north and is regarded as an incipient continental collision process.

El Arnauti et al. (2008) stated that during the Late Jurassic-Early Cretaceous, WNW-ESE and E-W faults are developed in Al Jabal Al Akhdar and considered as rift faults developed along the northern edge of the Cyrenaica platform. Rifting of this generation formed the Marmarica terrace and the north Cyrenaica rift system on the southern margin of the Tethys (Fig. 3.1). During this phase the overall movement of Africa was towards the ENE but with differentiations in magnitude within the sub-plates and the regional strain field can be described as a dextral rotational shear. The north Cyrenaica rift system is characterized by thick syn-rift sediments which constitute the shape of a half graben along its southern edge with the Cyrenaica fault zone. In this concern, they added the Cyrenaica fault zone distinguishes also the Marmarica fault terrace as a faulted step-down on the northern margin of the Cyrenaica platform. The main phase of rifting is recorded, during the Tithonian-Early Aptian, from stratigraphic evidences and appears to have ceased in the Albian. However, the general NW-SE extensional regime in Al Jabal Al Akhdar is continued throughout the Cenomanian and, consequently, produced a series of planar block faults along which subsidence (thermal subsidence) has been occurred. During Late Cretaceous-Paleogene, the main north Cyrenaica fault zone and internal rift faults were reversed by compressional events of a contraction regime forming the NE-SW, E-W to WNW-ESE folds accompanied with E-W and WNW-ESE strike slip faults (Laubscher and Bernolli 1977, Abdel Khalek et al. 1989, Moustafa and Khalil 1989, Anketell 1996, Suleiman 2007, El Arnauti et al. 2008, Farag 2009 and El Amawy et al. 2011).

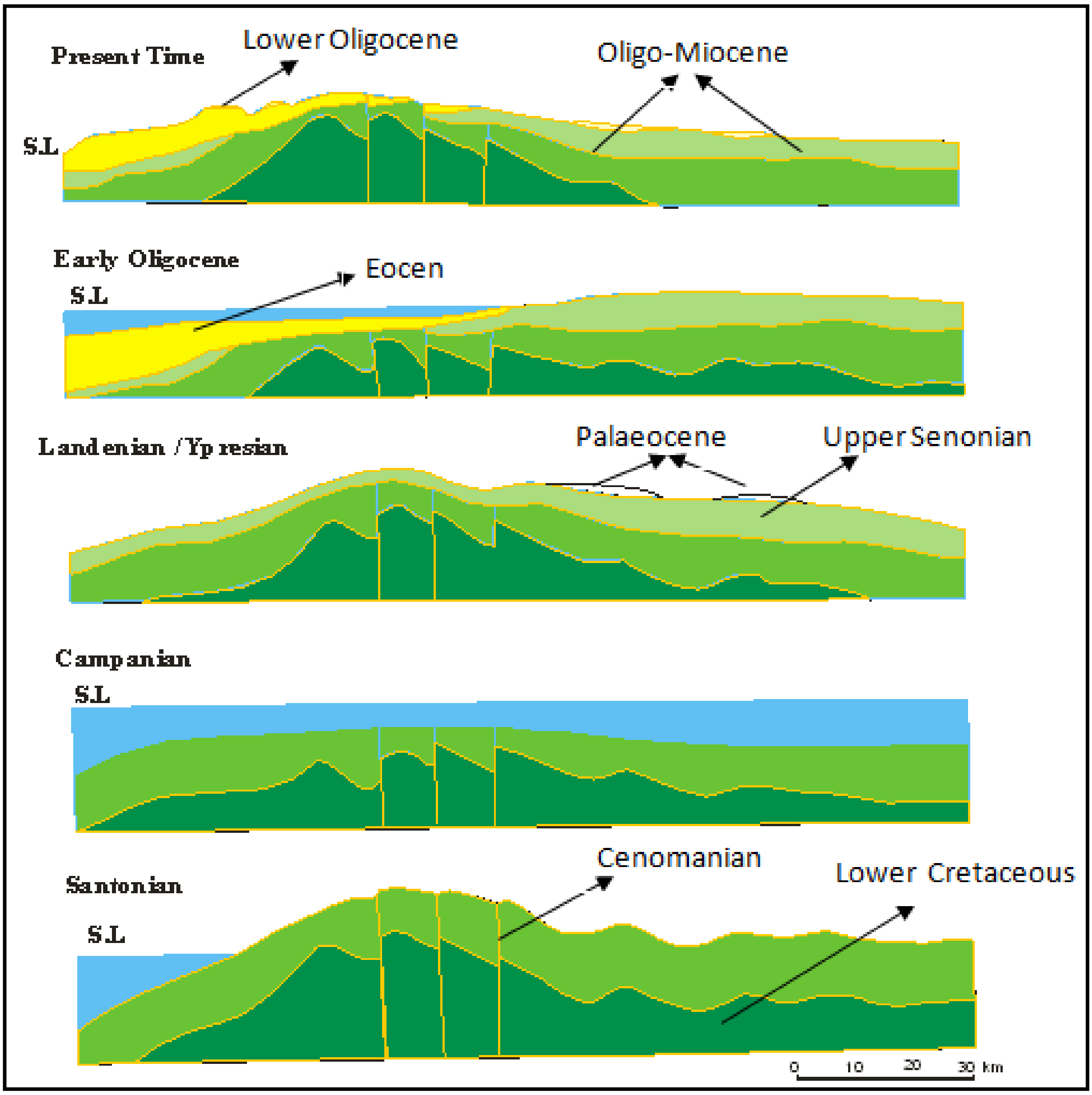


Fig. (4.1) Scheme of the tectonic development of the Al Jabal Al Akhdar in cross section (after Rohlich,1980).

4.3 Tectonic evolution of the study area

Tectonically, Al Jabal Al Akhdar - Marmarica uplifts consider a prominent promontory of sedimentary belt overlooking the southern margin of the Tethys and, consequently it is formed in response to the Alpine orogeny. In light of the aforementioned structural analysis, this orogeny commenced intensively in Late Cretaceous then continued but with mild effect during Tertiary times. Geometrically, the present structures reflected a dextral compressional shear model that accommodates with the wrench tectonic regime. Accordingly, they are themed by E-W to WNW-ESE majors strike-slip shear zones that is confined inside a system of ENE-WSW trending folds, NW-SE dextral strike-slip faults (Riedel shears R_1), N-S to NNE-SSW sinistral strike-slip faults (conjugate Riedel shears R_2), NNW-SSE normal faults and associated joints. Comparably, these structures are dominated with brittle to ductile effect in the Upper Cretaceous and a main factor of brittle to local ductile effect upwards in Tertiary. This effect played an important role in paleogeogrphic distribution of strata and the tectonic evolution in the study area is dealt with through successive three tectonic stages; one in Late Cretaceous and two in the Oligocene and Miocene.

4.3.1 Late Cretaceous tectonic Stage

The deep seismic data does not glean any knowledge of Palaeozoic underlain Al Jabal Al Akhdar Trough; the subsurface data outlined Triassic to Early Cretaceous of transistional and, elsewhere continental facies in the central area and further south to marine facies in the north (El Werfalli et al. 2000, El Hawat and Abdulsamad 2004). In northern Africa, Late Triassic-Early Jurassic marked the initial rifting, which enhanced in the Middle Jurassic by the opening of the Neotethys. The rifting resulted in relaxation and drifting away of small continental blocks to the north forming the southern margin of the Neotethys (Biju-Duval et al. 1979, Argyriadis et al. 1980, Robertson and Dixon 1984 and Dercourt et al. 1986). This effect extended until the Early Cretaceous and during it North Africa behaved like a passive continental margin. The result is the formation of extensional or normal faults along this margin. Opening of the Neotethys, on the other hand, was the source of transgression and deposition most of the Mesozoic sediments within the normal fault zones and alignment rift basins. The present Cyrenaica fault system and their alignment consider the traces of these underlying normal faults. Late Cretaceous tectonics represents the main structural inversion event and initial closure of the Neotethys but revealed, in the study area, by one sub-stage during the Campanian age.

4.3.1.1 Campanian tectonic substage

Locally in the study area, the uplift and erosion, by the end of Campanian, shaped uneven topography that controlled in the distribution and thickness changes during the subsequent sedimentation. Markedly, this is represented by angular unconformity between Al Majhair Formation and the overlying characteristic successions of Algal limestone Early Oligocene of (Al Bayda Formation). On the map (Fig. 4.2), Al Majahir Formation is not thicker and occupies just small areas along the southeastern sides of the study area (Wadi Al Raheb in particular). During this stage, the Santonian structure is rejuvenated again and resulted in subsequent erosion produced a second and major unconformity with the Tertiary boundary. This accounts from the paucity of the Maastrichtian, Paleocene and Eocene outcrops (Wadi Dukhan, Al Uwayliah, Apollonia and Darnah formations) in all parts of the area. In this context, some authors (e.g. Röhlich 1974 and El Werfalli et al. 2000) reported that the Palaeocene was initiated by a major transgression at the beginning of the Danian. This means that most outcrops during Late Cretaceous were high enough during this transgression and hence led to lacking and non-deposition, at least, the lower part of the Palaeocene on the higher lands. This explanation with the continuity of uplifting during most of the Palaeocene and Eocene induced paucity and missing of the Palaeocene and Eocene outcrops in the whole area, which were totally attributed to the subaerial erosion by Röhlich (1980).

Structurally, this tectonic sub-stage is formed under brittle regime and developed dextral movement along E-W to WNW-ESE striking faults that produced E-W, NW-SE, and N-S to NE-SW shear fractures in Al Majahir Formation.

4.3.2 Oligocene tectonic stage

As shown in Figures (4.2 and 4.3), Al Bayda and Al Abraq formations (Early-Late Oligocene) are restricted only further the southeastern part of the study area (at Wadi Al Raheb and the coast line of Al Burdia town) and exposed at levels 20 - 50m. To the north, where the Al Bayda Formation is missing, Al Abraq Formation (Middle-Upper Oligocene by Duronio et al. (1991) or Upper Oligocene; Late Rupelian-Chatian, by El Hawat and Abdulsamad (2004) is relatively extensive and attains the same level of elevation. In contrast, both formations are completely missing in the northwest and southwest of mapped area (Figs. 2.1 and 4.3). Taken together these features with the impact of structural elements there is indicative of remarkable tectonic changes had been occurred during the Oligocene from extension to compression.

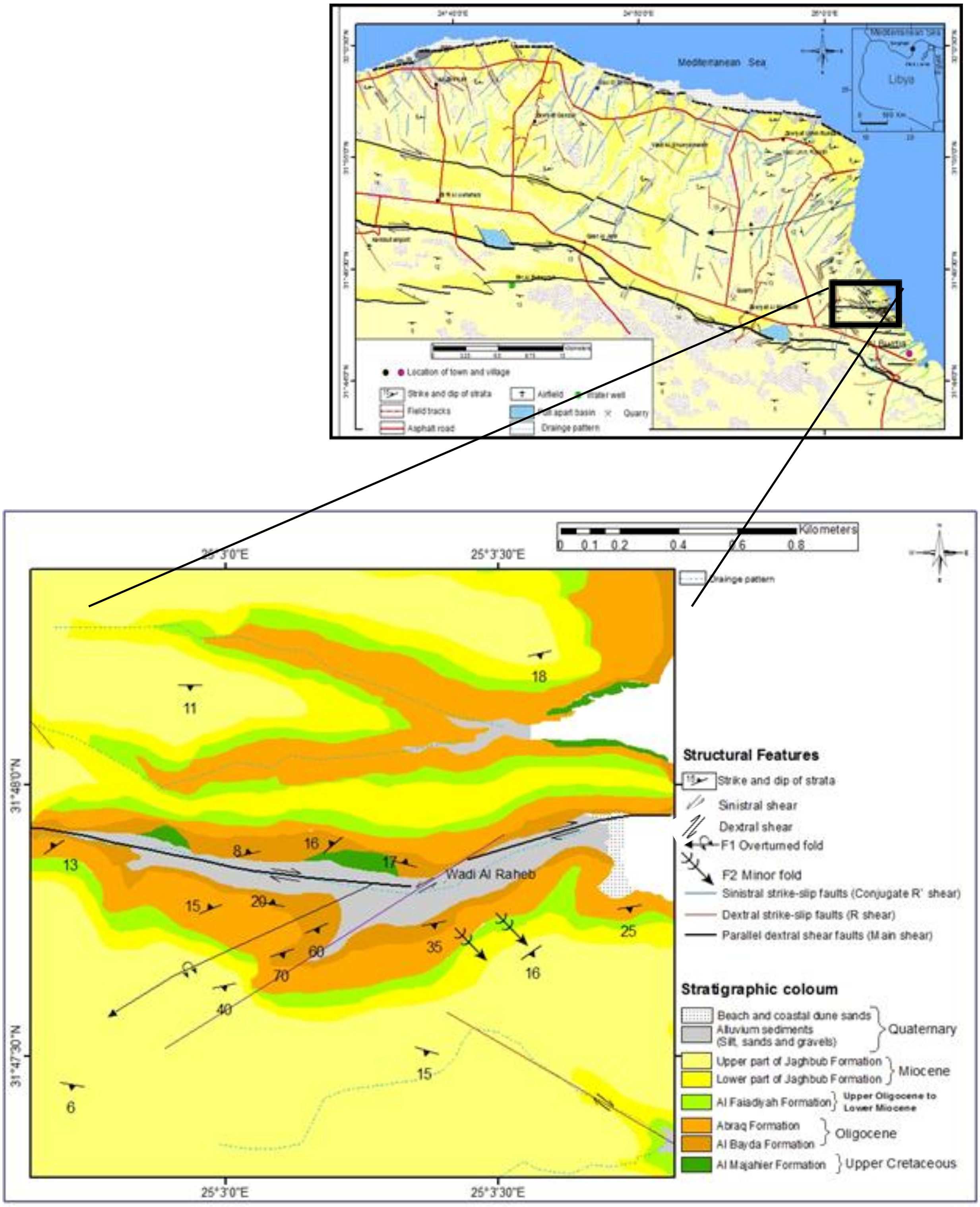


Fig. (4.2) Geological map focused in Wadi Al Raheb showing the distribution of Al Majahir, Al Bayda and Al Abraq formations.

To the north of Wadi Al Raheb the upper part of Al Bayda Formation (Algal Limestone Member) exhibits variations in the topography and thickness and sometimes pinches out leading to the contact between the overlying Al Abraq Formation and underlying Al Majahir Formation (Fig.4.2). This explains existence of a major unconformity with the Cretaceous /Oligocene boundary and how the emergence shaped the base on which Al Bayda Formation was deposited.

Missing of Shahhat Marl Member showed a remarkable large unconformity surface with the Cretaceous /Oligocene boundary and reflected a regressive phase and

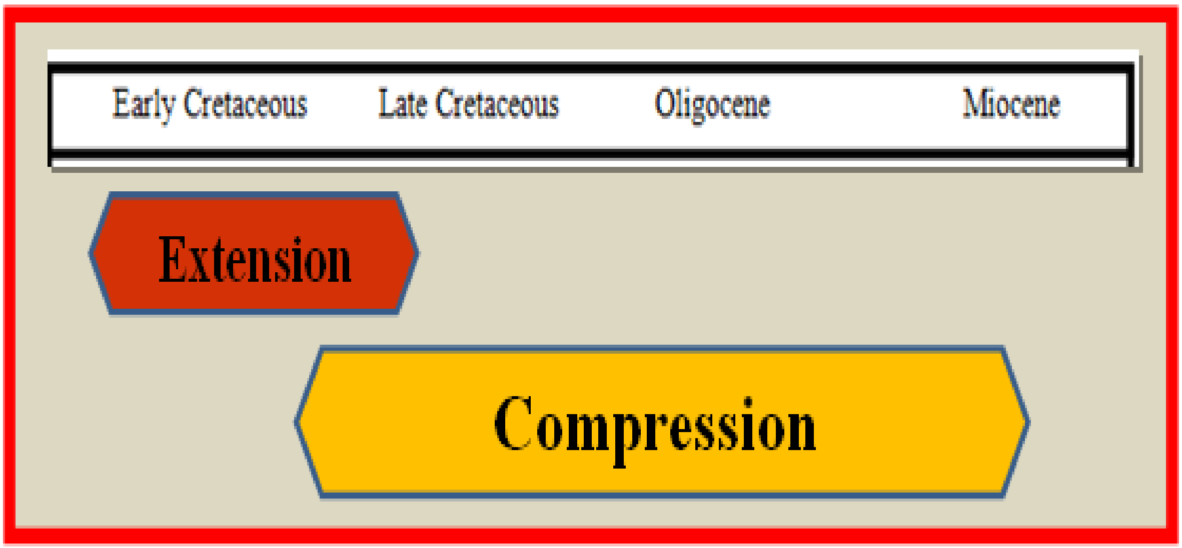
the emergence of a larger area at the end of Late Cretaceous to Early Oligocene. The emergence is related to the movement within the E–W shear zone and is themed by the spectacular feature of the small and minor F1 and F2 folds. Confirmation is added east of Libya from Issawi et al. (1999) whom showed that the Chatian age (Late Oligocene) marks the start of the main phase of Early Miocene extension in the Red Sea region and that terminated at about 21Ma; a boundary between Aquitanian and Burdigalian (Omar and Steckler 1995). However, dating of Al Faidiyah Formation in Al Jabal Al Akhdar whether it belongs to Late Oligocene or Early Miocene is still under debate (Röhlich 1980, El Werfalli et al. 2000, El Hawat and Abdulsamad 2004, El Mehdawy and El Beialy 2004 and El Amawy et al. 2011).

The unconformity noted further east in Wadi Al Al Raheb between Al Abraq and Faidiyah formations indicates retreating of the sea by the end of Al Abraq deposition (i.e. after Late Oligocene) and the oncoming into the Early Miocene by Al Faidiyah Formation. During the Oligocene tectonic stage, the dextral movement was continued with brittle force and produced the E-W, N-S to NNE-SSW striking strike-slip faults, which were still active. Also ductile forces formed F_1 and F_2 overturned and tight folds along ENE-WSW to NE-SW trends in Al Bayda and Al Faidiyah formatins (Fig. 4.2).

4.3.3 Miocene tectonic stage

On the mapped area (Fig. 4.4), the Early-Miocene of Al Faidiyah Formation exists mainly in the eastern part of the area and is missing in the other parts, while the Middle –Late Miocene transgression of Al Jaghbub Formation is covered most the parts. These features reflected the changes that occurred in the tectonic regime from compression to extension. The ductile and brittle forces are still active but with slight effect and accompanied by development of F_3 Major fold with normal faults and accompanied tensional joints. In the south of Al Burdia area and southwest at Qasr Al Gadi, an array of NNW-SSE normal faults is plotted and showing southwest downthrows (Fig. 3.2). However, the dextral displacement of the Quaternary on the both sides of the Northern Displacement Shear Fault (NDSF) and Southern Displacement Shear Fault (SDSF) suggests that the reactivation is still continued, but locally, in the study area (El Amawy et al. 2011).

In the study area, the tectonic evolution starts with inversion of the extension faults during Late Cretaceous-Miocene times, in response to a right lateral compressional shear. This inversion led to compression of the Marmarica basin and development of strike-slip faults. These faults were developed due to the movement of Africa westward relative to Europe during Late Cretaceous time (Figs. 4.3).



(Fig 4.3) Summary of the tectonic development of the study area.

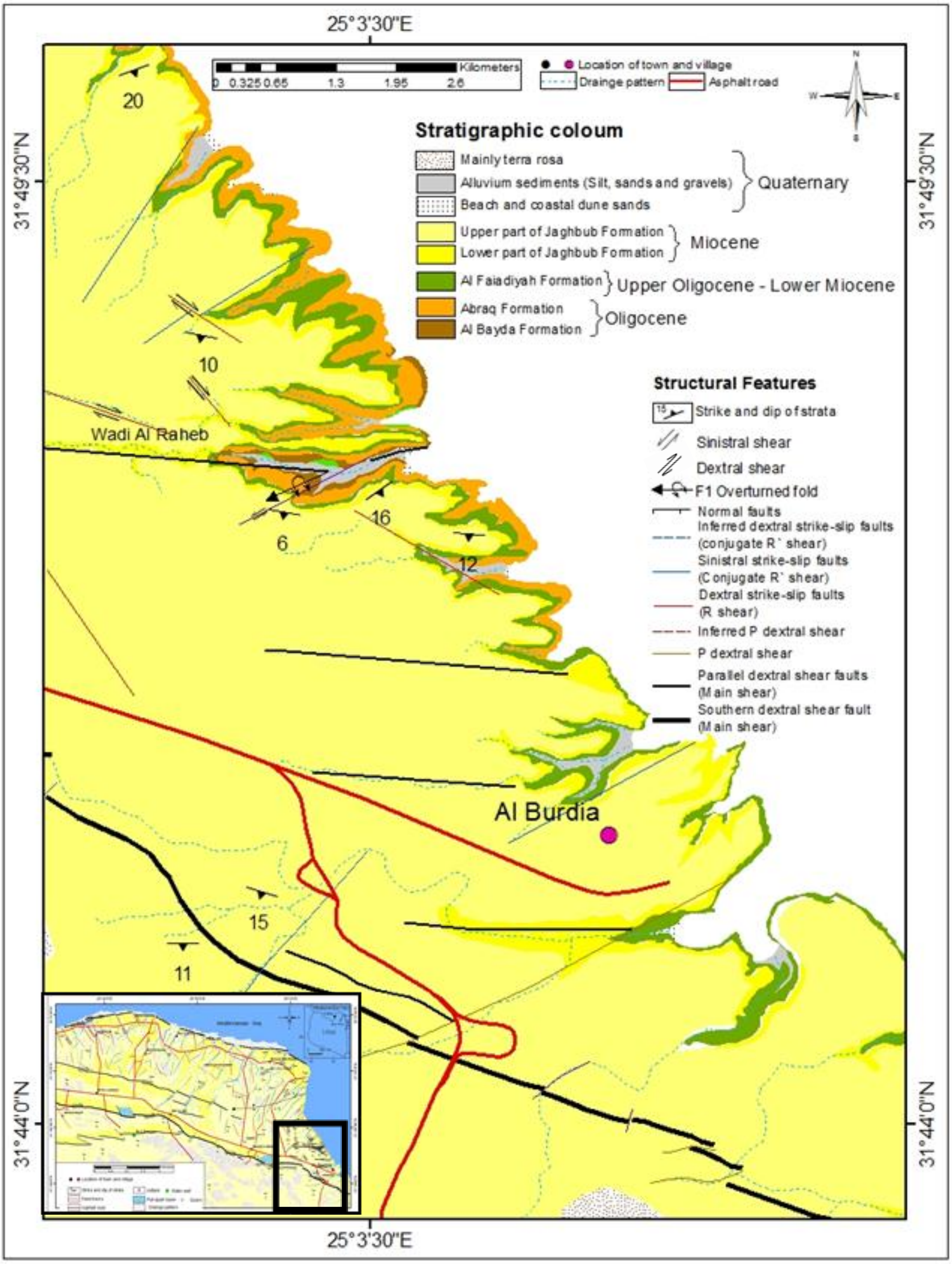


Fig. (4.4) Geologic map along the eastern side of the southern part of the study area , showing the distribution of Al Faidiyah and Al Jaghbub formations.

Conclusions

- The field geological mapping of the stratigraphic sequence confirmed at the contacts by microscopic observations. Stratigraphically, this sequence is started in the base by hard dolomitic limestone and marly limestone of Al Majhair Formation of Upper Cretaceous. Unconformably, this formation is overlain by Early Oligocene Al Bayda Formation then Middle to Late Oligocene Al Abraq Formation. The latter is followed by younger sediments Al Faidiyah Formation (Late Oligocene - Early Miocene) and Al Jaghbub Formation (Middle Miocene). In general, this stratigraphic sequence emphasizes shallow marine facies but is characterized by open marine conditions in the north and northwest.
- The structural setting, geometrical and stress analysis of folds, faults and joints can be summarize as the following:
- Folds are recognized, based on their intensity and style, into three phases (F_1, F_2, and F_3). F_1 fold is the oldest and recorded in Al Majahir and Al Bayda formations. The fold is recognized as overturned plunging anticline and its axis orients approximately ENE-WSW and extends for about 2km. F_2 folds are developed also at minor scale about 5.5km northwest of Al Burdia, in Al Faidiyah Formation. These folds are trending NE-SW with a general vergence SSE. Their styles are tight, overturned, open and asymmetric. F_3 phase of folding is a major and represents the final phase of folding. It is plunging SW and ended by the present morphology of gentle and elongated folding during Oligocene to Miocene ages.
- Faults are most prominent in the study area and markedly concentrated in al Burdia area and recognized by three main trends; the NW-SE dextral strike slip faults (synthetic shears) , N-S to NNE-SSW sinistral strike slip faults (antithetic shears), and E-W fault trends. Other array of the NNW-SSE normal faults are also encountered and run approximately perpendicular the folding axes. Kinematic indicators along these faults are documented in the field on the slickensides, flower structures, small scale of dextral and sinistral displacement, and pop up structure indicated that the sequence of faulting is initiated by pure wrenching and, in part, transpression in Late Cretaceous -Oligocene then continued with pure wrenching afterwards until the Miocene.
- Joints are distinguished into two types; shear and tensional joints. In the present area, the joints are regular and, sometimes, irregular and along their planes there are little or no displacements.

- The interpretation of the subsurface study of the two 2D seismic lines shows integration with surface analysis of the structure elements and confirms the surface geological mapping of the study area.
- The stress analysis diagrams in faults and joints with the trend of folding axes are accommodated with the model of simple shear mechanism in the study area. In this model, the NW-SE dextral strike-slip fault trends are kinematically coincident with the Riedel shears (R), while the approximate N-S to NNE-SSW sinistral strike slip fault trends are the main system of conjugated Riedel shears ($R^{/}$). Both shear trends intersect at acute angles with the major northern and southern shear faults (NDSF and SDSF). The ENE-WSW faults segments represent P shears on the major shear faults (master shear, M). This model assumed a principle horizontal stress acted from the NNW ($N10^{o}W$) direction.
- The tectonic evolution starts with the inversion of the extension faults during Late Cretaceous–Miocene times in response to a right lateral compressional shear. This inversion led to uplift of the Marmarica basin and development of strike-slip faults due to the movement of Africa westward relative to Europe during Late Cretaceous time. Based on this structural configuration and time constraints on each deformation, the study area is evolved through successive three tectonic stages as follow:
- Late Cretaceous tectonic stage is developed via dextral movement within about 20km wide E-W to WNW-ESE displacement shear zone that produced array of NW-SE with minor E-W to WNW-ESE dextral strike-slip faults that are linked with other N-S to NNE-SSW sinistral strike-slip faults and different styles of folds forming intricate structural pattern in the study area.

- Oligocene tectonic stage indicated the dextral movement continued with brittle to ductile structure producing the rejuvenation on the pre-existing E-W, WNW-ESE, NW-SE, N-S to NNE-SSW strike-slip faults, NNW-SSE normal faults and folds, which were still active in younger times.

- Miocene tectonic stage indicated the ductile and brittle forces are still active but with slight effect accompanied by development of F3 Major fold with normal faults and accompanied tensional joints. In the south of Al Burdia area and southwest at Qasr Al Gadi, an array of NNW-SSE normal faults is plotted and showing southwest downthrows.

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الملخص

يمتد مرتفع مارماريكا تقريبا شرق –غرب على طول الساحل الشمالي الشرقي من ليبيا ويحد الحافة الشمالية الشرقية من مسطح سيرينايكا. في السابق، هذا الرفع متعلق بصدع عادي من الحافة الشمالية من مسطح سيرينايكا، وآلية الرفع عبر تشوه التكتونيات ذات الحركة الأفقية لا تزال تفتقر وبعيدا عن أن تكون مفهومة تماما. تمثل منطقة البردية الجزء الشرقي من مرتفع مارماريكا ويمكن الوصول إليها من الطريق الرابط بين طبرق وامساعد وبعض الطرق والمسارات الترابية التي تساعد في الوصول الي المكاشف الصخرية .رواسب حقب الكريتاسي الأعلى إلى الميوسين تغطي المنطقة, وتمثلت بتكوينات من الأقدم إلى الأحدث كالتالي: تكوين المجاهير والبيضاء والابرق والفايدية والجغبوب ويمثل السطح الفاصل بينها وبين الحقب الرباعي سطح عدم التوافق. مع العلم صخور الباليوسين والايوسين مفقودة كلياً.

تم تقسيم الطيات إلى ثلاث حالات (F1,F2,and F3) بناءً عل حدتها, F1 هو الأقدم وتم تسجليه في تكوين المجاهير والبيضاء وصنفت عل انها طيات محدبه ومقلوبة ومحورها يوازي تقريبا شرق شمال شرق –غرب جنوب غرب ويمتد لمسافة 2 كم. ,من جهة اخري طيات F2 تكونت على نطاق صغير وعلى بعد 5.5 كم شمال غرب البردية، في تكوين الفايدية. وتتجه محاورها شمال شرق–جنوب غرب. أنماطها ضيقة، منقلبة، مفتوحة وغير متماثلة. مرحلة الطي الثالثة (F3) نمثل المرحلة النهائية من الطي. حيث تتجه محاورها الي الجنوب الغربي وانتهت بالتشكل الحالي للطي الخفيف وممدود خلال الفترة الاوليغوسين – الميوسين.

بالنسبة لتحليل الصدوع فهي كثيرة في منطقة الدراسة وتتركز بشكل ملحوظ في منطقة البردية وتعرف بها ثلاثة اتجاهات رئيسية. صدوع يمينيه تأخذ اتجاهات شمال شمال شرق –جنوب جنوب غرب و صدوع أخرى يسارية

تأخذ اتجاهات شمال غرب –جنوب –شرق . بالإضافة الي مجموعة اخري تأخذ اتجاه شرق –غرب ,,,انواع اخري من الصدوع الطبيعية تأخذ اتجاه شمال شمال غرب– جنوب جنوب شرق . كما تم توثيق المؤشرات الحركية على طول هذه الصدوع في الحقل والتعرف عل العديد من الاشكال التركيبية مثل تراكيب الزهرية، وعلى نطاق صغير من الحركات اليمينة واليسارية.

وتتميز الفواصل إلى نوعين, فواصل القص وفواصل الشد. في منطقة الدراسة، تكون الفواصل منتظمة، وأحيانا تكون غير منتظمة، وعلى طول الاسطح، تكاد تكون قليلة أو معدومة .اخيرا التحليل التركيبي التحت سطحي هو دمج ومكمل للتحليل التركيبي السطحي ويؤكد عملية الانقلاب عن طريق حركات الازاحة الافقية في أواخر العصر الطباشيري.

التحليل التركيبي السطحي والمطمور لمنطقة البردي, الجزء الشرقي لمرتفع مرماريكا, شمال شرق ليبيا.

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قدمت هذه الرسالة ضمن متطلبات الحصول علي درجة الماجستير في علوم الأرض (جيولوجيا تركيبية)

جامعة بنغازي
كلية العلوم

بنغازي- ليبيا
2018