Structural Characteristics And Analysis Of Jardas Al Jarari Inlier, The Central Part Of Al Jabal Al Akhdar, NE Libya

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Abstract

Al Jabal Akhdar represents a NE-SW inverted basin in northeast Libya and considered as prominent promontory of Late Cretaceous-Tertiary sedimentary belt overlooking the Mediterranean coast. The study area is chosen in the central part of this belt as it exhibits intense structural patterns and involves one of the Late Cretaceous inlier exposed within extensive outcrops of Tertiary sediments. However, the studied structures are re-assessed based on more detailed fieldwork, analysis of different kinematic shear indicators and whether the variations of both; the type of sedimentation and thickness of strata do occur. Upper Cretaceous-Oligocene sediments cover the present area and are represented from the oldest to youngest by these Formations: Al Majahir, Wadi Dukhan, Al Uwayliyah, Darnah, and Al Bayda. Elsewhere, these Formations are unconformably younger by Quaternary deposits.

During Jurassic to Early Cretaceous, Al Jabal Al Akhdar was a part of passive continental margin, it is considered as a large sedimentary basin in northeast Libya. By the end of the Cretaceous (mainly Santonian), this structure was inverted, in response of right-lateral shear, and the result was the uplift of Late Cretaceous sediments within Darnah and Al Baydah Formations (Eocene to Lower Oligocene) forming the inlier structure of Jardas Al Jarari. Late Cretaceous inversion was initiated with brittle shear deformation along E-W to WNW-ESE major dextral shear and enhanced with ductile shear forming a sequence of very tight and overturned F_1 and F_2 asymmetric open folds trending ENE-WSW and NE-SW respectively. At the final stage of Late Cretaceous to Early Tertiary, the whole structure is themed with array of Riedel and conjugate Riedel shears along the NE-SW to NNE-SSW sinistral strike-slip faults and NW-SE dextral strike-slip faults, finally enveloped with the formation of E-W to NE-SW trending F_3 major fold.

CHAPTER I

Introduction

1.1. Introduction

Al Jabal Al Akhdar is located in the northeast of Libya, and is bounded from the north by Mediterranean Sea, Cyrenaica platform in the south, Sirt Basin in the west and the Western Desert of Egypt to the east (Fig. 1.1). Many studies have been dealt with the sedimentologic and stratigraphic data in Al Jabal Al Akhdar, however the structural elements are still far from being well analyzed and completely understood, for this reason, Jardas Al Jarari area and environs are subjected to detailed field mapping and structural analysis of the exposed Upper Cretaceous, Paleocene, Eocene, and Oligocene sedimentary rocks Tracing of the regional structural elements by local analysis of study area, then extended outside Jardas Al Jarari area to involve most of the central part of Al Jabal Al Akhdar, to clarify the structural evolution on some of the ambiguities within the stratigraphic sequence during Late Cretaceous - Oligocene times. In the study area, the structural analysis included; recognition and distribution of different rock units and measurements on the folds, faults and joints.

1.2. Location of Study Area

Jardas Al Jarari area is located in the central part of Al Jabal Al Akhdar about 15 km south of Suluntah village and is bounded by the latitudes 32°33′ 30``to 32°28′30`` N and longitudes 21° 33′ 30`` to 22°40′ 30`` E (Fig. 1.1).

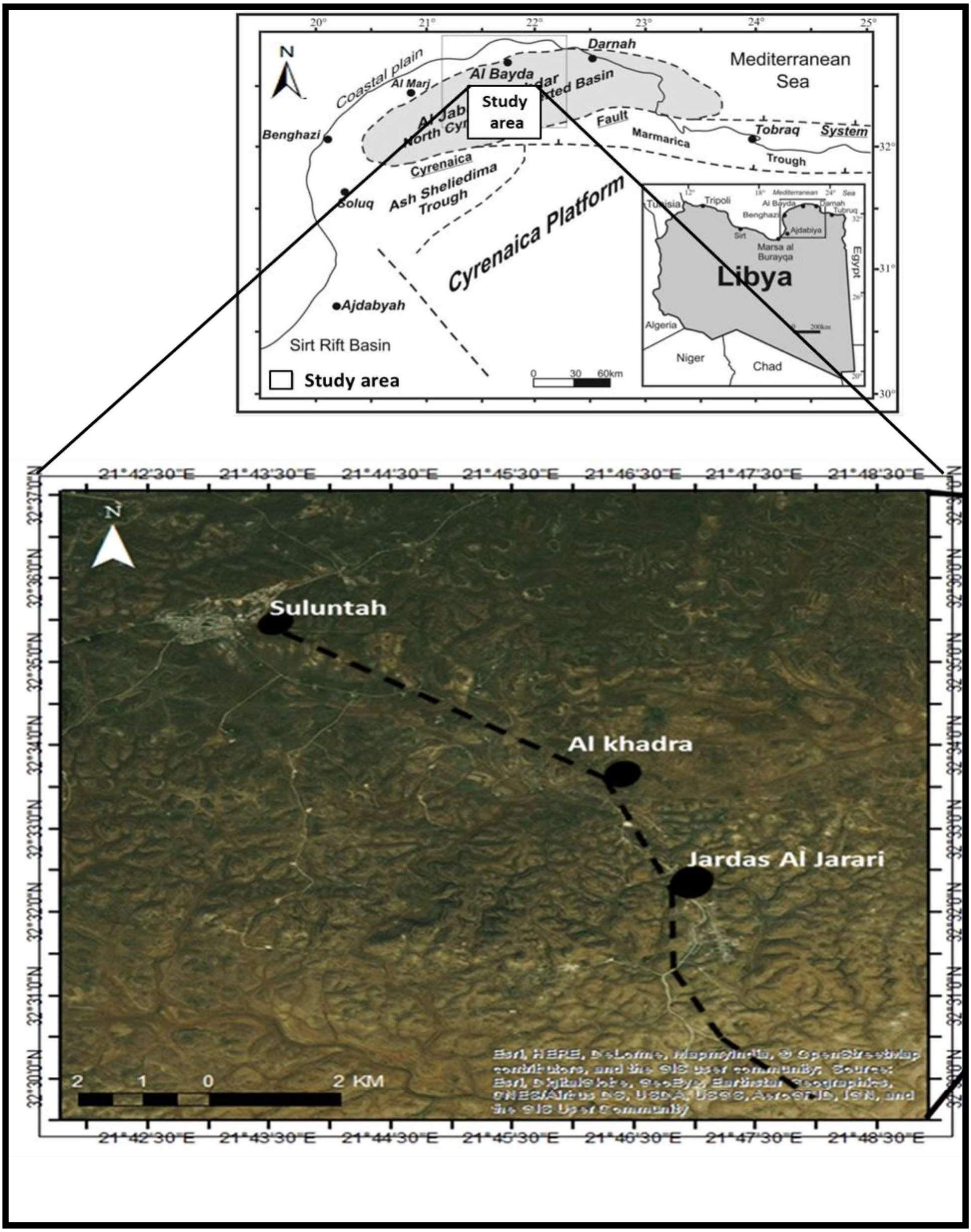


Fig. (1.1) Landsat image showing location of the study area. (after Abdelwahed et al 2011).

1.3. Objective of Work

The main objective of this study involves:

-Investigation the potential importance of wrench-dominated transpression in the development of the inlier structures that form the central part of Al Jabal Al Akhdar.

- Preparing a detailed structural analysis of the faults, folds, and joints.

- Interpretation the nature, geometry, and kinematics of individual centimeter- to kilometer-long fault zones.

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

1.4. Previous Work

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 studies are lacking and still far from being completely understood.

The first reconnaissance were made by Gregory (1911), who subdivided the Eocene sequence into lithostratigraphic units whose names (Solunta, Darnah and Apollonia) are still partly used. Marchetti (1934) presented the first results of the field missions made in the years 1933 – 1934. That is, a geological map at scale 1 : 1.500,000, the chronostratigraphic sequence from Cenomanian to Recent, the description of the lithostratigraphic sequence (Marchetti, 1934, 1935a, 1935b). Conant and Goudarzi (1967) gave an account on the stratigraphy and tectonic framework of Libya. Desio (1968) made review on the geological exploration in Cyrenaica and gave a summary on the stratigraphy and structural history of Al Jabal Al Akdar. Klensmiede and Van den Berg (1968) described the surface geology of Al Jabal Al Akhdar and classified Al Kuf Formation of Oligocene age into four members. They also gave a brief account on structure of Al Jabal Al Akhdar and considered it as gently folded anticlinorium in the Eocene while younger strata are generally horizontal. Hey (1968) worked on the Quaternary geology of Al Jabal Al Akhdar coast, where he recognized several dry and wet phases reflected on the type of recorded sediments. Pietersz (1968) designated an area south of Apollonia (Susa) village as the type locality of Apollonia Formation. Barr and Hammuda (1971) studied the basal part of Apollonia Formation in Wadi Al Athroun and Wadi Al Qalah in Marsa Al Hilal area and recorded the lower boundary of this formation which unconformable overlies Late Cretaceous Al Athroun Formation. The series of geological maps of Libya 1: 250,000 with Benghazi sheet was made by Klen (1974), Al Bayda sheet by Rohlich (1974) and Darnah sheet by Zert (1974). El Hawat (1985, 1986a and 1986b) and El Hawat and Salem (1985 and 1987) studied the Eocene and Miocene Formations in Al Jabal Al Akhdar region. El Khoudary (1980) discussed the planktonic foraminifera and their distribution within Apollonia Formation in the northern part of Al Jabal Al Akhdar. El Yagoubi (1980) studied the planktonic foraminifera in Al Uwayliah Formation and divided the formation into two bizones. El Mehdawi (1994) described Al Hilal Formation as argillaceous limestone of Coniacian-Santonian age based on planktonic foraminifera assemblage and associated Senonian dinocysts. El Mehaghag and Al shahomi (2005) studied the calcareous nannofossil in Al Bayda Formation. Klitzsch (1968) outlined the general structural pattern of Libya and its effect on the sedimentary history of rocks since the Early Paleozoic. He believed that in the Late Cretaceous Al Jabal Al Akhdar trough became an area of uplift and Late Cretaceous and Paleocene strata may be missing in some places. From Eocene to Miocene time, the area was inundated and a section consisting mainly of dolomite, limestone and marls, was deposited. In 1970, Klitzsch presented the most complete work on the structural and facies development of Central Sahara, including Libya and Egypt. In this work the shorelines of different periods together with the most dominant facies are shown. He also defined three major periods of structural development in the middle part of North Africa from the Precambrian to the Late Tertiary. The northwest-southeast compressnional forces, which he dated to the Jurassic or at the Jurassic-Cretaceous transition must had been rejuvenated in post Early Oligocene time.

Röhlich (1974, 1980) considered the central part of Al Jabal Al Akhdar as main Upper Cretaceous rocks exposed in the ENE/WSW-trending brachy anticlinal cores of Jardas Al Alabid and Majahir inliers and flanked by extensive exposures of Tertiary sediments. 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 emerging as an island, the central part of which was deeply eroded. According to Röhlich (1974), the climax event of ENE–WSW folding was in Santonian.

To the west, Anketell (1996) correlated the structural history in Sirte Basin with Cyrenaica region without introducing in more details in the structures of Al Jabal Al Akhdar. Moreover, he explained the structural configuration in Sirte Basin and Cyrenaica as a response to large-scale strike-slip movements along the South Atlas basement megashear that feathered out eastwards as it extended throughout Tunisia into Libya in terms of WNW/ESE-trending South Cyrenaica fault and E–W Cyrenaica and North Cyrenaica faults. The structures of Al Jabal Al Akhdar areattributed to the dextral contractional duplex induced from this bifurcation (Anketell, 1996).

El Arnauti et al. (2008) studied the structural styles in NE Libya and recognized five major geotectonic elements; each of them has been affected by one or more tectonic episodes which have resulted in a variety of structural styles involving both faulting and folding. The E-W or ENE-WSW fault trend represents as rift fault during Late Jurassic-Early Cretaceous, however, during Cenomanian - Santonian time; this trend is changed in a sense of horizontal movement with NE-SW trend referring as north cyrenaica shear system. Firstly, folding is noted in Santonian with E-W axial trends and represents as deformational episode of inversion structure on the original E-W rift faults. Herein, Al Jabal Al Akhdar uplift is interpreted to have been uplifted and deformed within a broad NE-SW trending shear system called the North Cyrenaica Shear System (NCSS).

Farag (2009) Studied the Western part of Al Jabal Al Akhdar with emphasis on Jardas Al Abid area and concluded that the deformation synthesis on the ductile and brittle structures, showed four phases of folding (F1, F2, F3 and F4) related originally to the movement on consistent series of faulting started intensively in Late Cretaceous then continued mildly until the Miocene time. F1 to F3 represent ductile deformational phases within and before outlining the final shape of F4 Jardas Al Abid fold.

El Amawy et al. (2010) 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 attributed the structural patterns to the movement within E-W strike slip shear zone. This movement induced wrench deformational structures accommodated with dextral simple shear mechanism in which $\sigma 1$ is acted from the NNW direction. They classified 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.

In Qasr Libya area, El Amawy et al. (2010) attributed the structural pattern, in the western part of Al Jabal Al Akhdar, as inversion structural during Late Cretaceous - Miocene times, in response to the influence by dextral shear of the Alpine orogeny. Qasr Libya area exposes wide exposures of Tertiary carbonate sediments and distinctively clarified the main effect of structures on the morphology, distribution and development of karst features. 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. The movement within the whole structure induced zones of broken and crushed rock fragments of varying sizes by which the dissolution becomes easier by the surface and underground water. Among the Tertiary sediments are Darnah Formation (Middle-Late Eocene) and Al Bayda Algal Limestone Member (the upper part of Early Oligocene) that display prominent and spectacular different shapes and sizes of karst (lapies, caves and dolines).

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.

1.5. Methods of Work

The structural investigation was performed according to the best practice that is currently used for detailed assessment of geologic structural features and involved the following:

1.5.1. Photogeological and Landsat Interpretation

The remote sensing observations are the most valid method in first step of the study as the physiographic features are shown better in the general view by the aerial photographs and landsat images than in the field reconnaissance where the landforms are usually seen for only limited extensions.

Firstly, it is essentially to describe the remote sensing approach used in this study. However, more details on the theoretical aspects of data acquisition and processing are not included here as they are interesting in the application.

This part presents the use of landsat image analysis in structural analysis. An integration of remote sensing with structural modeling and field observations will be dealt with in the next sections.

The aim of using remotely sensed observations in the present study is to determine the geometrical relations of structural discontinuities on the surface, which are used as a first step in analyzing and interpreting their tectonic meaning. The geometrical and geological relations between structures can allow a first relative timing of the structures. Analysis using the aerial photographs and landsat images will be completed with the field analysis. Here, the vertical aerial photographs are taken, at average scale 1:20,000. The instrument used for the described work is the professional mirror stereoscope and was applied to the whole study area. On the other hand, landsat images are used for tracing the regional and some mesoscopic structures at scale 1:100,000.

1.5.2. 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 Jardas Al Jarari area and other places in the central part of Al Jabal Al Akhdar of these studies are the followings:

1.5.2.1. Stratigraphic Studies

The stratigraphic studies performed in the field by measuring and collecting rock samples. For more clarification and understanding of these studies, basic rules are dealt with the following:

- The lithological description of rock units are made according to the classification of Dunham (1972).

- The fundamental units within the rock formations are established with boundary that have been readily traced in the field and represented on geological map.

- The chronostratigraphic interpretation has been based on the macro- and micropaleontological information existing in literature.

1.5.2.2. Structural Studies

The structural studies performed in the field by measuring the dip and strike of beds for outlining the type and axes of different styles of folds. Measurements along the fault and joint planes are also collected for determining the type and direction of movements and, consequently, position and orientation of the principle stresses $\sigma 1$, $\sigma 2$ and $\sigma 3$.

1.5.3. 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 includes the distribution of different rock units, dip and strike of beds, faults joints and fold axes.

A lot of 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 v.10.2.2). The Geographical Information Systems (GIS) can be used for data capture, storage, analyses, prognostication, presentation, and follow-up and constitutes an excellent tool for modeling 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. By the way, 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 v. 6.0). Furthermore, the (Win-Tensor v. 5.0.1) software was utilized to determine the principle stress axes of faults in the study area (Fig .1.2).

Fig. (1.2) different types of computer softwares used in the present study.

CHAPTER II

Geological Setting

2.1 Introduction

Al Jabal Al Akhdar extends for about 360 km in length and 60 km in width along the Mediterranean coast. It was a part of passive continental margin which subsequently underwent rifting in Late Triassic–Early Cretaceous followed by inversion in Late Cretaceous–Eocene time (El Werfalli et al. 2000; El Hawat and Abdulsamad 2004; El Arnauti et al. 2008).

Upper Cretaceous and Tertiary marine deposits, often rich in fossils, are well exposed and many geological conclusions may be drawn from a surface study (Fig. 2.1). Due to its accessibility, Al Jabal Al Akhdar was the subject of an intensive geological survey as early as since the 1950s. More geological exploration studies are stimulated by oil prospecting, useful knowledge about stratigraphy of Sirte basin is recorded in the collected papers edited by Barr (1968a).

The cycles of sedimentation in Al Jabal Al Akhdar are particular importance for the study of tectonic history. The oldest cycle of sedimentation that can be distinguished in Al Jabal al Akhdar is represent by Cenomanian to Coniacian deposits (Qasr al Abid and Al Baniyah Formations). The next cycle of sedimentation dates from Campanian to Landenian. The environment during Late Senonian times was largely neritic and the total thickness of deposits in the central part of the Al Jabal Al Akhdar did not exceed some 150m. Only small denudation relics of the Palaeocene strata remain as evidence of persisting and deepening marine waters during the Palaeocene. This interpretation is based on fine textured, chalky limestones containing planktonic foraminifers. There are two reminant exposures of the Palaeocene strata preserved: (i) located east of Al Uwayliah

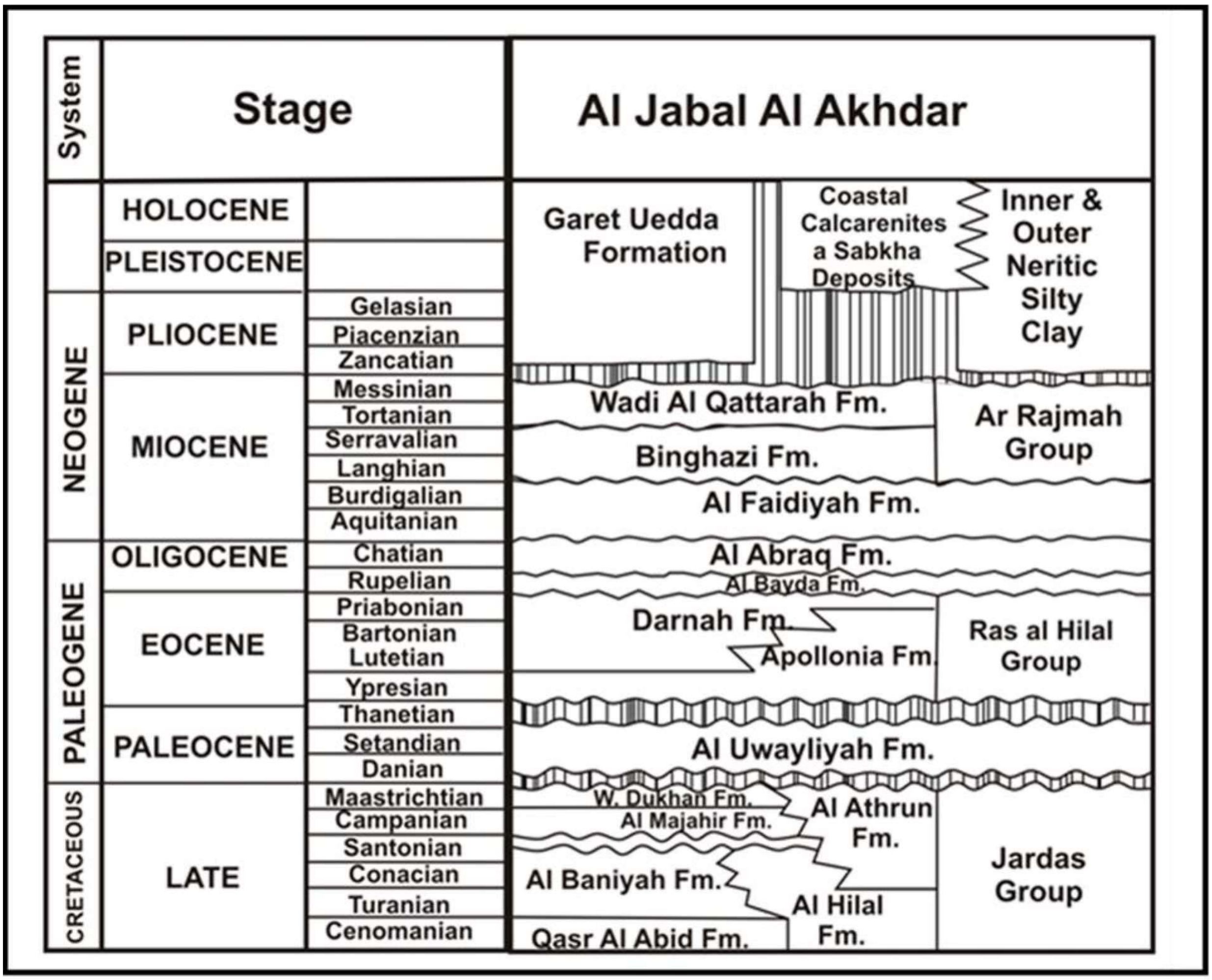


Fig. (2.1) Surface stratigraphic chart of Al Jabal Al Akhdar, NE Libya (After El Hawat and Abdulsamad 2004).

village, with a Landenian microfossil assemblage (Barr, l968; El yagoubi et al. 1980). (ii) near Jardas Al Jarrari, with a Danian assemblage determined by Hanzlikova (in Rohlich, 1974). However, the middle Paleocene is not exposed in Al Jabal al Akhdar as noted discussed, in more detail, by Tmalla (2007). The third cycle of sedimentation is developed from Ypresian to Priabonian. During late Ypresian and Lutetian times the sea progressively covered the northern periphery of the Early Eocene uplift. The largest inundation during Eocene dates from the Priabonian age.

2.2 Tectonic Setting

Al Jabal Al Akhdar is an "Alpine" deformed region where the European plate moved eastward with respect to Africa as a consequence of rifting in the central Atlantic during the Late Cretaceous (Guiraud and Bosworth 1997). The Alpine orogeny led to an overall compressional regime in North Africa from Middle Cretaceous through Recent time, and the previous sinistral transtensional movements were replaced by an extended phase of dextral transpression resulting from the collision of Africa and Europe (Guiraud and Bosworth 1997).

Al Jabal Al Akhdar considers one of the structural belts that characterize the Late Cretaceous compressional structures. It is part of the Syrian Arc belt that extends from northeast Libya across northern Egypt to Syria. The major structure elements in NE libya include Cyrenaica platform, Soluq flank, Soluq depression, Marmarica terraces, Al Jabal AlAkhdar and Marmarica uplift (Fig. 2.2).

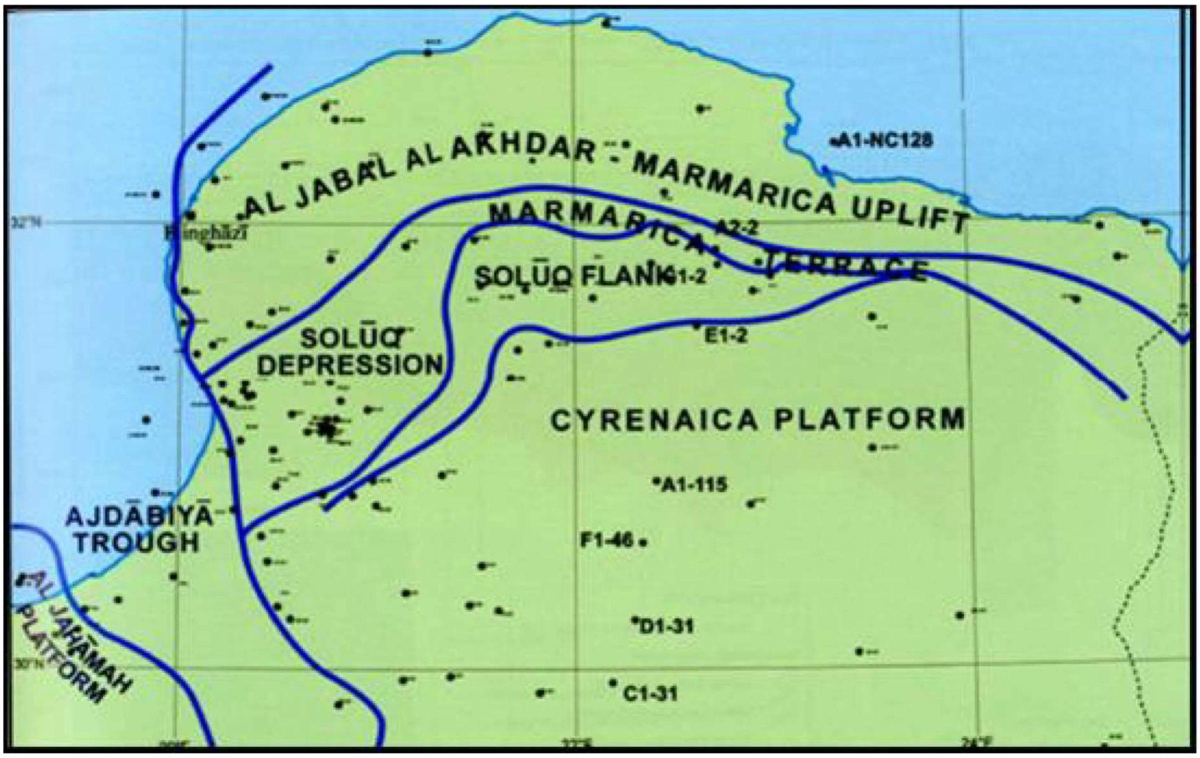


Fig.(2.2) major structure element of NE Libya (after El Arnauti et al. 2008).

2.2.1 Cyrenaica Platform

This platform occupies the southern part of North east Libya 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 (Fig.2.2). An infra-Cambrian basin is interpreted as occupying a large part of the central and southern sector of the platform. The northern and NE 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, fiat-lying and generally displays coherent seismic character. Faults control the northern and southeastern edges of the Cyrenaica Platform (El-Arnauti et al. 2008).

2.2.2 Al Jabal Al Akhdar Uplift

Al Jabal Al Akhdar uplift was formed due to inversion structure during the Santonian, with reactivation during the Middle Eocene. It is characterized by thick Lower Cretaceous-Upper Cretaceous syn-rift sediments (Fig.2.3) of the North Cyrenaica rift which were deformed and uplifted during the Late Cretaceous-Early Tertiary (i.e. 'Syrian Arc Orogeny'). It extends for about 360 Km or even more: from the northeastern border of Benghazi in the west to farther east of Darnah city. The uplift represents approximately E-W faulted arch with steeply dipping faulted margins, exposing Cretaceous rocks in the core of the center within the Jardas Al Ahrar and Majahir inliers.

Inversion structure is dramatically took place in two stages, during the Santonian but continued with mild effect in Tertiary. It appears that the Santonian inversion affected most of the area of Al Jabal Al Akhdar trough, but the Eocene reactivation affected only the western part of the former trough. The uplift was produced by wrench faulting and compression within what (Anketell, 1996) has termed the Al Jabal Al Akhdar duplex, located between the Cyrenaica and the North Cyrenaica Faults (Hallet, 2002).

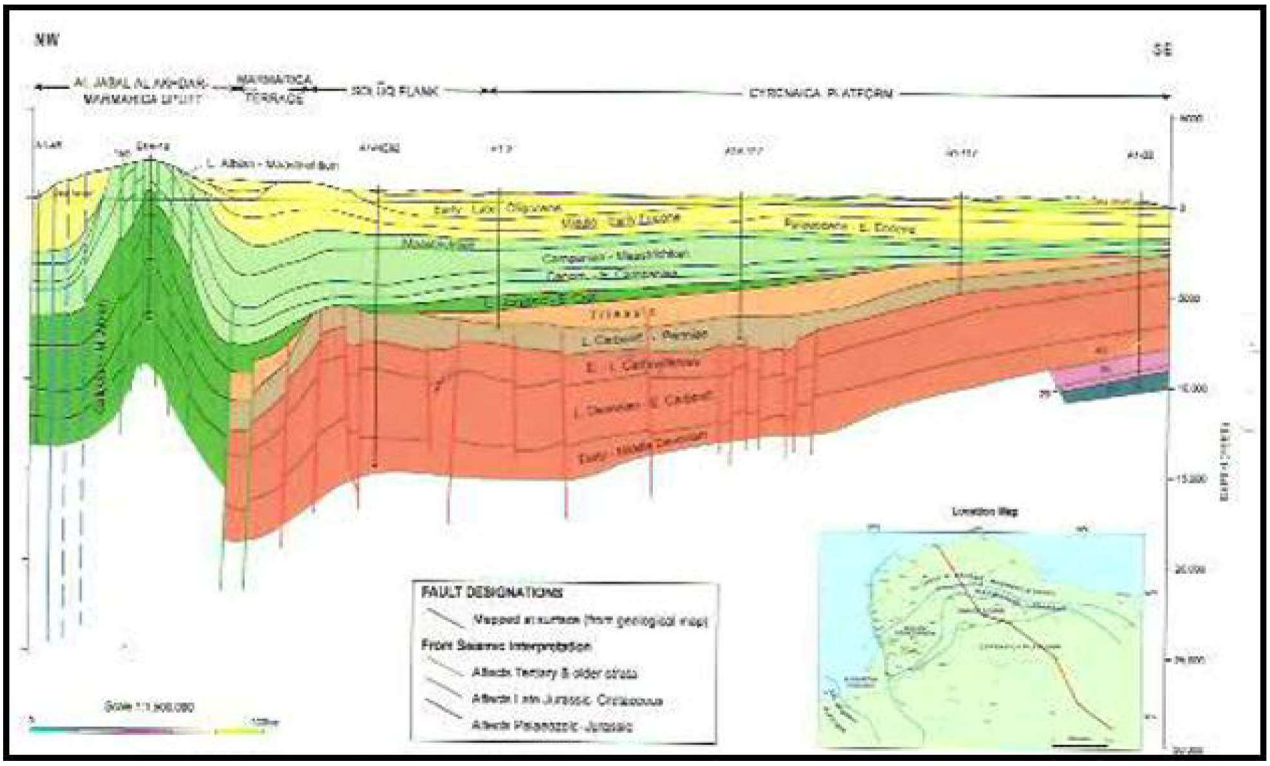


Fig. (2.3) Photographical subsurface cross section of Cyrenaica platform, Soluq flank, Marmarica terrace and Al Jabal Al Akhdar uplift (after El Arnauti et al. 2008).

2.2.3 Marmarica Uplift

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'). However, WNW-ESE rift trends are shown by mapped surface faults and faults recognized from seismic interpretation (El-Arnauti et.al. 2008).

2.2.4 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).

2.3 Depositional Setting and Stratigraphy

Stratigraphically, the study area is covered by Upper Cretaceous – Lower Oligocene sedimentary rocks, which are characterized, from the base to top, by Al Majahir, Wadi Dukhan, Al Uwayliah (Danian part), Darnah and Al Bayda formations (Figs. 2.4 - 2.5). Based on the fieldwork, microscopic observations and previous stratigraphic studies, the exposed successions of the mapped area are generally described, starting with the oldest formation as follow:

2.3.1 AL Majahir Formation

Al Majahir Formation was introduced by Röhlich (1974). About 27m was measured and described in Jardas Al Jarari area. Based on the lithology, it has been divided into two main rock units: the lower rock unit is mainly composed of marly limestone, which is characterized by creamy to yellow, soft to moderately hard, thin bedded with rich small-sized macrofossils especially pelecypods (*Oysters and Inoceramus*), Echinoids and shell fragments. In the southern part of the study area, this limestone is interbedded with soft marly clay (Fig. 2.6). Petrographically, this unit is characterized by mudstone to wackestone texture (Fig. 2.7). Foraminiferal tests are rare and molluscan shell fragments are present in form of *Inoceramus* prisms (Fig. 2.8). The lithology, however, is poorly sorted and embedded in a lime mud matrix. The upper unit consists mainly of white color hard limestone, thick bedded with some pelecypods, gastropods and shell fragments. Petrographically, it is characterized by wackestone to packestone texture (Fig. 2.9) with common quartz silt and rare glauconite grain, rich Ostracoda, Echinoids spines and spars of *Inoceramus* prisms and foraminifera.

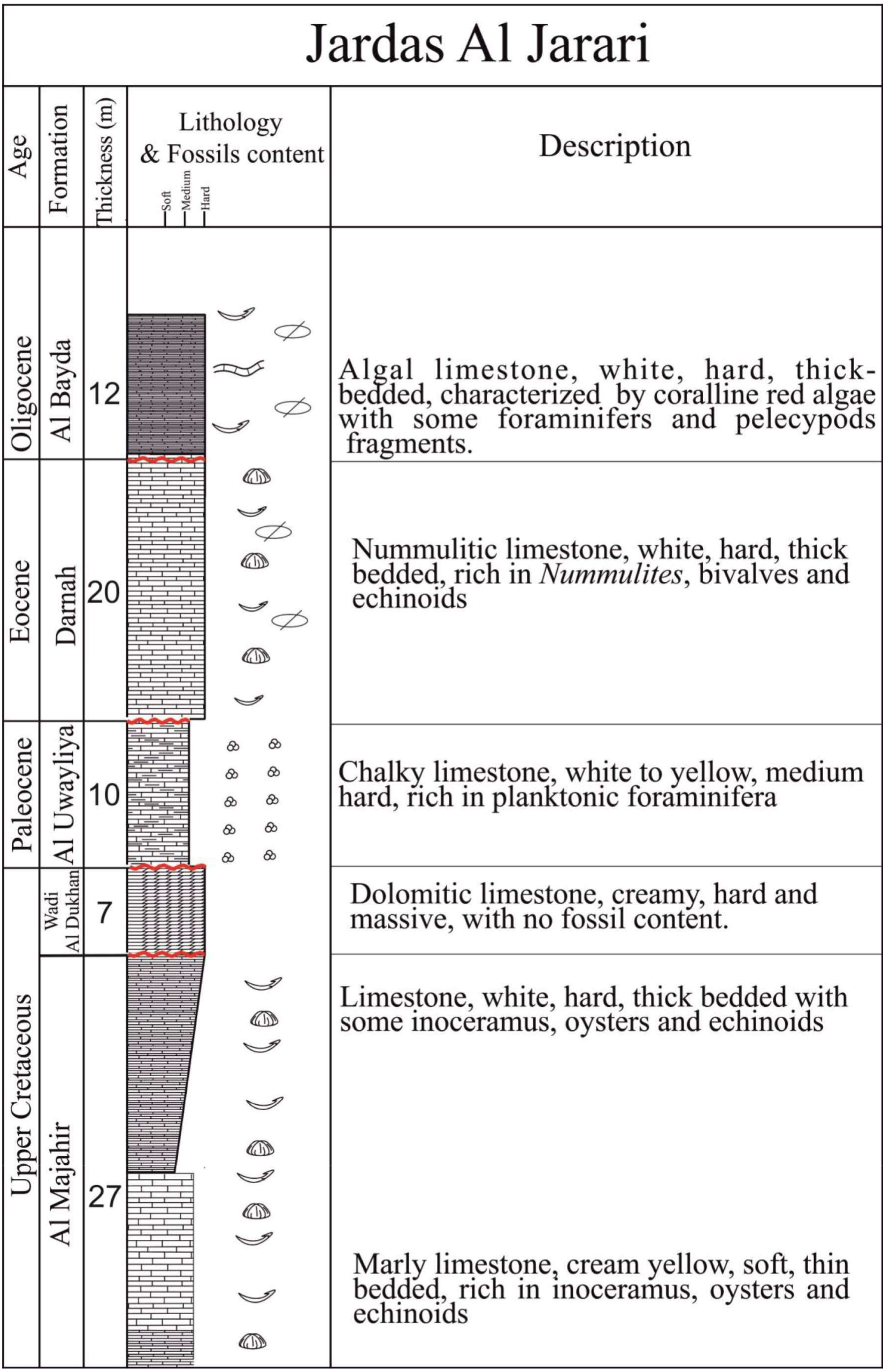


Fig. (2.4) Stratigraphic composite columnar section in Jardas Al Jarari area.

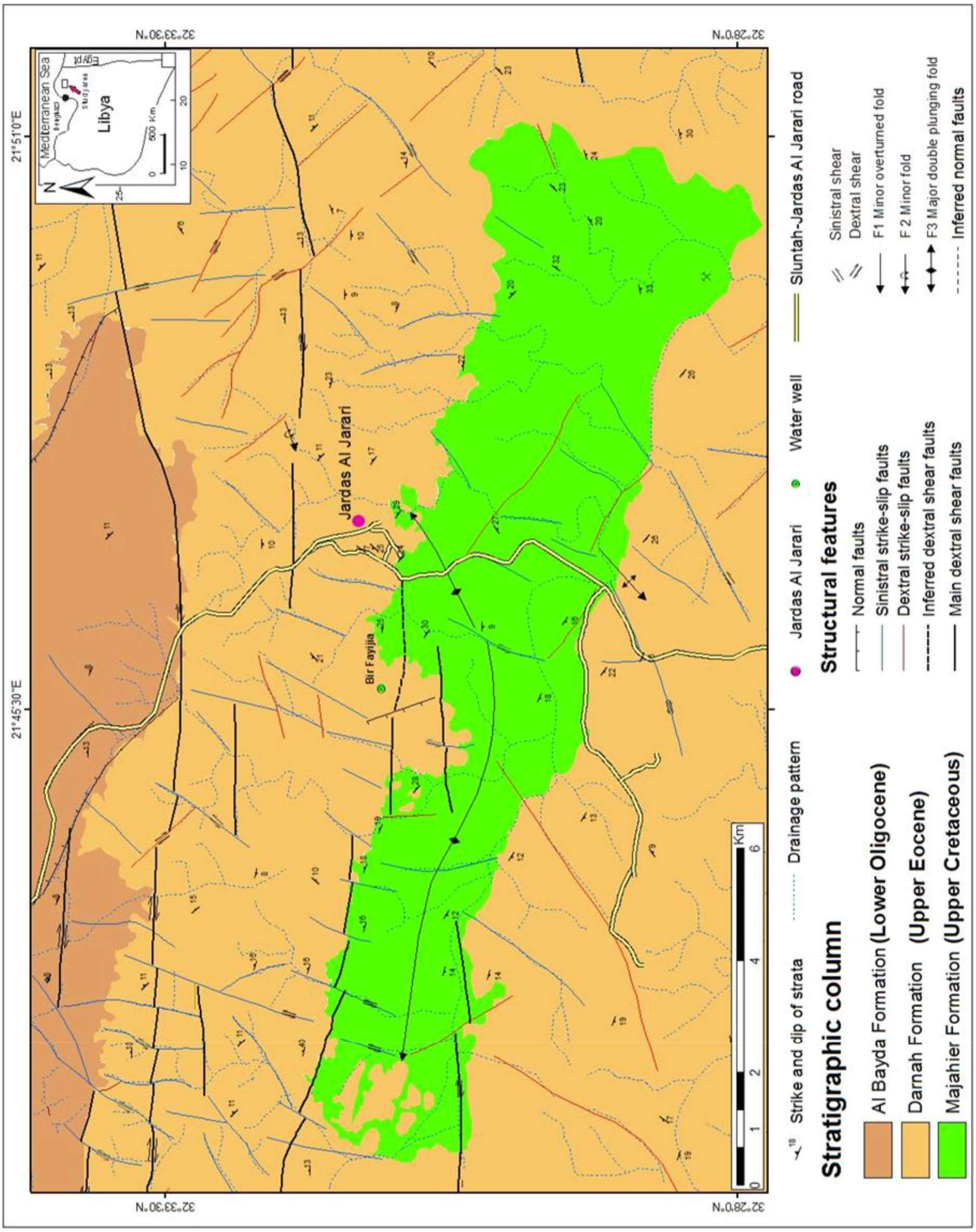


Fig.2.5, Geologic map of the study area.

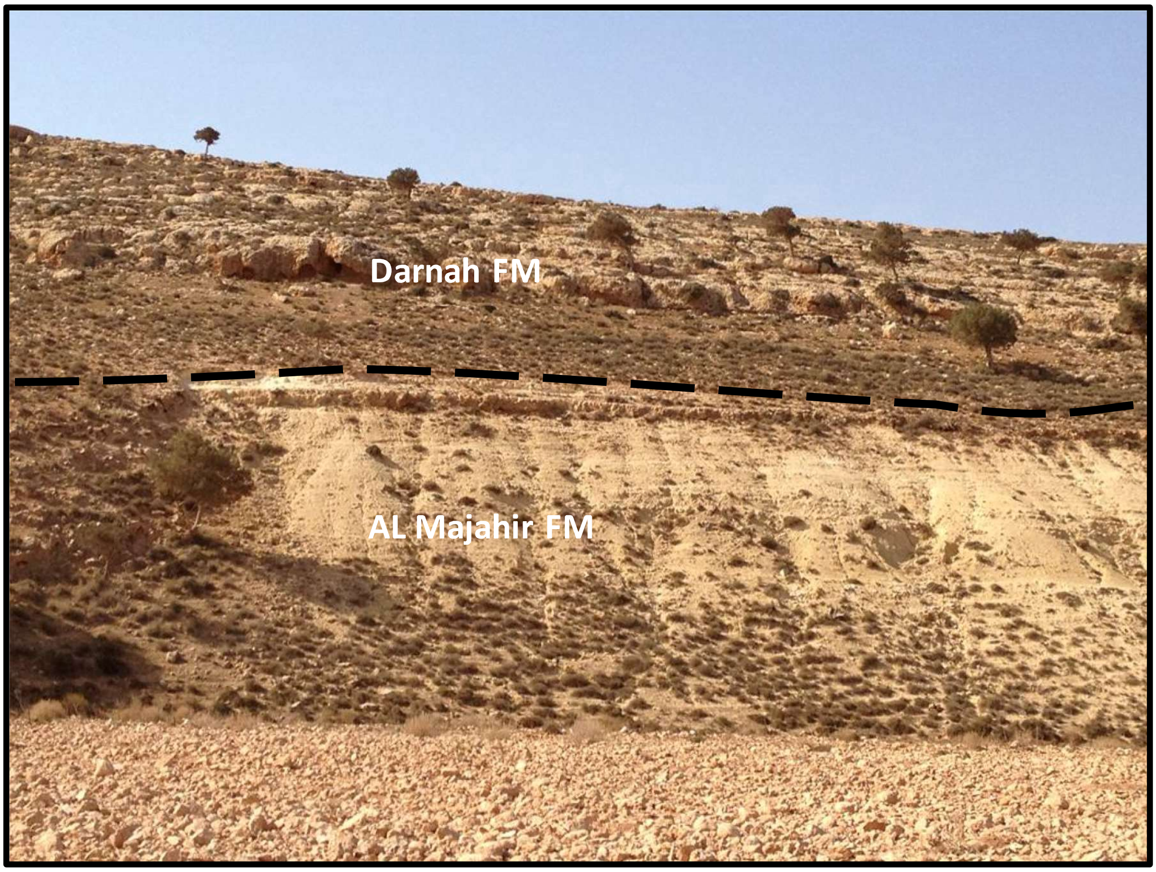


Fig. (2.6) Limestone is interbedded with soft marly clay in Al Majahir Formation south Jardas Al Jarari area. The dip in generally 20° NE; Photo looking S.

Fig. (2.7) Marly limestone in Al Majahir Formation showing the internal mold of Inoceramus shell.

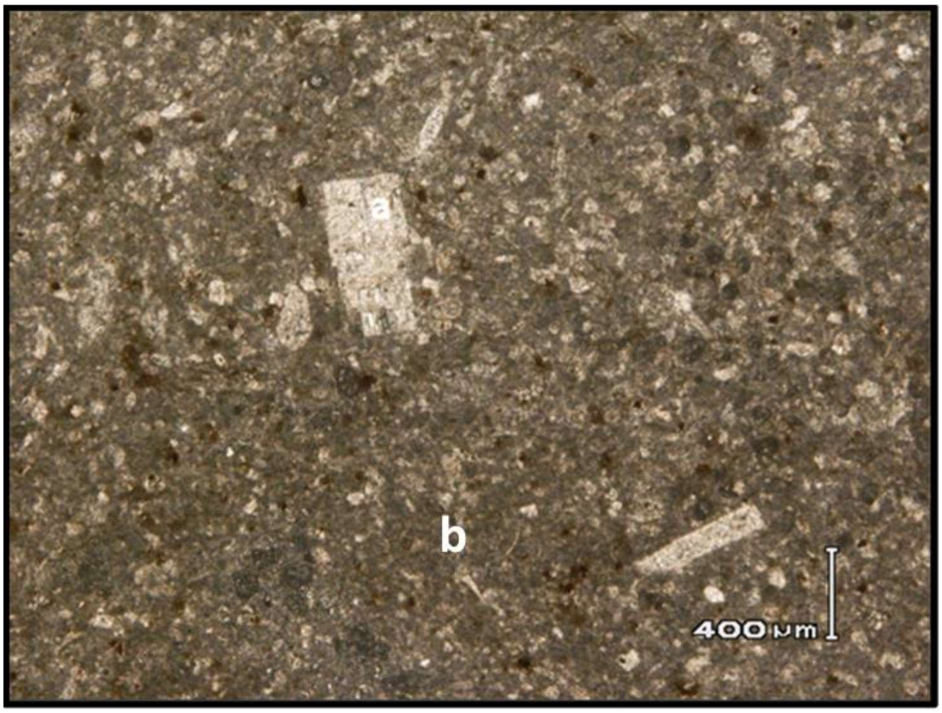


Fig. (2.8) Photomicrograph of mudstone to wackestone texture in the middle part of Al Majahir Formation, with (a) Inoceramus prisms, (b) Quartz crystals.

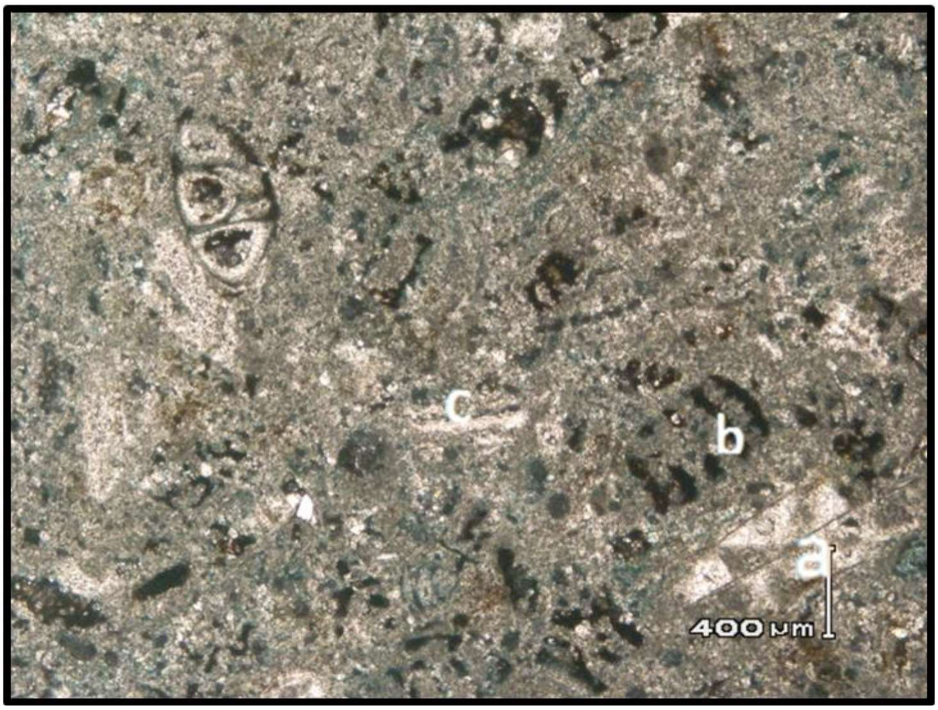


Fig. (2.9) Photomicrograph of wackestone to packestone texture in the upper part of Al Majahir Formation, with (a) bryozoan fragment, (b) Miliolid, (c) Inoceramus prisms.

The lower contact of Al Majahir Formation with the underlying Al Baniyah Formation is not exposed. However, the upper contact is unconformable with the overlying Wadi Dukhan Formation. Al Majahir Formation is rich in the foraminifers and moullsca (notably *Inoceramus*). According to Barr (1972), these fossils refer to the Campanian age based on the retrieved Foraminifers and the identified *Inoceramus such as Inoceramus balticus SSP.*

The vertical distribution of the benthic and planktonic foraminiferS is indicative of a neritic (sublittoral) zone (Röhlich, 1974).

2.3.2 Wadi Dukhan Formation

Wadi Dukhan Formation was introduced and described by Klen (1974). In Jardas Al Jarari area, the thickness of this formation reaches up to 7m and consists of creamy dolomitic limestone (Fig. 2.10). The dolomitic limestone is hard to moderately hard, massive, compact and thin-bedded. In places, however, the rocks are highly porous as manifested by dissolution and cavities, resulted in rough and rugged weathered surface. Dolostone is generally nonfossilferous, except in some parts some fossil molds were observed.

Petrographically, the Formation is characterized by very fine crystalline texture made of dolomite rhombohedra crystals with badly preserved small sized-shell fragments (Fig. 2.11).

In the field, Wadi Dukhan Formation overlies unconformably the Al Majahir Formation and, meanwhile, is conformably overlain by the Al Uwayliyah Formation.

The presence of typical Masstrichtian larger foraminifera in Wadi Dukhan Formation confirm its age as suggested by Tmalla (2007), who noted several species of larger foraminifera in the Wadi Dukhan Formation in subsurface such as *Omphalocyclus macroporus*, *Siderolites cf. calcitrapoides* and *Orbitoides cf. media*. However in surface exposures such as in Wadi Statah close to Al Uwayliyah village, Muftah et al. (2010) determined rudistids of Masstrichtian age. The lithology dolomite and the presence of Milliolids in several levels of the formation suggest deposition in shallow water, probably restricted, marine environment.

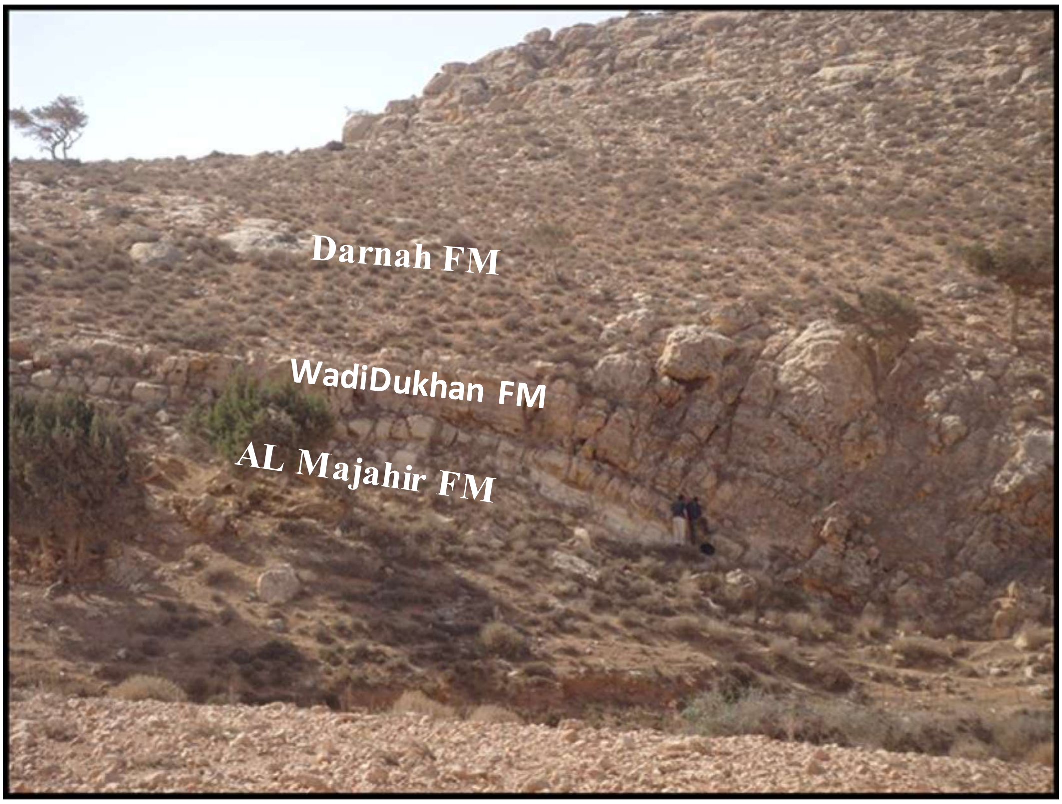


Fig. (2.10) Wadi Dukhan Formation is exposed about 5km south JardasAl Jarari village; Photo looking SW.

Fig. (2.11) Photomicrograph of finely crystalline dolostone at the lower part of Wadi Dukkan Formation.

2.3.3 Al Uwayliyah Formation

The Palaeocene strata of Al Uwayliyah Formation in Al Jabal Al Akhdar is cropped out in two places, these are : (i) east of Al Uwayliah village with a Landenian foraminiferal assemblage is described by Barr (1972); (ii) near Jardas Al Jarrari, with a Danian assemblage determined by Hanzlikova (Rohlich, 1974). However, the lower Paleocene (Danian) is only exposed at the Jardas Al Jarari area, where Rolich (1974), represented *Globoconusa cf. daubjergensis* and *Guembelitria cretacea*, which used in the dating of this rock unit.

In study area, Danian exposure consists of chalky, cream coloured, thin bedded mudstone with interbeded layers of greenish-yellow marl, with few skeletal shells fragments such as Echenoids and rare Planktonic foraminifera "G. daubjerensis" (Fig. 2.12). Further to the south and away from the anticlinal axis, the Danian outcrops are underlain by brownish to light gray dolomite beds of the Maastrichtian Wadi Dukhan Formation. Stratigraphically, the formation rests conformably on the dolomite of the Wadi Dukhan Formation and is unconformably overlain by the Darnah Formation (Fig,2.13).

Barr (1972) described from the exposed section close to Al Uwayliya village several planktonic foraminiferal species of Paleocene (Landenian) age: *Morozovella angulata* (White), *Globanomalina chapmani* (Parr) and *Subbotina triloculinoides* (Plummer). which indicates that the Upper Paleocene (Landenian) Al Uwayliah Formation at this locality was deposited in open marine condition (Röhlich 1974).

Fig. (2.12) Alternation of limestone (a) and chalky limestone (b) in Al Uwayliah Formation located east of Jardas Al jarari village; Photo looking S.

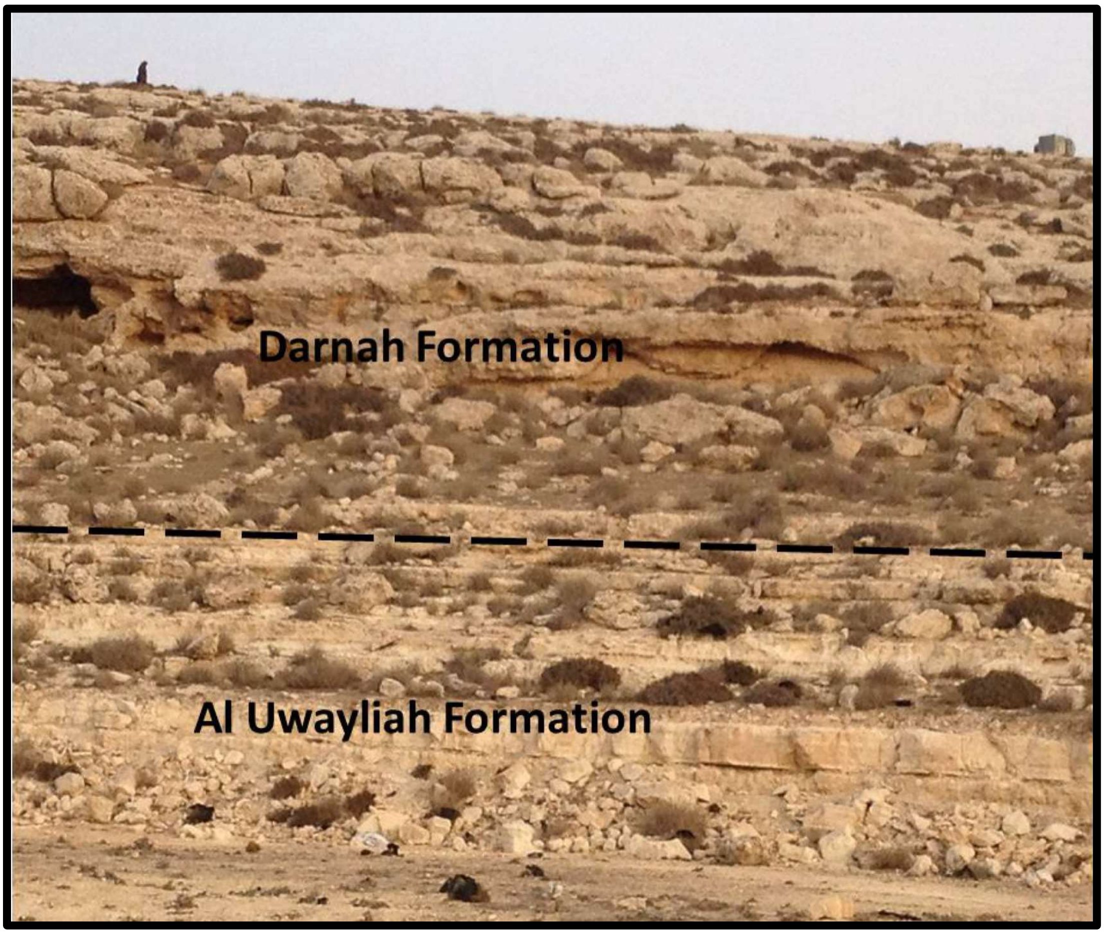


Fig. (2.13) Al Uwayliah Formation located east of Jardas Al jarari village overlain by the Darnah Formation ; Photo looking S.

2.3.4 Darnah Formation

The sequence of Darnah exposed rock unit is first described by Gregory (1911). In the study area, a section of about 20m is measured and described consisting of commonly thick-bedded limestone. The limestone is white, hard, coarse-grained, fossiliferous and containing *Nummulites* spp (Fig. 2.14), pelecypods, gastrpods and Echinoids. Lithologically, the wackestone to grainstone textures dominate the lower and middle parts of the section. The lower boundary of the Darnah Formation is unconformable with underlying Danian Al Uwayliyah Formation and is unconformably overlain by the Oligocene Al Bayda Formation.

Petrographically, the studied samples are mainly made of foraminiferal tests (notably, *Nummulites* sp. *Milliolides* and *Discocyclina* sp.), molluscan shell fragments, rare echinoid spines and red algae. The allochmes are poorly sorted, closely packed in a microcrystalline calcite matrix (Fig. 2.15).

The diagnostic *Nummulits gizahensis*, are indicative Middle to Late Eocene age. The Darnah Formation may indicate a low energy in carbonate shelf environment.

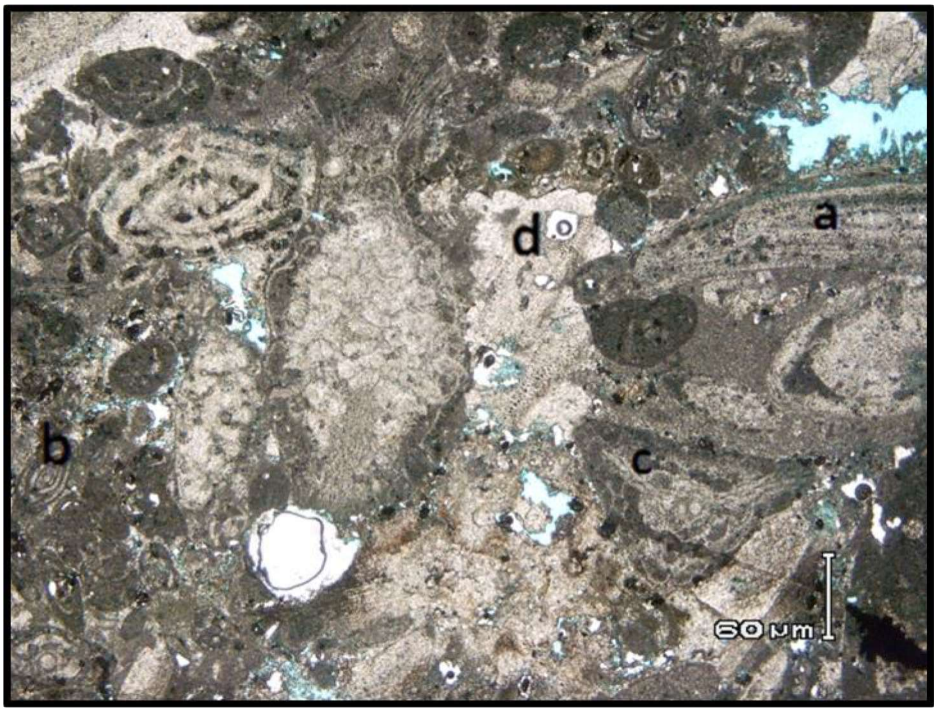


Fig. (2.14) Photomicrograph of packestone texture in the upper part of Darnah Formation, with (a) Operculina SP, (b) Milliolides, (c) PLacogypsina SP, (d) shell fragment.

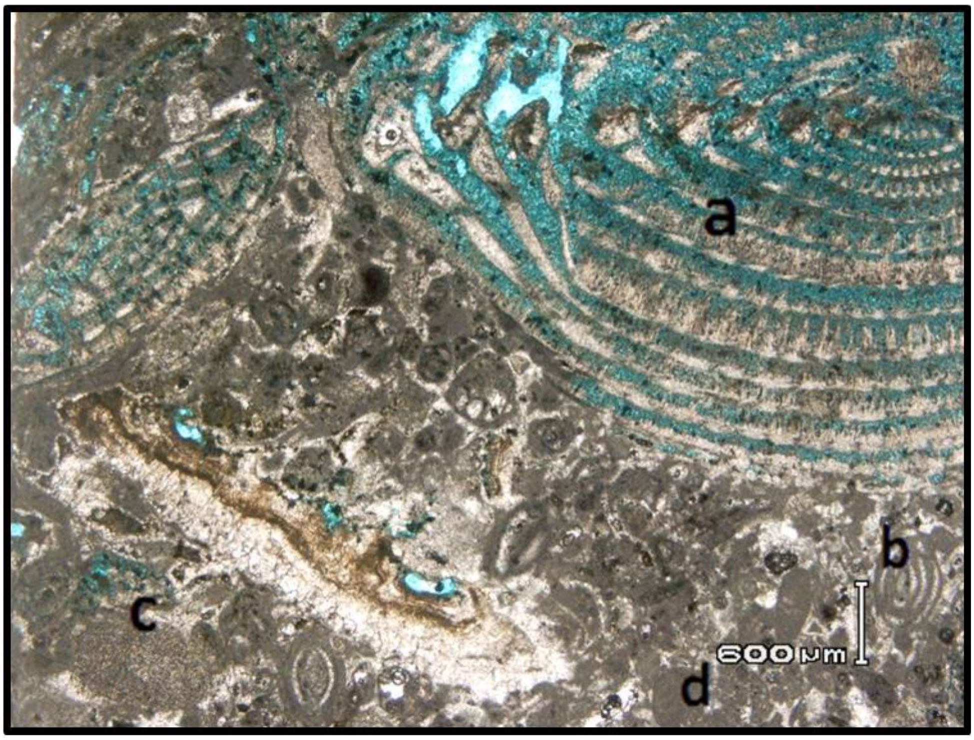


Fig. (2.15) Photomicrograph of packestone texture in the lower part of Darnah Formation, with (a) Nummulite gizahensis, (b) Milliolides, (c) shell fragment,(d) Algal peloids, Intra skeletal porosity.

2.3.5 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).

2.3.5.1 Algal Limestone Member

This member is exposed at Suluntah village and attains about 12m thick and consists of hard to moderately hard, medium to thick-bedded of greyish to white limestone with abundant algal balls associated with *Nummulites* sp, echinoids, pelecypods and shell fragments. The contact of this member with the underlying Darnah Formation is unconformable. Because of missing Shahat Marl member.

The stratigraphic distribution of rock units and fossils contents of Al Bayda Formation indicate a shallowing – up trend of Algal Limestone Member after deep neritic condition of Shahat Marl Member.

CHAPTER III

Structural Analysis

3.1 Introduction

Al Jabal Al Akhdar considers one of the five major geotectonic elements in NE Libya identified by El Arnauti et al. (2008). It is part of the Cyrenaica platform and is one of the structural belts characterized by Late Cretaceous compressional structures (Fig. 3.1). Al Jabal Al Akhdar belt represents a part of the Alpine system in the southern margin of the Tethys as evidenced from the similar Alpine folds; the Upper Cretaceous anticlines of Jardas Al Jarari, Jardas Al Abid, Suluntah, and Al Majahir (Klitsch 1970, 1971; Röhlich 1974; El Hawat and Abdulsamad 2004 and others). 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 anticlinal cores of Jardas Al Abid 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; Fig. 3.1). The structural features and their analysis in the present work are explained how the uplifting is related to the deformation via wrench tectonics and not only to normal block faulting as was believed before in Al Jabal Al Akhdar?.

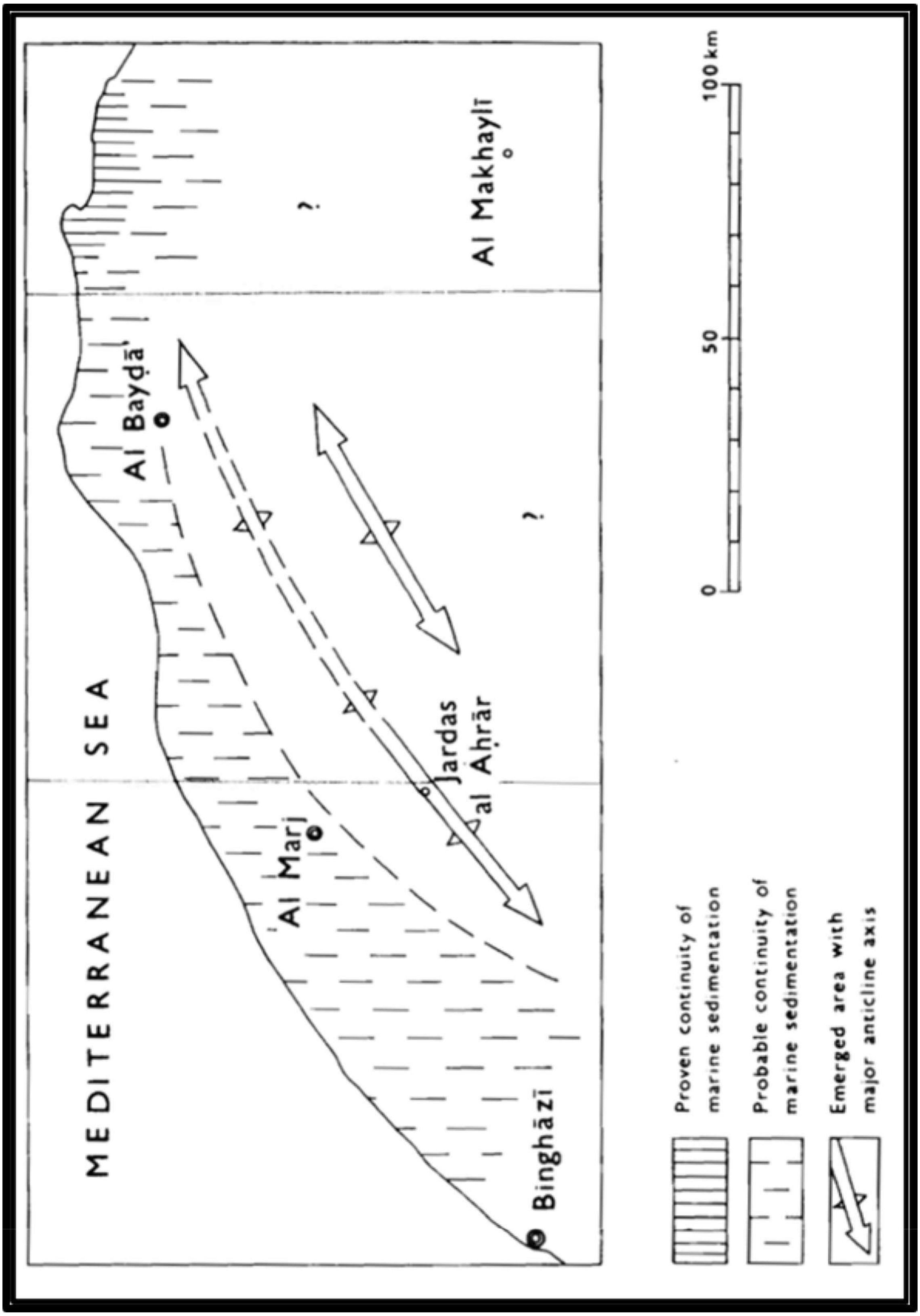


Fig. (3.1) Santonian folding phase in Al Jabal Al Akhdar (After Röhlich 1980).

The present study involves the structural characteristics and analysis of Jardas Al Jarari 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 attains an average 35°, sometimes become steep and overturned in Upper Cretaceous, while in Tertiary, the dip amount decreases to less than 8°. In the study area, the Upper Cretaceous rocks form low-lying to unmapable exposures and occupy the core of a major E-W to NE-SW plunging anticline. These rocks are flanked by a higher relief of extensive exposures of Tertiary sediments. Directions of dip are different as they are SW, S, and SE in the southern part and N, NE in the northern part outlining the major ENE-WSW Jardas Al Jarari double plunging anticline within approximately E-W major shear zone (Figs. 3.1 and 3.2). Detailed field mapping and structural measurements showed the association of E-W major dextral shear faults, concurrent right and left lateral strike-slip faults, minor reverse faults, minor folds, very limited normal faults, shear and tensional joints. This structural regime had produced stepped topographic profiles across the bedding and a complexity during subsequent sedimentation and, in turn, created several unconformities in the stratigraphic sequence.

Kinematically, the movement within this structural regime is initiated by wrenching to transpression then continued slightly by pure wrenching and showed the evolution by three phases of deformations (D_1, D_2 and D_3) coincident with lower, and upper structural levels.

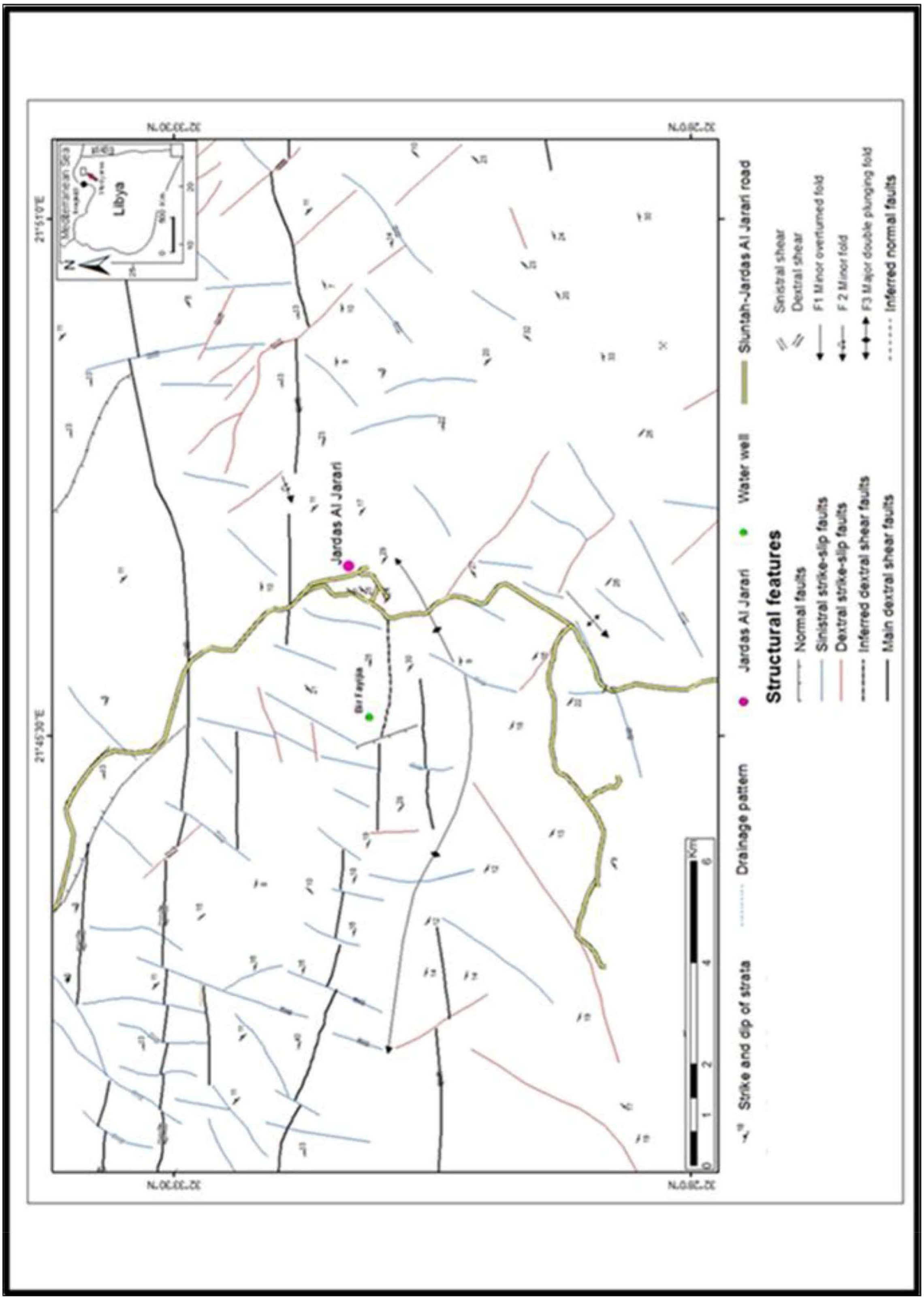


Fig. (3.2) Structural map of the study area.

3.2 Structural Characteristics and Division.

The analysis of discontinuous deformations has been carried out by field mapping (scale 1:20.000, Figs. 2.3 and 3.2) and detailed structural analysis of brittle and ductile structures. The fault network affecting the study area has been compared with the pattern of the lineaments detected by multi-scale photo-interpretation (by means of Landsat7 and aerial images) to obtain a better insight into the geometry and hierarchy of the observed structures. This integrated approach allowed us to distinguish different structural domains with distinctive fault patterns and to locate the traces of inferred faults that separated sectors with different internal fault geometries. The interpretation of the data is based on the definition of distinct structural associations, which represent different tectonic stages recorded during the tectonic stages evolution. As proposed by some authors (Dehandschutter 2001; Rossetti et al. 2002; Perello et al. 2004b), the structural characterization of faults in the field was carried out on the basis of: (1) geometry, (2) analysis of kinematic indicators and distribution of slip vectors, (3) rheology and thickness of fault-related rocks. Major and minor faults also were differentiated on the basis of their length and the width of the damage zone.

In the following is the description of different structural elements:

3.2.1 Folds

Generally, the folds are intense in the Upper Cretaceous but their effect extends slightly upward in the Eocene and rarely in Oligocene beds. In the present area, Jardas Al Jarari fold represents the third phase of folding and considers one of conspicuous folds in Al Jabal Al Akhdar. The fold axis traverses the southern boundary of Jardas Al Jarari village and orients E-W to ENE-WSW. It extends for a distance 30km or even more. The core of this fold is dome-like and occupied by moderate and nearly horizontal exposure of Al Mjahir Formation followed conformably, in part, by moderate to high reliefed Wadi Dukhan Formation. To the southeast, south and southwest, Al Mjahir Formation exhibits wide exposures, but is relatively narrow in the northeast. For this reason, it attains moderate dips (18^o to 25^o) along the southwestern flank of the fold and steeper ones (30^o and, in places, 50^o) on the northeastern flank. Field measurements within Al Majahir and Wadi Dukhan formations revealed a gradual decreasing in the dip amounts (15^o to 20^o in the S, SE and SW to an average 35^o in the NE). Following upward, the different stratigraphic levels and areal distribution of the Eocene strata as well as the disappearance of lower Eocene and Palaeocene, in most outcrops, indicate that the emergence of the inlier had been reached its climax and severely eroded by the end of Cretaceous. This effect is coupled, as shown in the field, with the slight deformation during the Eocene (Darnah Formation) and resulted in the extension of Jardas Al Jarari fold to occupy vast area and, in turn, minimize the intensity of the Late Cretaceous folding. In this concern, the field observation showed that the steeper Late Cretaceous strata (Al Majahir and Wadi Dukhan formations, in particular) exhibit thick successions of Eocene overburden so as to compensate the higher amounts of dip values. Accordingly, away from the Upper Cretaceous contact, the amount of dip decreases in the Eocene strata ranging from10^o to 12^o in the NE, N and NW within the northwestern flank and 13^o to 16^o on the southeastern flank of Jardas Al Jarari F_3 fold. These values diminish also gradually ongoing upward on the Oligocene strata giving amounts between 5^o and 8^o.

Geometrically, about 1050 measurements are taken, in the field, from the different directions of bedding planes and orientation of minor folds. All these measurements are plotted on the stereonet, taking into consideration that the plotting and analysis of data are subdivided based on the intensity and prominent of deformation relative to the areal distribution and sequence of the stratigraphic units. Consequently, the Upper Cretaceous rock units are the oldest, very limited and characterized by intense deformation. Hence, their measurements are taken on a minor scale and considered as data for D_1 analysis. In contrast, the Tertiary rock units (Eocene outcrops in particular) are widespread and reflect a pervasive but with less intense deformation, and therefore, the measurements are generally taken on a major scale and accommodated for D_2 deformation.

Folds are developed in the area at different structural levels and within Jardas Al Jarari major fold. These folds range from cm 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_1 phase of folding is the oldest and well documented in Al Majahir Formation. Generally, the trend of these folds is identical with the major trend of Al Jabal Al Akhdar. The fold dominate at the lower 20 m of Al Majahir Formation and are concentrated as the bedding has anisotropic physical behavior. They are minor in scales and possess asymmetric, recumbent, very tight and overturned styles. Their axes orient E-W to ENE-WSW and plunge at gentle to moderate angles WSW (Fig. 3.3). The geometry of Upper Cretaceous folds and other associated structures are conformable with the macroscopic structures outlined in the area, indicative of a genetic relationship to tectonic stresses consistent during Late Cretaceous–Tertiary times. The planar and linear fabrics are well developed and enough for representation on the stereonets. Plotting of F_1 minor folding axes exhibits the poles of bedding planes in great girdle patterns, where the strike of beds, in the upper limb, attains an average NE-SW and β1 determined gives a general dipping 14° N39°W (Figs. 3.3a,b). In lower limb, the bedding planes are striking NE-SW and β2 gives dipping 24° S28°E. The intersection of β1 and β2 plots exhibits plunging S55°W /7°. Upward in the upper limb, Al Uwayliyah Formation (mainly Danian part) covers unconforambly Al Majahir Formation.

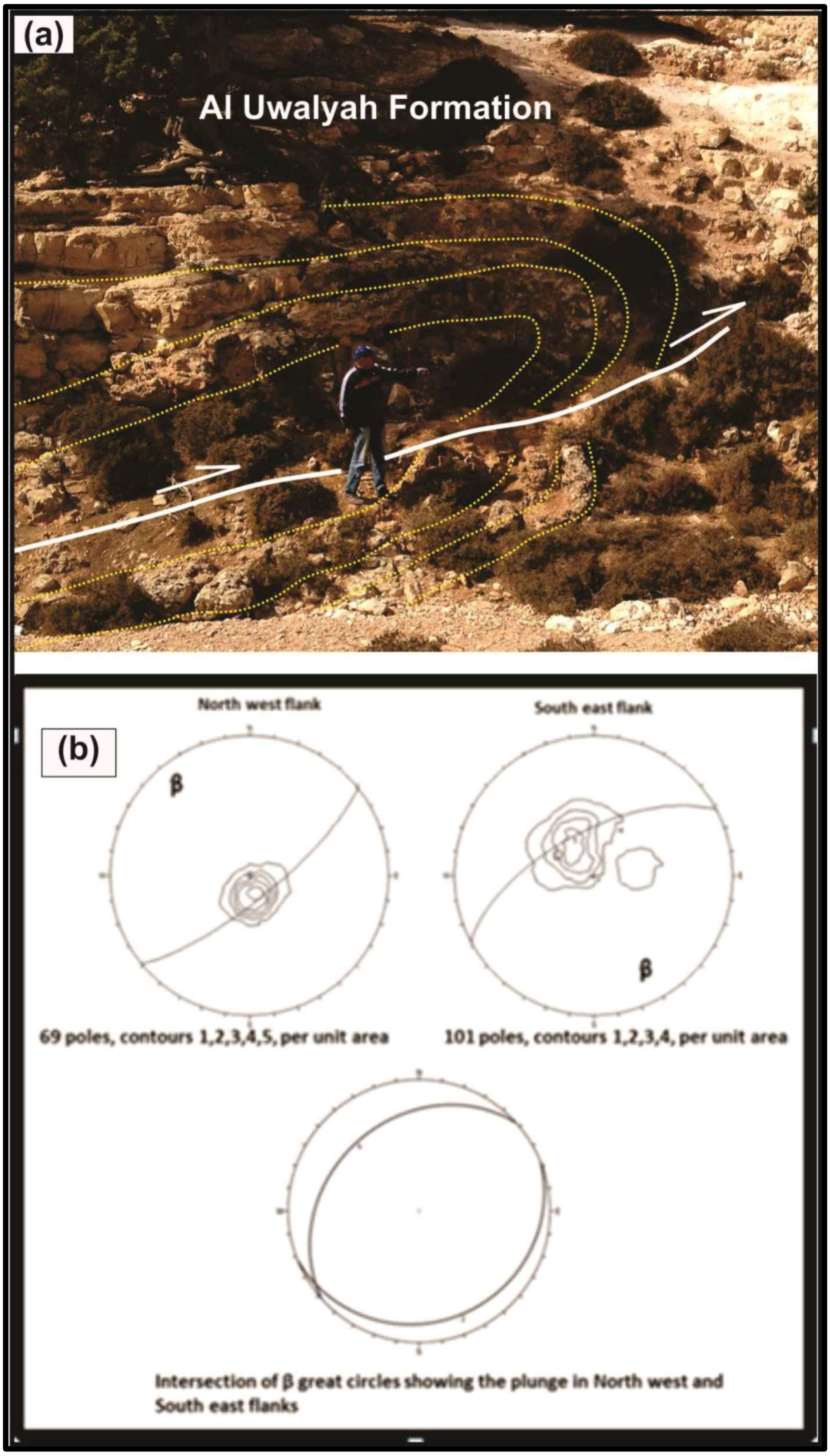


Fig. (3.3) a. F_1 recumbent fold in Al Majahir Formation to the northeast of Al Jarari village. Sold white line refers to a minor oblique thrust or transpression fault, where the upper limb is displaced and moved upward, relative to the lower one, in a way up structure; Photo looking NW. Al Uwalyah Formation follows uncormformaby up the transpressed Al Majahir Formation. (b) Equal area lower projection of the field measurements of this fold.

F_2 folds are comparably rare in the study area and exemplified in Majahir and Wadi Dukhan formations about 5km south of Jardas AL Jarari village. The folds are less tight, open and asymmetric. They have open to gentle styles and are found as the strike-slip fault is accompanied by thrust component. Figure (3.4a) represents example of these folds affecting Al Majahir and Wadi Dukhan Formations and is flanked unconfarmably by Eocene (mainly Darnah Formation) and plunging SW. The poles of bedding planes spread over great girdle patterns (Fig. 3.4b). In the northwest limb, the strike of beds attains an average NE-SW and β1 determined gives a general dipping 29^o N28^{o}W. In southeast limb, the bedding planes are striking ENE-WSW and β2 gives dipping 7^o S21^{o}E. The intersection of β1 and β2 plots exhibits plunging S50^{o}W /4^o (Fig. 3.4 b). Field observation showed that the fold is localized within a zone of ENE-WSW dextral strike-slip fault then enhanced intensively by the anticlockwise internal rotation along the N-S sinistral strike slip fault.

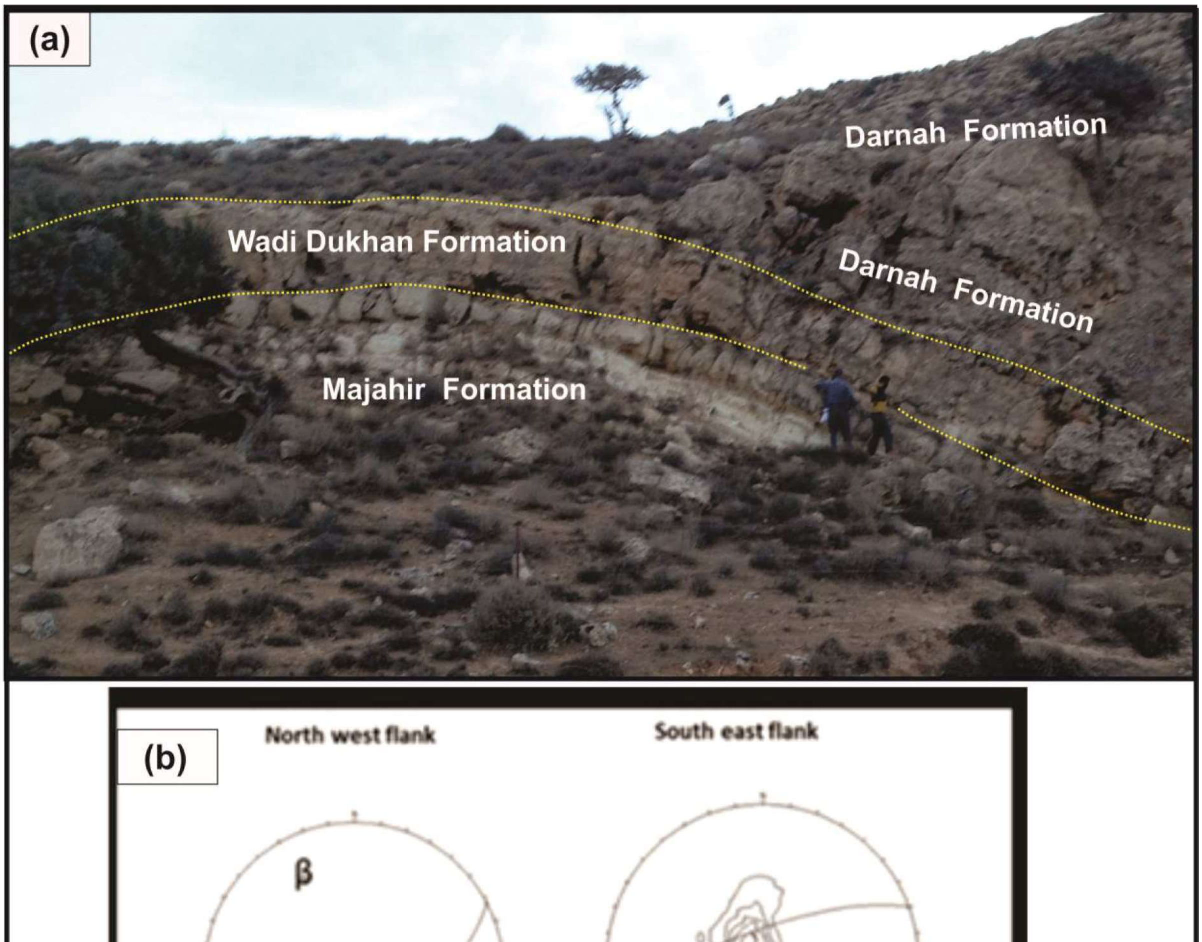


Fig. (3.4) a. F_2 fold affecting Al Majahir, Wadi Dukhan and Darnah formations south west of Al Jarari village; Photo looking SW. (b) Equal area lower projection of the field measurements of this fold.

F_3 phase of folding is not recorded, at minor scales, but represents the final phase of Jardas Al Jarari major folding as it ended by the present morphology of gentle and elongated folding during Upper Cretaceous - Middle Eocene. Most part of Jardas Al Jarari anticline is localized within E-W major dextral shear zone (Fig. 3.2). It represents as a major double plunging anticline trending E-W to NE-SW and extends about 13 km. To the east, the axis of fold is dislocated in a sense of sinistral movement along NNE-SSW strike-slip fault and the result is rotation of its axis to constrain the NE-SW direction (Fig. 3.2). On close observation, the effect by this fault induced refolding, in the central part of the major fold, along N-S direction and development of antifomal style with a syncline to the north inside which Darnah Formartion was deposited (Figs. 2.5 and 3.2). The fold is cored by Al Majahir Formation, which is flanked with higher relief of rare Wadi Dukhan and extensive outcrops of Darnah formations.

Geometricall, the procedure of analysis in the last phase of folding F_3 of Jardas AL Jarari major folding, where the field measurements are collected from all formations and subdivided into four domains I, II, III and IV (Figs. 3.5 -3.6). Domains I and II involve readings within the northwestern and southwestern limbs around the eastern closure, whereas domains III and VI represent the readings within the southern and northern limbs of the western closure. Plot diagrams of the data in both closures validate great girdle patterns of bedding planes. In Domain I, the strike of beds attains an average ENE-WSW and β1 determined gives a general dipping 11° N10°W. In Domain II, the bedding planes are striking NE-SW and β2 gives dipping 21° S35°E. The intersection of β1 and β2 plots exhibits plunging N65°E /3° (Fig. 3.6). Domains III and IV cover respectively the readings around the western closure and their poles exhibit, to some extent, great girdle patterns. In domain III the bedding planes are striking WNW-ESE and β3 gives dipping 11° S21°W, while in domain IV they are striking NE-SW and dipping 10° N25°W. The intersection of β3 and β4 plots gives the plunge of the fold S85oW / 8o (Fig. 3.6). This analysis deciphers that Jardas Al Jarari fold is asymmetric and verging generally towards the SSW (Figs. 3.5 - 3.6).

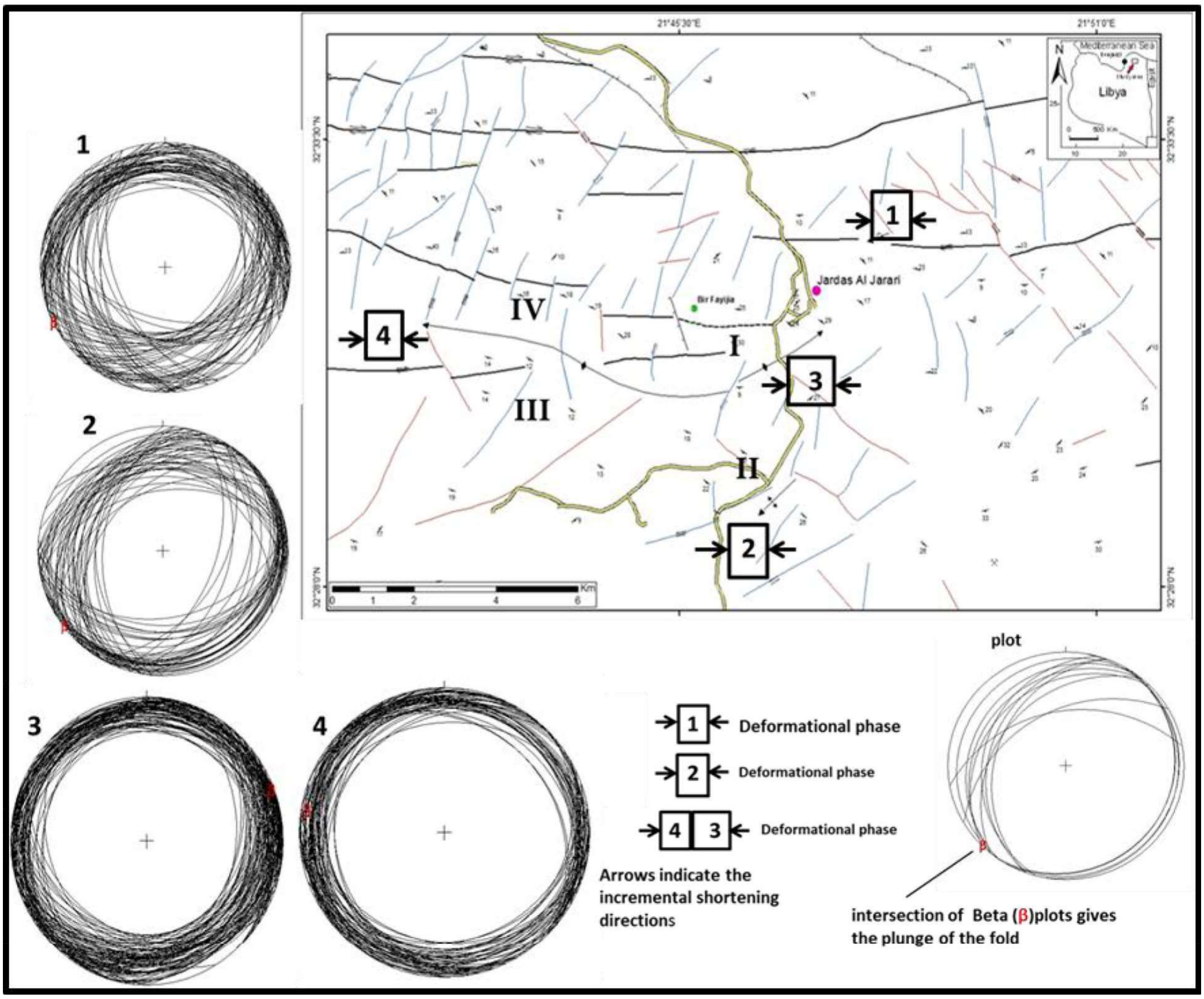


Fig. (3.5) Structural domains and analysis of field measurements collected on the eastern and western closure of Jardas Al Jarai F_3 major fold. Stereonet diagrams explain planes of bedding taken inside each domain.

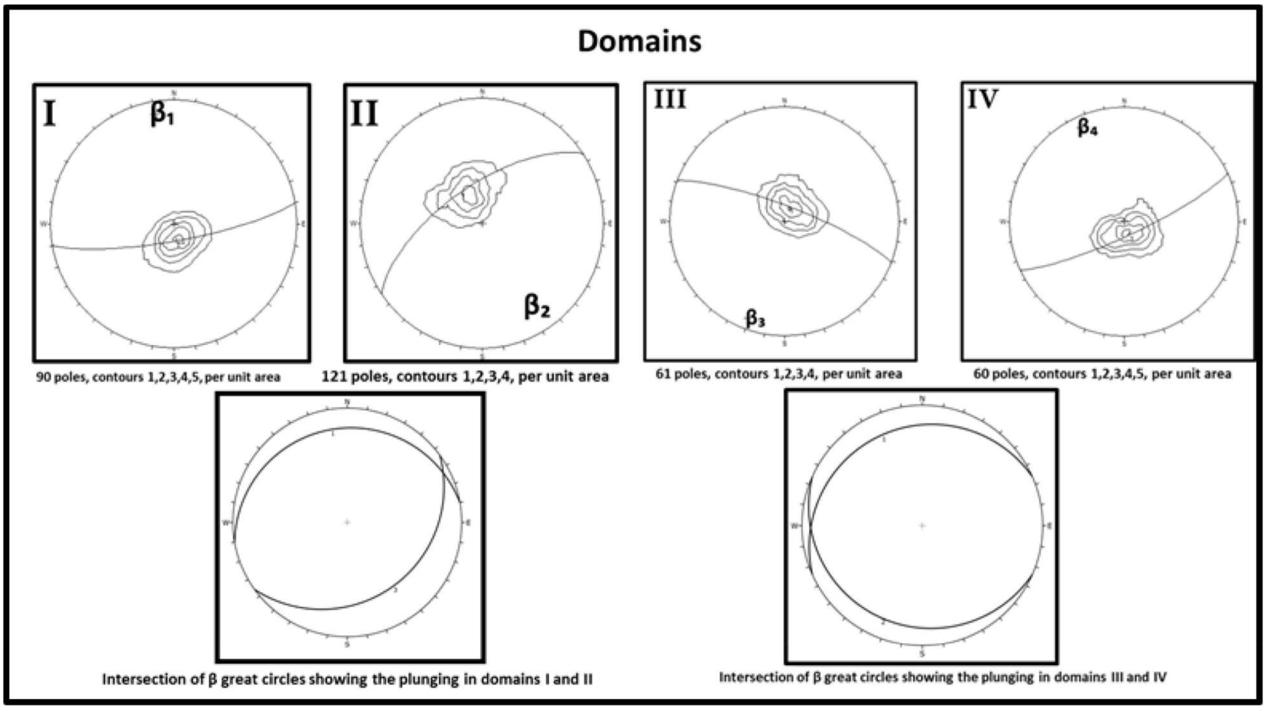


Fig. (3.6) Equal area lower hemisphere projection of the field measurements within the northwestern and southwestern limbs (Domains I and II) around the eastern closure and southern and northern limb (Domains III and VI) of the western closure of F_3 major fold affecting Jabal Al Jarari area.

3.2.2. Faults

In the following paragraphs, the hierarchy, geometry and kinematics of the different fault systems are first analyzed then the paleostress analysis of fault-slip data is discussed in order to deduce the orientation of the principal stress axes. Faults are one of the most prominent geological features in the study area (Figs. 3.2 and 3.7). The effect of these faults is markedly concentrated in the central part and localized within E-W trending three major dextral shear fault zones. Trace of these fault zones swings WNW-ESE and, elsewhere ENE-WSW. The northern boundary of fault zones is delimited by continuous trace of major strike-slip fault that defines the Upper Eocene / Lower Oligocene boundary (i.e. Darnah against Al Bayda Formations), while the traces of the other two fault zones are disconnected and affect the Darnah and northern and southern extremities of Upper Cretaceous rock units (Figs. 2.3 and 3.2).

In general, four main fault systems are developed with average strike E–W to WNW-ESE and ENE-WSW, N-S to NNE–SSW, NW-SE and NNW-SSW (Figs. 3.2 and 3.7). These faults bounds approximately homogeneous structural domains, characterized by a distinctive internal fault pattern. In comparison, these trends reflect an intimate relationship with the trend of joints (Fig.3.7). The less common faults may represent segments along the main fault trends or types of other faults. Kinematic indicators along these faults are documented in the field on the slickensides, fault blocks (fault breccia, conglomerates and gouge), repetition and visible dislocation of beds. Types of these faults are involved by strike-slip and normal faults accompanied, elsewhere, with minor thrusts.

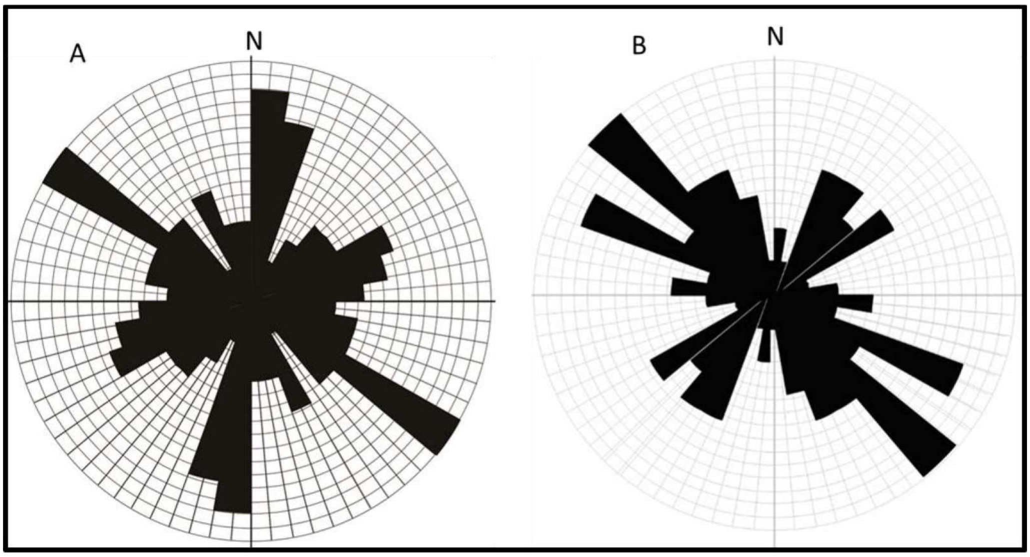


Fig. (3.7) Rose diagram of faults (a) and joints (b) in the study area

In the following is the description and characteristics of the main fault trends:

3.2.2.1. E-W Fault Trends

On the map scale, the E-W fault trends comprises several sub-parallel and discontinuous E-W striking faults and, sometimes swing along WNW-WSW and ENE-WSW trends. Their planes are usually sub-vertical and dipping generally N and rarely S. These fault trends are major and dissect the study area into three dextral displacement shear zones. The first defines the northern and southern extremities of the Upper Cretaceous (the western part, in particular), the second affects the Upper Eocene, while the third fault zone delimits the Upper Eocene/Lower Oligocene boundary. The result is the initiation of these fault zones was during Upper Cretaceous then their reactivation continued during the Eocene and Oligocene times. The effect by these fault trends is characterized by the alignment ridges, scarps and straight valleys. This category of fault trends exhibits dextral sense of movement and, sometimes is associated with transpression movement along F_1 minor fold (Fig. 3.3). North the central part, the movement along these faults is accompanied with development of pull a part basin that is bounded by a pair of NNW-SSW normal dip-slip faults inside which big accumulation of Al Bayda Formation was deposited. To the west of this basin, the major fault starts along E-W trend then turns left to the east along WNW-ESE trend inducing releasing bend and formation this basin. The effect by transpression and pull apart basin development, along these faults, assumes a combination of contractional (or transpression) and extensional (or transtension) recognized by many authors along of similar major strike-slip faults (Harland 1971; Sylvester and Smith 1976; Schubert 1980; Coward and Gibbs 1988; Moustafa and Khalil 1995; Corsini et al. 1996; Tikoff and Blanquat 1997 and Michael 2001; Fig. 3.8).

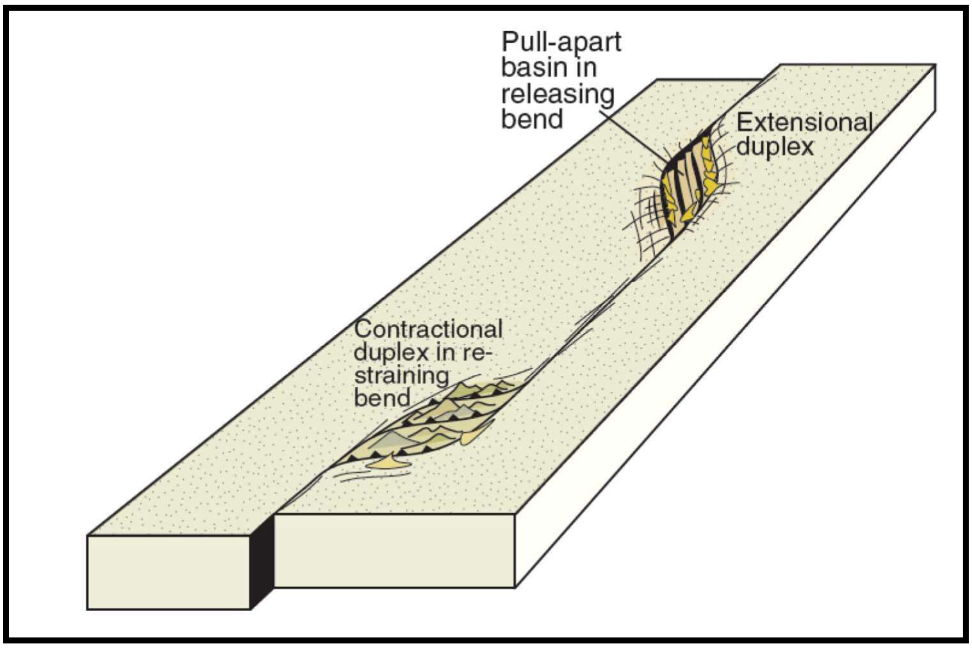


Fig. (3.8) Extensional (transtension) and Contractional (transpresion) developed at bends or stepovers along a strike slip fault system noted by many authors (e.g. Corsini et al. 1996; Tikoff and Blanquat 1997 and Michael 2001).

3.2.2.2. NW-SE and N-S to NNE-SSW Fault Trends

Both fault trends consider as two categories of secondary faults developed due to the movement within the E-W major shear fault zones. They represent the second rank and stage of pure wrenching in the study area. Field observations and analysis showed that the NW-SE and N-S to NNE-SSW faults have inconsistent cross cutting interrelationship in-between, where they are coeval and each fault in one category dislocates the other in second category and vice versa. Therefore, they display as two segments of Riedel and conjugate Riedel shears (R and R`). The NW-SE fault trends are Riedel shear and characterized by dextral displacement that reaches few centimeters to tens of meters, while the N-S to NNE-SSW category represents a conjugated Riedel shear and exhibits sinistral strike-slip movement along their fault trends (Fig. 3.2). The fault planes of the latter category are dipping generally SW at average amount 85^o, whereas in the NW-SE category the fault planes are dipping NE with amount 70^o. The intersection of the present two categories and sense of displacement on the major E-W shear zones can readily be resolved by postulating acing of principle principal stress ($\sigma 1$) from the NNW direction (Fig. 3.9).

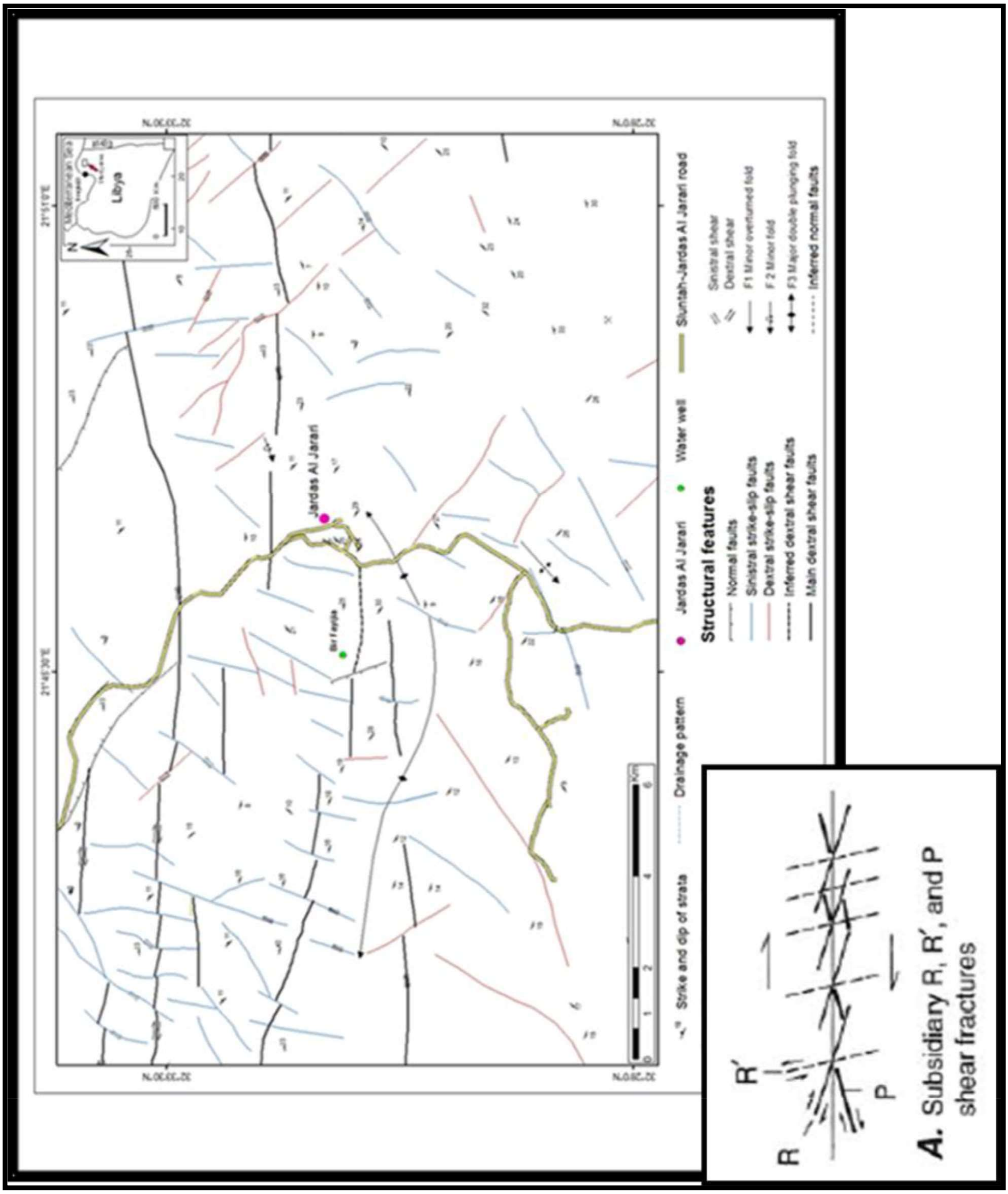


Fig. (3.9) View of structures formed by dextral strike-slip motion, where R and R' are synthetic and antithetic Riedels. P-shears are secondary and connect R and R' surfaces.

3.2.2.3. Interpretation

The en echelon arrangement of component faults within individual shear zones is closely comparable to the fracture patterns produced in shear box experiments by Riedel (1929) and further investigated by Hills (1963), Tchalenko (1967,1970), Courtillot et al, (1974) and Naylor et al (1986). These experiments were designed to study the fracture patterns produced in the overburden during subjecting to strike-slip fault. It was shown that shearing is propagated through the overburden in a wedge-shaped zone widening towards the surface and that the shears display a characteristic en echelon arrangement on the top surface (Tchalenko, 1967 and 1970). Two sets of shears, referred to as Riedel (R), oriented at 12^{o} and conjugate Riedel (R') oriented at 80^{o} to the trend of the major shear, are the first to develop (Fig.3.10). The dominant characteristic of Riedel shear zones is not only the en echelon arrangement of the shears but the fact that their orientations relative to the major shear direction in clockwise for dextral displacement and anticlockwise for sinistral displacement (Tchalenko, 1970).

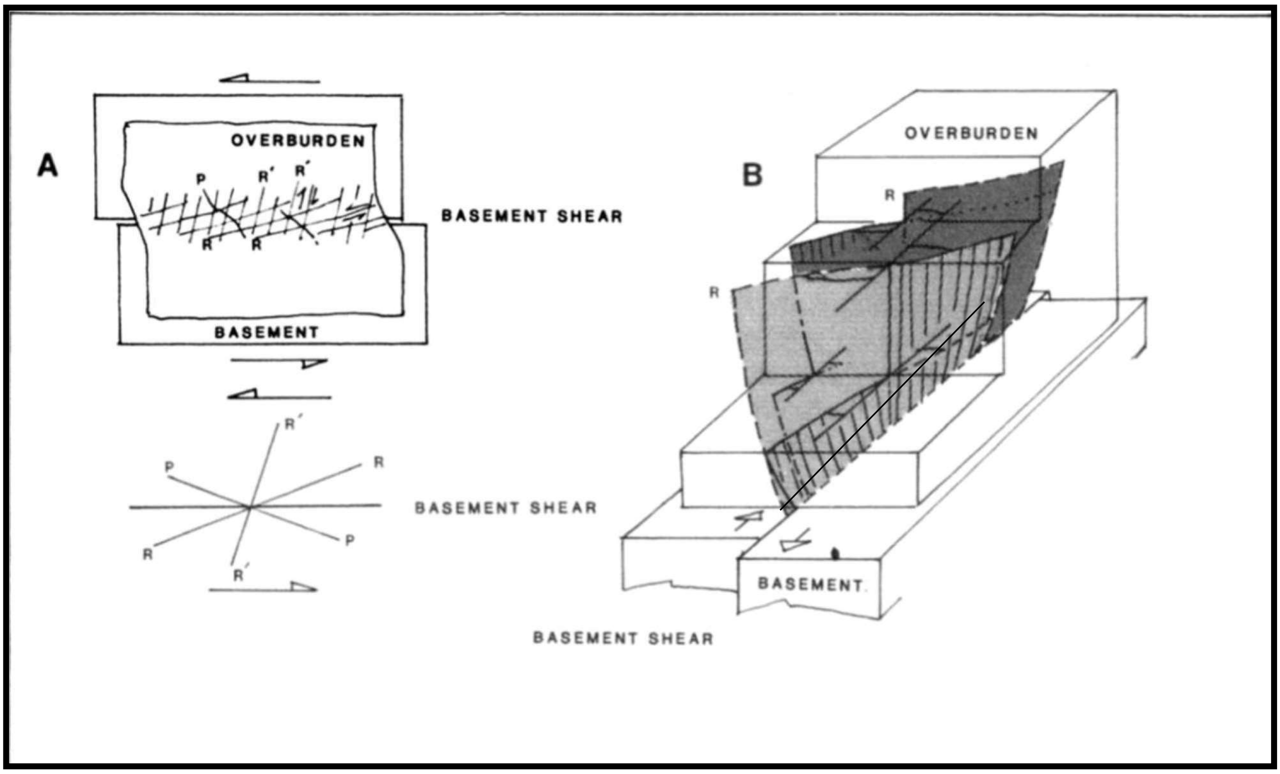


Fig. (3.10) A. Shears and Riedel experiment, R = Riedels; R' = conjugate Riedels; P = P shears. B. Comparison of Riedel shears patterns at different levels in fault wedge (Woodcock and Fischer, 1986).

3.2.2.4. NNW- SSE Fault Trends

These fault trends are fewer in number and well demonstrated by two spectacular fault trends affecting Al Bayda Formation in the northern part of the study area. The two faults run oblique to the northern E-W major shear zone and display down throw towards WSW and ENE and confine the boundary of pull a part basin that show a thick deposition of Al Bayda Formation. To the east of Jardas Al Jarari village, where a type section of the Danian exposures of the Al Uwailyah Formation is recorded, a system of NNW-SSE normal faults are also recognized along N25^{o} W trend and with a general down throw a few centimeters towards the SW direction (Fig. 3.11).

Fig. (3.11) Exposure of Al Uwailyah Formation to the east of Jardas Al Jarari village showing N25^{o}W striking normal fault with a few centimeters down throw in the SW direction; Photo looking N.

3.2.3. Joints

Joints are mostly used to infer the paleostress orientations and, thus give evidence of the tectonic history of a region (Dyer 1988 and Bahat 1999). In the present study, joints analysis is conducted on about 1550 readings at different places in different stratigraphic rock units (See Appendix) . The aim of this analysis is to know the major direction of the joints in relationship with the fault trends.

In the present area, the joints are regular and, sometimes, irregular and along their planes there are little or no displacements. They are distinguished into two types; shear and tensional joints. On the outcrops, some of joints (the shear joints, in particular) form conjugate arrays and are infilled with crushed rock fragments.

Generally, the shear joints are mostly spread out and represented by two sets striking NW-SE and NE-SW. The tensional joints orient generally NNW-SSE and give, on the composite rose diagram, an intimate interrelationship with the present faults (Fig. 3.7). 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:

In Al Majahir and Wadi Dukhan Formations, the shear joints are prominent along the N50-60W and N20E trends. Subordinate joints are recognized by N10-20W tensional joints (Fig. 3.12 a). On the outcrops, the joints are well-developed inside the very crystalline limestone in Al Majahir Formation and dolomatic limestone of the Wadi Dukhan Formation. Comparably, the joints are common in Al Majahir Formation and with slight effect in Wadi Dukhan Formation. In Al Uwailyah Formation, the joints are well developed; the main directions of joints are striking N40-60W and N20E with minor trends along the NNW-SSE and ENE-WSW (Fig. 3.12 b). Most joints noted in Al Uwailyah Formation are mostly tensional joints. On the other hand, the length of the joints ranges from 1m to 6m. In Darnah Formation, the joints are widely distributed. They are recognized as shear joints with rare tensional ones. The shear joints are mostly spread out and represented by two sets striking N20-30E and N50-60W (Fig. 3.12 c). The tensional joints orient generally N10W. In the present area, displacement on joint surfaces is very rare except in some parts where there is dextral movement along the NW-SE trend (Fig. 3.13 a).

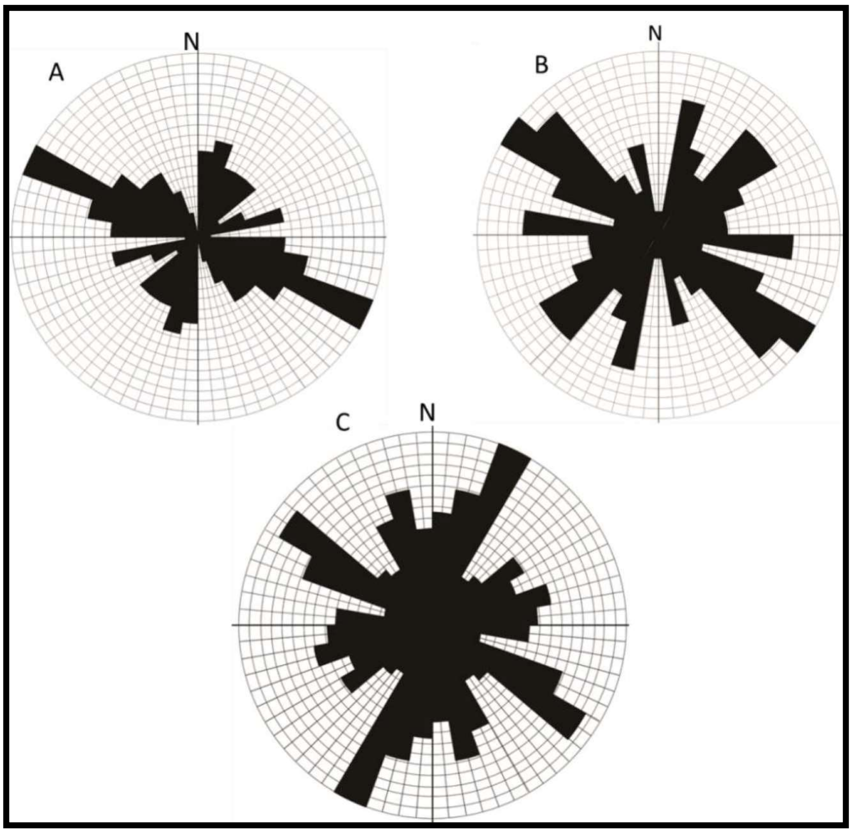


Fig. (3.12) Rose diagram of joint measurements in Al Majahir and Wadi Dukhan (A), Al Uwayliah (B), and Darnah formations (C).

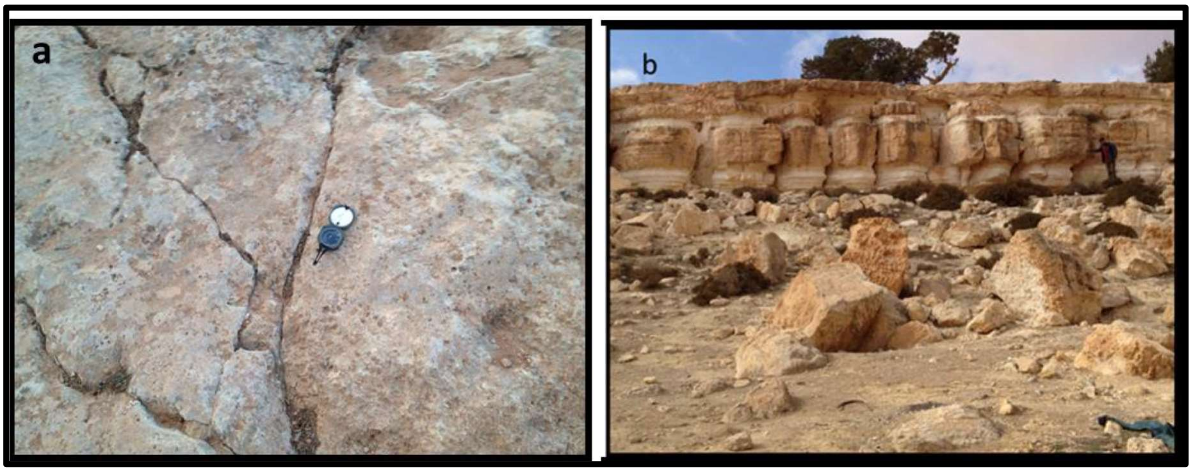


Fig. (3.13) a. Dextral displacement along NW–SE shear joints in Al Majahir Formation; Photo looking WSW. b. Highly joints in well-bedded limestone of Al Uwayliyah Formation to the east of Jardas Al Jarari village; Photo looking NE.

3.3 Structural geometry and stress analysis

Geometrically, about 1050 measurements are taken, in the field, from different directions of bedding planes, fault and joint planes, orientation of minor folds, and other linear fabrics. All these measurements are plotted on the stereonets, taking into consideration that the plotting and analysis of data are subdivided based on the intensity and prominent of deformation relative to the areal distribution and sequence of the stratigraphic units. Consequently, the Upper Cretaceous rock units are the oldest, very limited and characterized by intense deformation. Hence, their measurements are taken on a minor scale and considered as data for D_1 analysis. In contrast, the Tertiary rock units (Eocene outcrops, in particular) are widespread and reflect a pervasive but with less intense deformation, and therefore, the measurements are generally taken on a major scale and accommodated for D_2 deformation. On the other hand, the measurements on D_3 structures are represented on the stereonets where the intensity of deformation diminishes gradually moving northward and as the Upper Cretaceous and Eocene strata conceal in depth underlying the Oligocene outcrops.

The geometric analysis in Al Majahir Formation is prominent, the planar and linear fabrics are well developed and enough for representation on the stereonets (Fig. 3.14). Plotting of F_1 minor folding axes exhibits a common plunging 7°/ S55°W. Plots of Al Majahir fault planes document an interaction of two main fault planes striking dominantly N50°W and N10°E. β1 and β2 depict dips 78° WNW and 76°NNE, respectively. Field measurements of Al Majahir joints reflect, to some extent, wide spreading of the poles on great girdles of two main sets of joints striking N65°W and N20°E. β1 and β2 determined from these poles depict maximum concentration of the dip along the joint planes 73° NW and 70° NE, respectively.

In the Wadi Dukhan Formation, is prominent, the planar and linear fabrics are well developed and enough for representation on the stereonets (Fig.3.14) Plotting of F2 minor folding axes exhibits a common plunging S50°W /4°. Plots of Wadi Dukhan fault planes document an interaction of two main fault planes striking dominantly N50°W and N10°E. β1 and β2 depict dips 78° WNW and 76°NNE, respectively. Field measurements of Wadi Dukhan joints reflect, to some extent, wide spreading of the poles on great girdles of two main sets of joints striking N65°W and N20°E. β1 and β2 determined from these poles depict maximum concentration of the dip along the joint planes 73° NW and 70° NE respectively.

In the Paleocene (Al Uwayliyah Formation), the faults reflect a mild reactivation and continuation of the Cretaceous faults, and consequently, their field measurements are approximately the same in Cretaceous faults, but they are insufficient for representation on the stereonet. The planar fabrics of joints are, however, enough for representation and define two main trends of shear joints and rarely one set of tensional joints. Inconsistent crosscutting interrelationship is generally present between these two shear joints. On the stereonet (Fig. 3.14), the plotting of S poles revealed two prominent sets of the shear joints spreading out on great girdle striking N50°W and N20°E. β1 and β2 determined from these S-poles indicate average of dip 72° on a bearing NE and 76° on a bearing NW respectively.

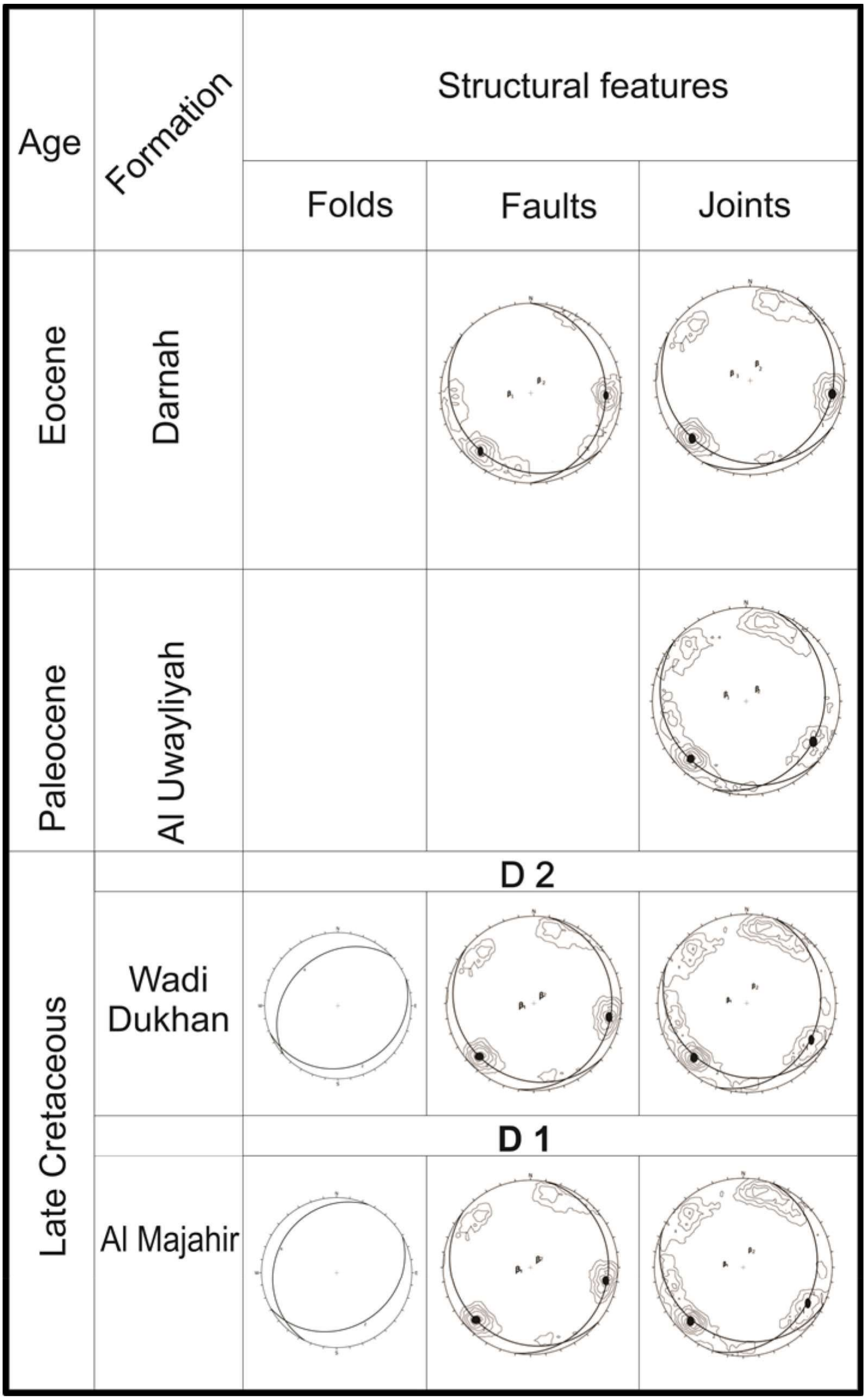


Fig. (3.14) Equal area lower hemisphere projection of the structural features in Late Cretaceous, Paleocene, and Eocene rock formations of Jardas Al Jarari area.

In the Darnah Formation, on the other hand, the plot diagram of faults in Darnah Formations form generally great circle patterns. S-poles of the strike-slip faults display dominant right lateral trend striking N50°W and left lateral strike-slip trend striking N-S, and their β1, β2 exhibit common dips 76° WNW and 75° NE, respectively (Fig.3.14). S-pole plot of joints in the Eocene rocks showed two main sets of shear joints with maximum concentration at N30°E/76°NW and approximately N60°W/75° NNE.

3.4 Stress Analysis

Strike-slip faults may occur as simple structures or in zones of more or less parallel fault trends. However, strike-slip faults can also form conjugate sets implying that they were active at about the same time under the same regional stress field (Fig. 3.15). Conjugate strike-slip faults fit well into both Anderson's model and the Coulomb fracture criterion. In simple terms, the acute angle between the two sets is bisected by σ_1 (red arrow in Fig 3.15), and the angle itself is determined by the internal friction of the rock. Kinematically, such faults result from pure shear in the horizontal plane, where shortening in one direction is compensated by orthogonal extension in the other. In this ideal model, no extension or contraction occurs in the vertical direction. As shown above in the geometrical analysis, each conjugated and prominent two sets of faults and joints are more or less conformable in the orientation since Late Cretaceous to the Eocene. In the field, this relationship is found as well and where members of one set of faults and shear joints exhibit inconsistent crosscutting interrelationship with members of the another set. This assumes their development under similar stress conditions, and hence, σ1 and σ3 are the bisectors of the acute and obtuse angles between the conjugated trends; the orientation of σ2 represents the point of their intersection. Figure (3.16) shows the stress diagrams, in the present area, where the orientation of principle stress σ1 axis lies within the shaded quadrants and σ3 axis extends across the opposite unshaded quadrants.

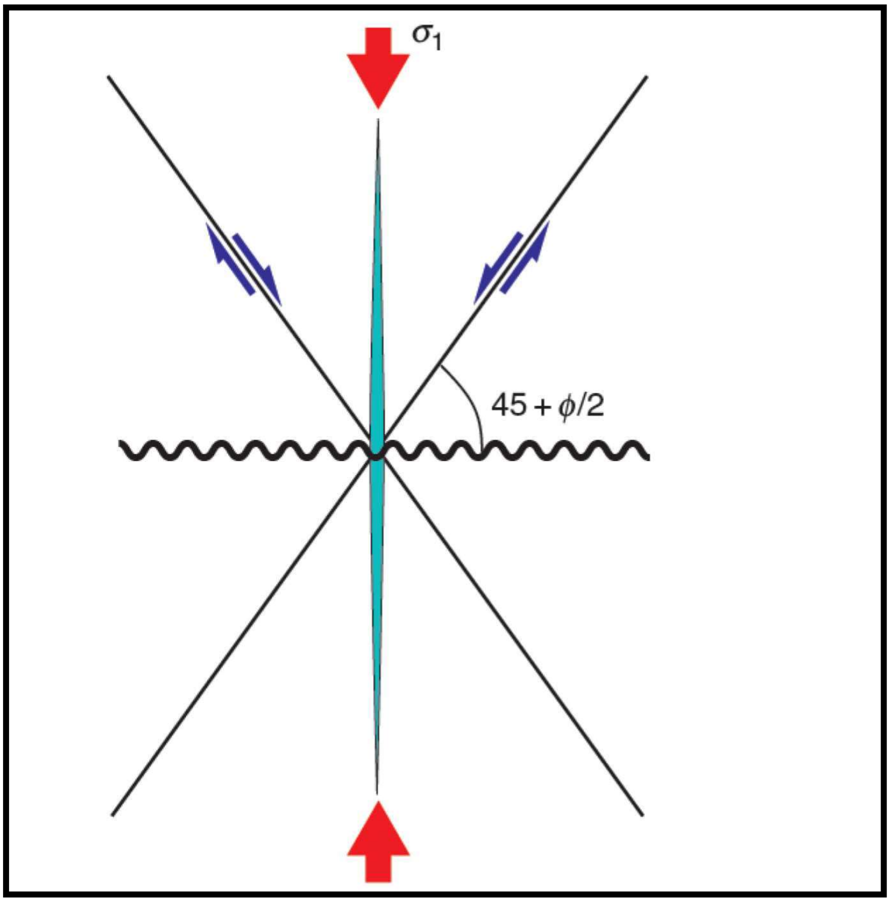


Fig. (3.15) Conjugate pure shear model for the formation of strike-slip faults. The orientation of extension fractures (vertical) and stylolites (horizontal) are indicated.

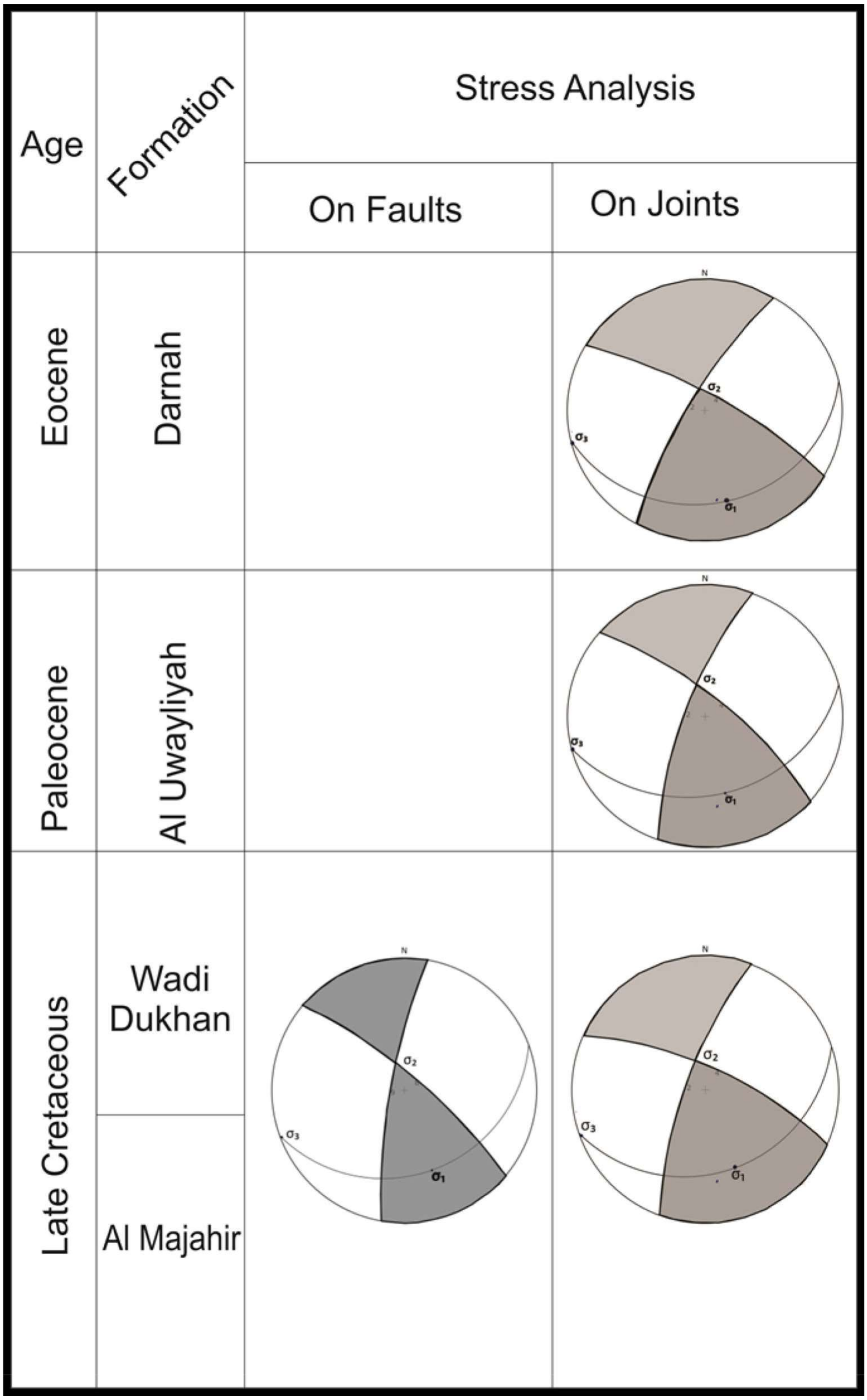
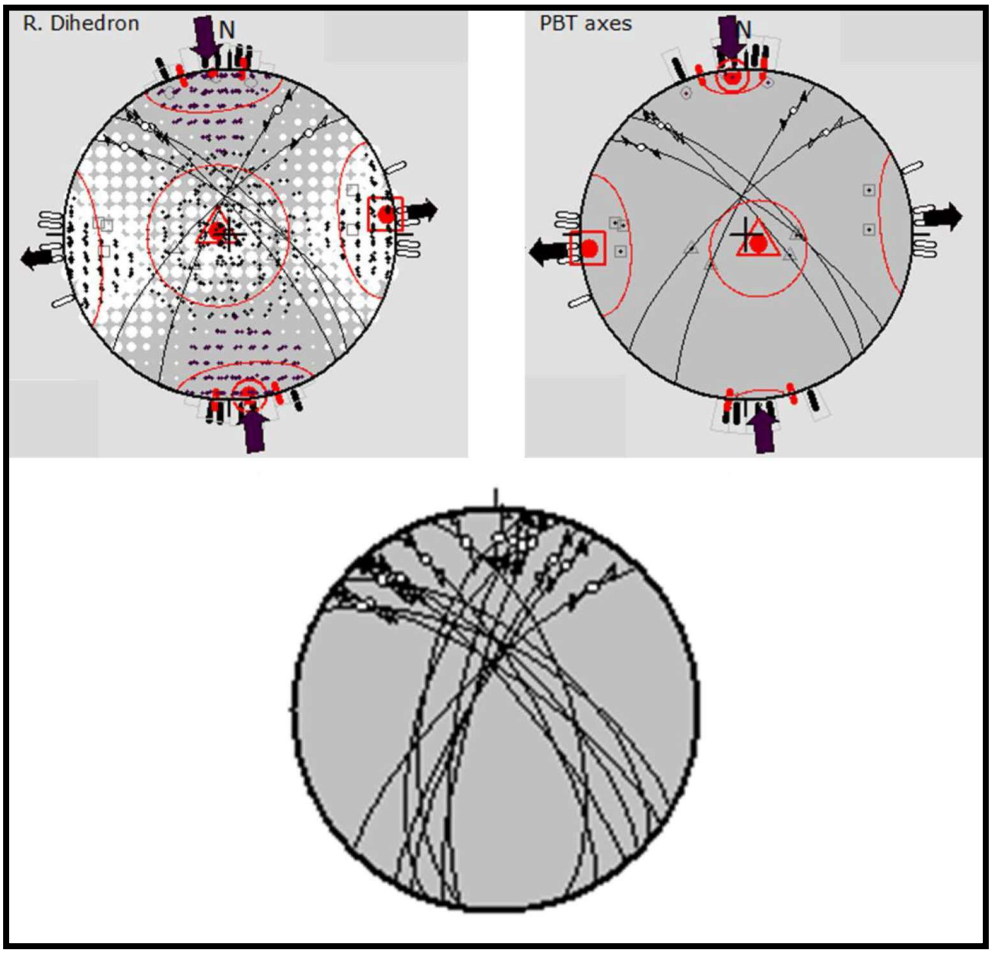


Fig. (3.16) Stress analysis on the faults and joints of Late Cretaceous, Paleocene, and Eocene rocks. Plotting on the stereonets represent the average of measurements on faults and joint planes.

In Al Majahir and Wadi Dukhan formations, the fault analysis reveals that σ1, σ2, and σ3 operate in the directions S19°E (N19°W) /25°, N20°W/65°, S69W (N69°E) /1° respectively (Fig. 3.16). On joint plot, these orientations become S21°E (N21°W) /27°, N18°W /64°, S70°W (N70°E) /2° for σ1, σ2 and σ3. On the other hand, in the Al Uwayliyah Formation, the stress plot of the joints indicates the orientations of σ1, σ2, and σ3 at S15°E (N15°W) /26°, N10°W /64°, S76°W(N76°E) /3° respectively.

In Darnah Formation the stress analysis in joints assumes that σ1, σ2, and σ3 are acted along S15°E (N15°W /20°, N15°W /70°, S75°W (N75°E) /1° respectively.

To sum up, the stress analysis precludes that the principal stress σ1 is acted on all cases along the NNW-SSE direction. Moreover, positions of σ1, σ2, and σ3 are conformable with the mechanism of strike-slip tectonics in which σ1 and σ3 are more or less horizontal, while σ2 is vertical (Fig. 3.17).



Stress Parameters	Faults
σ_1	09/350 or 170
σ_2	83/335 or 155
σ_3	01/265 or 85
Stress ratio (R)	0.2
Tensor type	Pure strike slip

Fig. (3.17) Results of different stress phases in the study area. Stereographic projections of the fault-slip subsets and corresponding stress tensor. Computed stress axes are represented as circle (σ_1), triangle (σ_2) and square (σ_3). Small divergent black arrows indicate the horizontal extensional stress direction (σ_3), whilst large convergent black arrows indicate maximum principal stress axis (σ_1).

On the ellipse diagram (Fig. 3.18) and based on the stress analysis, attitudes, kind and magnitude of different structural elements, the inconsistent crosscutting interrelationship between the main trends in faults and shear joints is attributed to the characteristics of simple shear wrenching mechanism. The association of NNW–SSE normal faults and parallel tensional joints are coincident with the basic concept of wrenching tectonics (Wilcox et al. 1973; Lowell 1990; Dewey et al. 1998; Destro et al. 2003). On a proposed strain ellipse, the NW–SE right lateral strike-slip faults and related joints are trends coincident with the Riedel shears (R), while the N–S to NNE–SSW sinistral strike-slip fault and associated joint trends are the main system of conjugated Riedel shears (R'). Both trends intersect at acute angle with each other and E–W main shear zone trend (M).

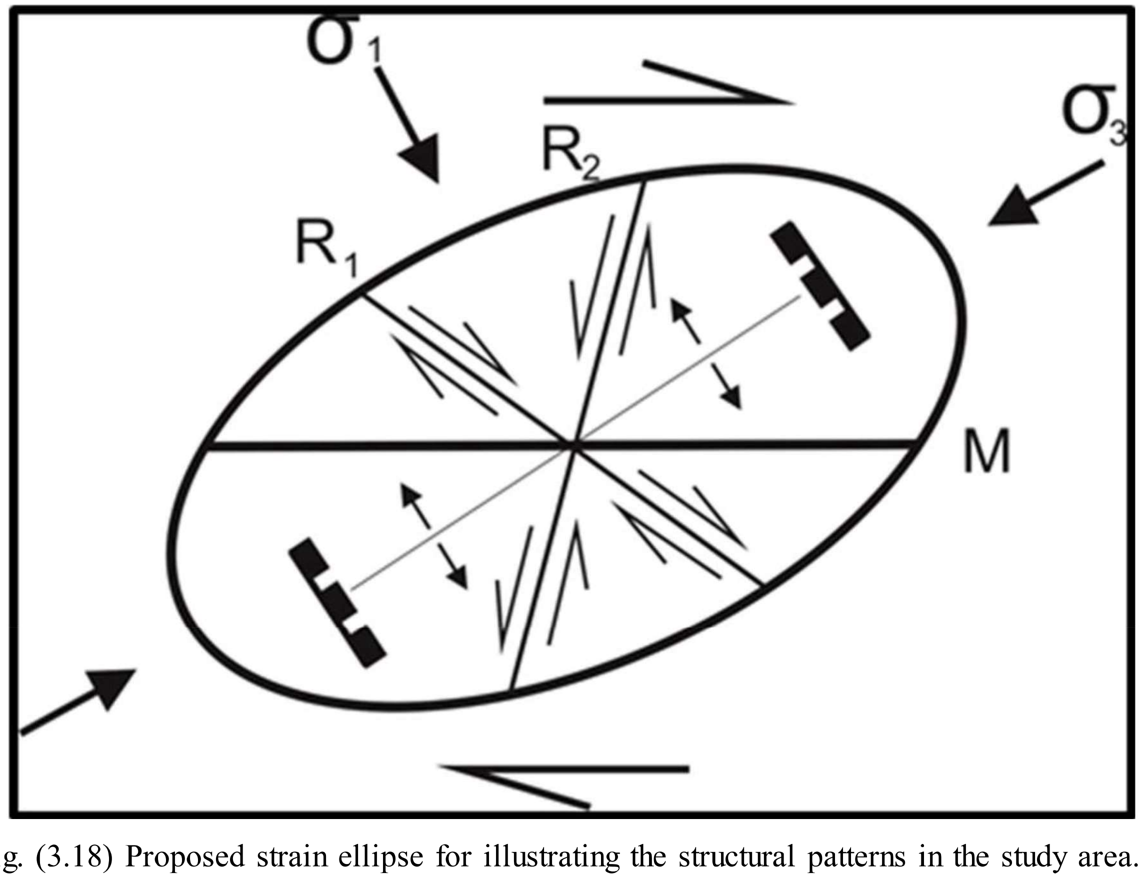


Fig. (3.18) Proposed strain ellipse for illustrating the structural patterns in the study area. R_1 Riedel shear with average N50°W, R_2 conjugate Riedel shear with average N10°E and M is equivalent to E-W main shear.

CHAPTER IV

Tectonic Development

4.1 Introduction

Al Jabal Al Akhdar anticlinorium was developed south of the Mediterranean geosyncline, the Tethys, on the attenuated continental crust of the northern passive margin of the Afro-Arabian shield (Biju-Duval et al. 1979; Argyriadis et al. 1980; Robertson and Dixon 1984; Dercourt et al. 1986; Moustafa et al. 1989; Anketell 1996). This margin consists of a system of E-W trending, basin-arch half grabens that run parallel to the NE African coast. These evolved following the opening of the Tethys during Jurassic time. The age of the remnants of the Tethy's oceanic crust, discovered in the central Mediterranean, suggest that the opening started during the Middle Jurassic (Laubscher and Berboulli, 1977). An extensional phase of deformation was initiated in North Africa in the Triassic-Early Jurassic with the opening of the central Atlantic and the separation of the Turkish-Apulian Terrane from NE Africa (Luning et al. 2005). Neotethys opened in the Middle Jurassic, creating a passive southern continental margin (Anketell 1996) marked by E-W-trending normal faults. This was accompanied by rifting from Syria to NE Libya (Cyrenaica) and a sudden change in the movement of the European plate, which started to move eastward relative to Africa (Savostin et al. 1986; Le Pichon and Gaulier 1988; Guiraud and Bosworth 1997). An extensive phase of dextral transpression was initiated in the Upper Cretaceous replacing the previous sinistral movements due to collision of Africa and Europe (Guiraud and Bosworth 1997; Yem et al. 2011). The Alpine compression in North Africa resulted in intra plate inversion and uplift of Late Triassic-Early Jurassic grabens and the formation of the Syrian Arc fold belt in NW Arabia, NE Egypt, Libya (Cyrenaica Platform). Evolution of deformation styles in Al Jabal Al Akhdar was formed through three major compressional events that occurred in the Santonian, Campanian - Maastrichtian, and early Late Eocene. These events developed folding and strike-slip faulting along the northeastern African-northern Arabian margin (Syrian Arc). 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.

In the study area, disconformity is markedly noted with the Late Cretaceous - Palaeocene boundary and, elsewhere Eocene strata, where the moderately dipping beds of Al Majahir Formation are overlain by the gently dipping Al Uwayliah and Darnah formations (Fig. 4.1). About 5km south of Jardas AL Jarari village and at elevation 622m, Al Majahir Formation is capped by Darnah Formation without any successions or reworking of Palaeocene in-between. Down-section unmappable exposures of Al Uwayliyah Formation (Danian part) rest unconformably over the Al Majahir Formation and, meanwhile, are covered by the extension of this Darnah Formation.

Fig. (4.1) Panorama showing disconformity surface between Al Majahir Formation and Darnah Formation; about 5km south of Jardas Al Jarari village. Photo looking

Tectonically, the study area is affected by three E-W dextral major shear fault zones that is approximately parallel to the E–W Cyrenaica fault. In places, the trend of these faults turns, some degrees, left and right along the ENE-SWS and WNW-ESE directions. The movement within this structural regime promoted the existence of wrenching tectonics in the area and is kinematically accommodated with the right lateral simple shear mechanism. The geometry of folds and faults, in the study area, reflected a dextral transpressional shear model (Fig. 3.18). The wrench system is manifested by the development of secondary array of Riedel shear (R) and conjugate Riedel shear (R`) along NW-SE dextral and N-S to NNE-SSW sinistral strike-slip faults, three phases of fold, NNW-SSE normal faults and enhanced with tranpression along E-W fault trend.

4.2. Tectonic Evolution

The deformation in the present area is evolved through three tectonic stages; one in Late Cretaceous and two stages in the Eocene and Oligocene.

4.2.1. Late Cretaceous (Campanian-Maastrichtian Compressive Episode).

This stage post-dates the climax of Santonian folding which clearly produced a general NE/SW- to ENE/WSW trending uparching of the central part of Al Jabal Al Akhdar (Röhlich 1974, 1980; El Hawat and Abdulsamad 2004). The Upper Cretaceous is well exposed in the surface Al Jabal Al Akhdar Uplift, as well as being present in drilled wells. The Late Cretaceous in Al Jabal Al Akhdar was influenced by global eustacy and tectonics. The event was associated with the opening of the Northern Atlantic during Santonian time and led to the replacement, by dextral and compressional tectonics, of the sinistral and extensional tectonic movements between Africa and Eurasia which is dominated in the Early Mesozoic. In the central axis of Al Jabal Al Akhdar, the Late Cretaceous sequence was interrupted in intra-Santonian time by a major tectonic event, which initiated the development of an unconformity. This unconformity separates the Cenomanian-Coniacian, from the Campanian sequence (Rohlich, 1980). El Werfalli et al. (2000); El Hawat and Abdulsamad (2004) classified the Late Cretaceous rocks of the central part of Al Jabal Al Akhdar into four formations; two before Santonian folding (Qasr AL Aid and Al Baniyah Formations) and two after this event (Al Majahir and Wadi Dukhan Formations), with a distinct unconformity in between.

In the study area, the Late Campanian- Early Maastrichtian compressive event rejuvenated dextral movement along E-W striking faults that produced NE-SW to ENE-WSW-trending F1 and F2 minor folds in Al Majahir and Wadi Dukhan formations, NW-SE dextral and N-S to NNE-SSW sinistral strike slip faults and the prominent Al Majahir and Wadi Dukhan folding as spectacular uplift in the central part of the study area (Fig. 4.2). Al Majahir and Wadi Dukhan folding orients E-W to NE-SW and is attributed to the dextral movement along the E-W major shear fault zones. However, Al Majahir Formation is thick and occupies the core of the fold so as to compensate the steeper beds of topography and the underlying Al Baniyah Formation. During this stage, the Santonian structure is rejuvenated again and resulted in upheaval the central part of the study. The first major tectonic phase, in the present area, is interpreted to have taken place in Late Campanian–Early Maastrichtian. Confirmations are also added from: (1), Al Majahir formation was assigned only to the Early to Late Campanian.

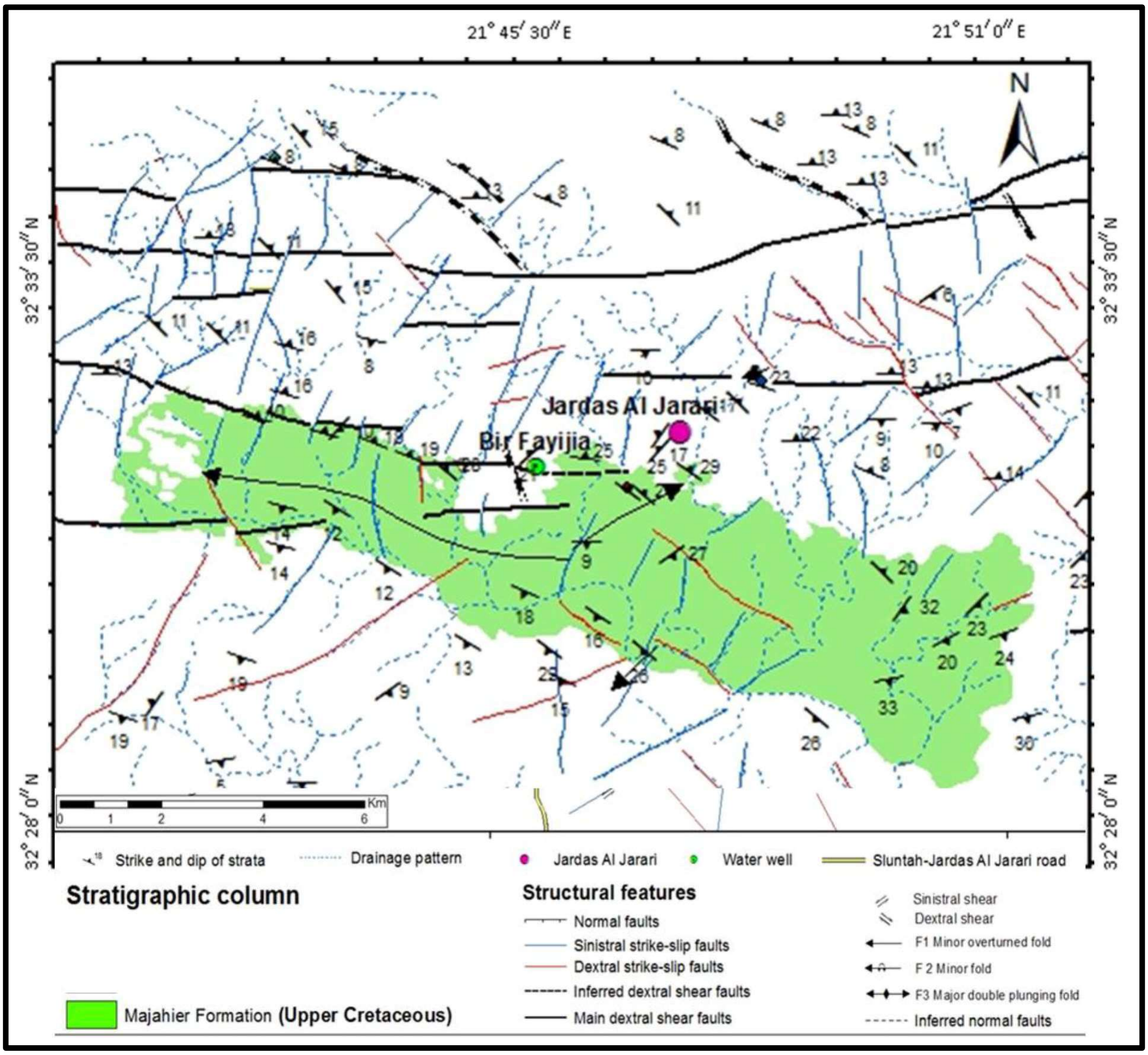


Fig. (4.2) Distribution of Al Majahir Formation.

(2) Structurally, Al Majahir section displays intense NE-SW to ENE-WSW-trending folds, minor E–W to WNW-ESE, NW-SE and N-S to NNE-SSW strike-slip faults, NW-SE, WNW–ESE, and NNE–SSW shear joints. This pulse of tectonism triggered a major hiatus contact between Al Majahir, Wadi Dukhan Formations and the overlying Tertiary rocks. Investigating this contact showed that the Palaeocene is generally missing except a thin marly limestone beds between Al Majahir and Darnah Formations. This explanation with the continuity of uplifting during most of the Palaeocene induced paucity and missing of the Palaeocene strata in the whole area, which were totally attributed to the subaerial erosion by Röhlich (1980).

4.2.2. Eocene Tectonic Stage

In the present area, the lower part of Eocene section (Apollonia Formation) is absent and deformation during this stage was dominated with brittle structures in the upper part (Lutetian-Priabonian) of Darnah Formation. To the north of the study area, (in Ras Al Hilal-Al Athrun area) the Apollonia Formation (Early to Middle Eocene) rests unconformably over the Al Athrun Formation and locally over the Paleocene Al Uwayliyah Formation, while to the south the Middle to Late Eocene Darnah Formation rests unconformably over Wadi Dukhan with a complete absence of the Apollonia Formation. During this episode, shortening and inversion tectonics developed again and documented minor thrusts structures in the Lutetian section as well as the reactivation on the E–W to NW-SE, and N–S to NNE-SSW strike-slip faults in the whole Eocene section. The sequence of structures within the Eocene section indicates that the cycle of sedimentation started with the inundation during Ypresian to the Lutetian then followed by a tectonic event by the end of Lutetian. As shown in Figure (4.3), the Eocene outcrops Darnah Formation (Middle to Late Eocene), cover most the northern and southern sides but pinch out northwest ward and disappear along the central part of the mapped area. All these data speculate that the Late Cretaceous tectonic event continued during the Palaeocene and the early stage of Eocene and, consequently, the main tectonic reactivation of this stage had been started in Late Lutetian, which rests elsewhere unconformable over the Wadi Dukhan Formation. As the Late Cretaceous folding in the central part of Al Jabal Al Akhdar belt was high against the Tethyan transgression during the Eocene in the northwest and north, this thereby explains the extension of the Eocene outcrops along the northern periphery of this belt (Röhlich 1980). The extensive distribution of the Darnah Formation and the difficulty of recording the underlying Apollonia Formation may reveal that the Lutetian tectonic event was shortly followed by the largest inundation and before, hence the cycle of sedimentation became abundant in the Priabonian age. Missing of Shahhat Marl Member mostly along the northern limit of Darnah Formation showed a remarkable unconformity with the Eocene-Oligocene boundary and reflected a regressive phase and the emergence of a larger area at the end of Eocene 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 major F3 folding. Most probably, this feature is coeval with the first pulse of tectonism started at about 34Ma (Priabonian–Rupelian), east of Libya, as the early stage of rifting in the Red Sea region (Issawi et al. 1999).

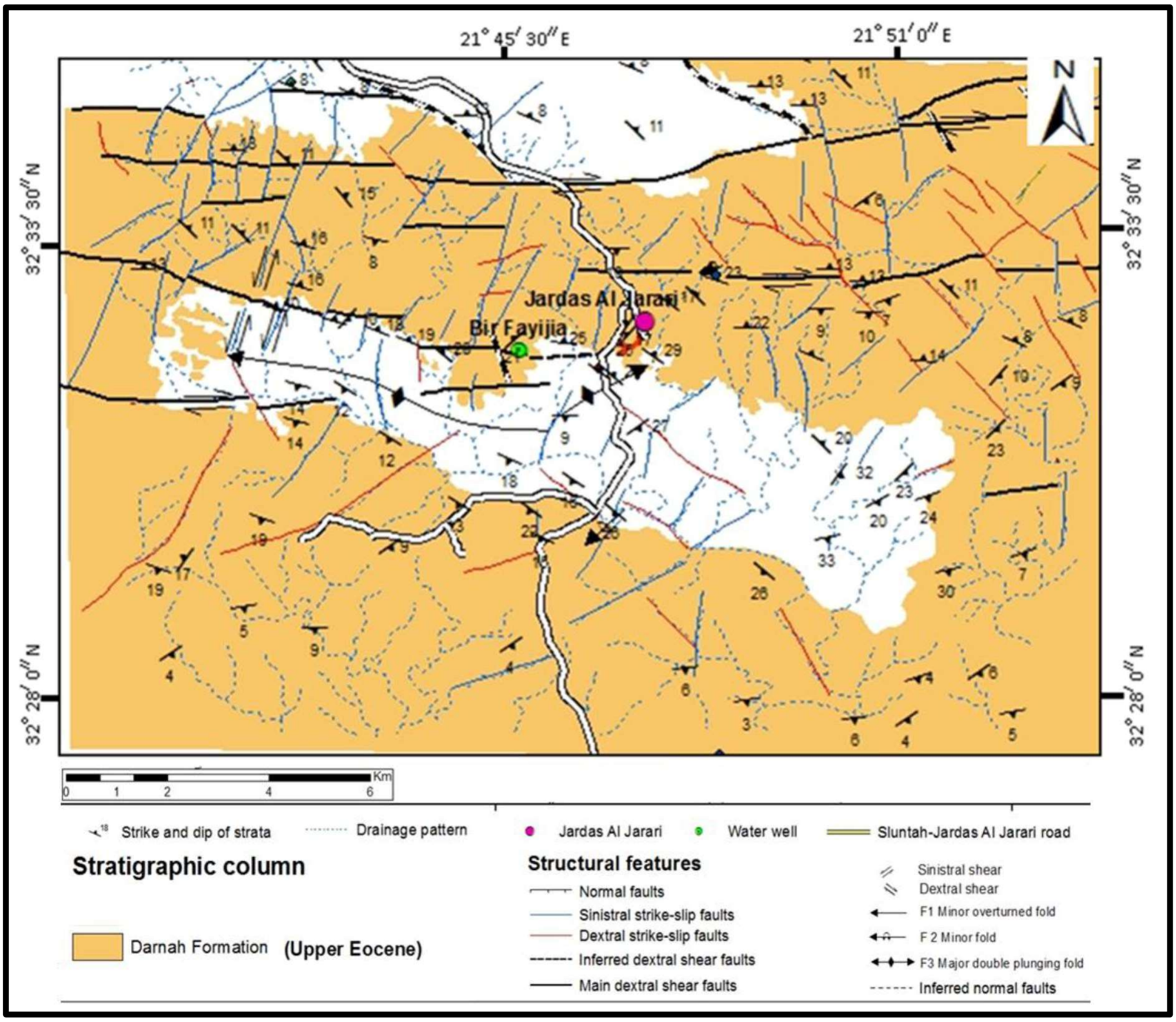


Fig. (4.3) Distribution of Darnah Formation.

4.2.3. Oligocene Tectonic Stage

The inundation during Early Oligocene was restricted and witnessed via deposition of Al Bayda Formation along the northern to northwestern part of the mapped area, and exposed at level about 700m. During the lower Oligocene, the dextral and sinistral faults were still active but with minor effect. To the northwest (south of Suluntah), the lower part of Al Bayda Formation (Shahhat Marl Member) is missing leading to the contact between the overlying Al Bayda Algae Member and underlying Darnah Formation (Fig. 4.4). This explains existence of a major unconformity with the Eocene-Oligocene boundary and how this emergence shaped the base on which Al Bayda Formation was deposited. Outside the present area, some authors (El Hawat and Abdulsamad 2004 and El Amawy et al. 2011) recorded also such variations and common disappearance of Shahhat Marl Member between the Eocene boundary and Al Bayda Algal Limestone Member. The Early Oligocene started with a new inundation in the northwestern part but the area covered by Al Bayda Formation was small from that of the preceding transgression cycles. This reflects emergence of a larger area at the end of Eocene. However, the variation of vertical thickness, underlain by this formation, in Al Bayda Algal Limestone Member, precludes a period of regression and hence led to the development of unconformity at the end of Early Oligocene. As shown in the field, the remarkable coincidence of the bedding above and under this unconformity indicates that eustatic sea level changes and not tectonics-related regression had occurred after Al Bayda sedimentation cycle. The existence of block normal faulting with rare strike-slip faults, shear, and tensional joints in Al Bayda Formation are indicative of the continuity of the inversion during the Oligocene time.

During the Oligocene tectonic stage, the faults were still active but with slight effect and dominated with normal faults and accompanied tensional joints. In the northwestern part south of Sulontah, array of NNW-SSE synthetic normal faults is plotted and showing northeastern and southwestern downthrows.

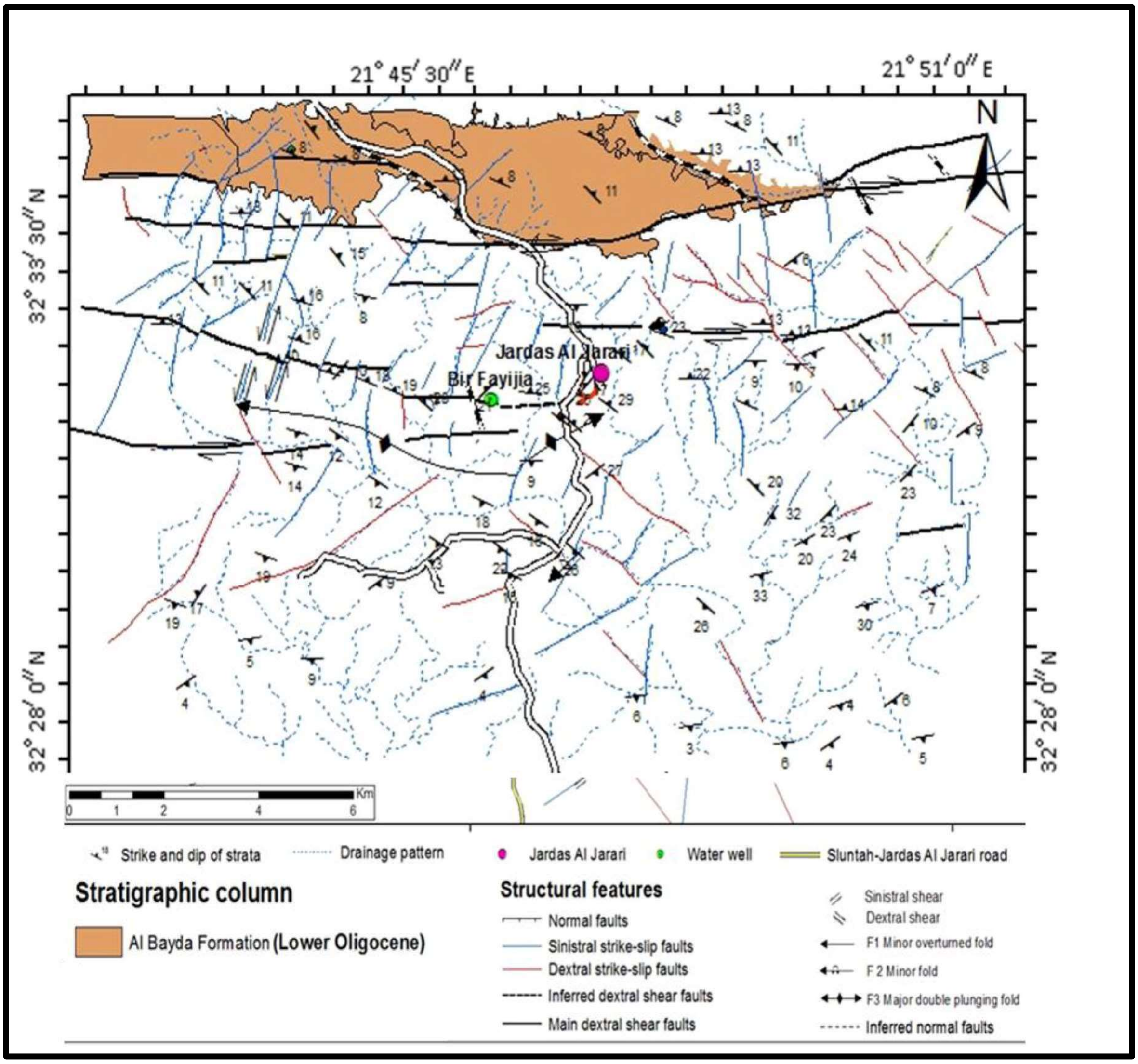


Fig. (4.4) Distribution of Al Bayda Formation (Algal Limestone Member).

CHAPTER V

Conclusions

Al Jabal Al Akhdar was formed through three major compressional events that occurred in the Santonian, Campanian-Maastrichtian, and early Late Eocene. These events developed folding and strike-slip faulting along the northeastern African–northern Arabian margin (Syrian Arc). The study area is located in the central part of this belt and exhibits different varieties of structural patterns and involves one of the Late Cretaceous inlier within outcrops of Tertiary sediments. Because of there is still lacking and ambiguity on the structural interpretation in Al Jabal Al Akhdar, the studied structures are re-assessed based on more detailed fieldwork, analysis of different kinematic shear indicators and the variations of sedimentary facies and thickness of strata. In this concern, the thesis dealt with the work in four chapters.

The dextral wrench-dominated transpression is responsible for the formation of the strike-slip faults, folds, and thrusts that deform the Cretaceous - Eocene sedimentary sequences.

The principle structural elements of the wrench pattern in the central part of Al Jabal Al Akhdar are E-W- to NE-SW-trending en echelon folds, the main ENE-directed wrench faults, conjugate ENE-WSW and NNE-SSW strike slip duplexes, and NW-SE oriented normal faults.

The model we present supports wrench-dominated transpression and development of dextral ENE-WSW and sinistral N-S conjugate strike-slip duplexes in the central part of Al Jabal Al Akhdar. The maximum principal stress axis was approximately horizontal and NNW trending, whereas the minimum principal stress axis was horizontal and ENE trending.

During Late Cretaceous, these normal fault trends are inverted into right lateral strike-slip major shears similar to those in the Alpine Mountains, Atlas Mountains, and Northern Egypt In the context of this concept and aforementioned discussion, the deformation in the present area is evolved through three tectonic stages as follows:

1. Campanian-Maastrichtian Compressive Episode

In Campanian-Maastrichtian time, the Al Majahir Formation accumulated to the south of the Santonian barrier and overlying unconformable by Darnah Formation. The late Campanian early Maastrichtian compressive event rejuvenated dextral movement along E-W- to ENE-WSW-striking faults that produced ENE-WSW-trending folds and NW-ES, and N-S shear fractures. Investigating this contact showed that the Palaeocene is generally missing except a thin marly limestone beds between Al Majahir and Darnah Formations. This explanation with the continuity of uplifting during most of the Palaeocene induced paucity and missing of the Palaeocene strata in the whole area, which were totally attributed to the subaerial erosion.

2. Eocene Tectonic Stage

In the present area, the lower part of Eocene section (Apollonia Formation) is absent and deformation during this stage was dominated with brittle structures in the upper part (Lutetian-Priabonian) of Darnah Formation. During this episode, shortening and inversion tectonics developed again and documented minor thrusts structures in the Lutetian section as well as the reactivation on the E–W to NW-SE, and N–S to NNE-SSW strike-slip faults in the whole Eocene section. The sequence of structures within the Eocene section indicates that the cycle of sedimentation started with the inundation during Ypresian to the Lutetian then followed by a tectonic event by the end of Lutetian.

3. Oligocene Tectonic Stage

During the Oligocene tectonic stage, the faults were still active but with slight effect and dominated with normal faults and accompanied tensional joints. In the northwestern part south of Sulontah, array of NNW-SSE synthetic normal faults is plotted and showing northeastern and southwestern downthrows.

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Appendix

Data Analysis of Faults | Data Analysis of Folds

Dip Direction	Dip	Dip Direction	Dip
360	75	345	25
360	85	350	20
360	70	10	25
360	80	5	20
350	65	10	25
350	75	5	20
345	80	355	20
340	70	355	20
340	85	360	20
345	65	10	20
345	80	355	15
340	85	20	15
340	70	25	25
345	85	15	20
350	70	330	15
350	85	315	25
360	70	345	15
360	65	350	10
360	70	15	10
360	75	325	20
360	70	345	15
360	65	30	20
355	75	355	21
350	80	345	21
340	85	5	10
340	85	10	5
340	80	5	15
340	70	10	10
360	75	350	10
360	80	15	5
355	75	355	7
355	80	350	8
350	75	5	5
340	70	350	12
345	65	15	5
345	85	350	8
340	65	10	15
340	85	350	12
345	80	20	10
325	75	345	10
340	70	5	4
300	80	5	12

360	85	360	12
350	80	360	12
345	65	345	7
340	75	5	5
325	85	340	10
345	80	10	10
340	75	30	25
345	80	30	20
355	75	35	20
350	80	35	15
325	85	40	20
325	80	40	25
325	65	275	20
360	70	270	15
20	75	280	25
10	85	285	10
15	70	285	5
25	80	285	5
25	65	280	5
30	75	290	10
30	80	290	25
35	70	295	15
15	85	295	10
30	65	290	15
20	80	300	10
5	85	300	12
5	70	310	15
5	85	300	15
10	70	300	15
10	85	310	5
10	70	310	5
10	65	315	10
10	70	315	15
15	75	290	12
15	70	285	15
15	65	290	10
15	75	290	15
15	80	290	10
20	85	300	10
20	85	300	15
20	80	310	14
20	70	30	10
20	75	45	10
20	80	45	5
20	75	45	15
25	80	40	12
25	75	50	12
25	70	345	25
25	65	350	20
25	85	10	25

30	65	5	20
30	85	10	25
30	80	5	20
30	75	355	20
35	70	355	20
35	80	360	20
35	85	10	20
35	80	355	15
35	65	20	15
30	75	25	25
20	85	15	20
15	80	330	15
10	75	315	25
5	80	345	15
15	75	350	10
25	80	15	10
20	85	325	20
15	80	345	15
30	65	30	20
202	70	355	21
160	75	345	21
160	85	5	10
165	70	10	5
165	80	5	15
165	65	10	10
165	75	350	10
160	80	15	5
165	70	355	7
170	85	350	8
170	65	5	5
170	80	350	12
175	85	15	5
180	70	350	8
180	85	10	15
180	70	350	12
180	85	20	10
180	70	345	10
180	65	5	4
180	70	5	12
180	75	360	12
180	70	360	12
180	65	345	7
180	75	5	5
175	80	340	10
175	85	10	10
175	85	30	25
175	80	30	20
175	70	35	20
175	75	35	15
170	80	40	20

170	75	40	25
180	80	275	20
180	75	270	15
180	70	280	25
180	65	285	10
160	85	285	5
165	65	285	5
155	85	280	5
155	80	290	10
165	75	290	25
165	70	295	15
165	80	295	10
160	85	290	15
150	80	300	10
150	65	300	12
150	75	310	15
150	85	300	15
155	80	300	15
170	75	310	5
180	80	310	5
185	75	315	10
180	80	315	15
180	85	290	12
180	85	285	15
180	80	290	10
185	65	290	15
185	70	290	10
185	75	300	10
185	85	300	15
185	70	310	14
185	80	30	10
185	65	45	10
185	75	45	5
190	80	45	15
190	70	40	12
195	85	50	12
195	65	345	25
195	80	350	20
200	85	10	25
200	70	5	20
205	85	10	25
205	70	5	20
205	85	355	20
210	70	355	20
210	65	360	20
215	70	10	20
215	75	355	15
215	70	20	15
220	65	25	25
220	75	15	20

210	80	330	15
205	85	315	25
210	85	345	15
210	80	350	10
210	70	15	10
210	75	325	20
215	80	345	15
215	75	30	20
210	80	355	21
220	75	345	21
225	70	5	10
210	65	10	5
210	85	5	15
205	65	10	10
205	85	350	10
205	80	15	5
210	75	355	7
200	70	350	8
195	80	5	5
190	85	350	12
185	80	15	5
190	65	350	8
190	75	10	15
190	85	350	12
190	80	20	10
195	75	345	10
195	80	5	4
195	75	5	12
200	80	360	12
205	85	360	12
120	65	345	7
130	80	5	5
115	85	240	20
100	75	245	15
95	80	250	10
110	80	260	10
115	75	270	15
120	70	230	10
125	80	220	20
100	85	240	10
95	75	200	25
140	65	190	25
250	80	180	20
255	85	210	20
255	70	180	10
240	75	170	15
235	70	175	10
230	65	155	20
270	80	150	15
260	85	180	20

240	75	150	20
235	75	160	15
95	75	180	15
100	80	260	10
115	65	250	15
125	65	260	20
130	70	190	20
105	75	220	15
100	65	230	20
110	80	180	15
120	75	270	25
125	65	260	10
140	75	180	15
150	80	250	20
155	70	200	15
160	75	270	10
165	80	260	25
260	75	255	20
260	70	200	15
240	80	270	10
220	65	190	25
230	85	190	25
225	80	170	25
240	85	160	25
230	75	185	20
235	80	260	20
225	70	255	10
255	85	270	15
240	65	280	10
230	70	240	15
250	75	180	10
250	80	180	12
270	80	185	5
230	85	190	5
245	80	265	5
275	65	240	20
270	65	245	15
278	70	250	10
274	75	260	10
275	80	270	15
270	85	230	10
277	80	220	20
276	75	240	10
275	80	200	25
270	85	190	25
274	85	180	20
275	80	210	20
270	75	180	10
275	70	170	15
276	65	175	10

270	70	155	20
270	75	150	15
280	80	180	20
274	70	150	20
274	65	160	15
278	85	180	15
275	80	260	10
274	85	250	15
278	85	260	20
275	80	190	20
274	85	220	15
278	70	230	20
285	60	180	15
285	65	270	25
285	80	260	10
285	70	180	15
285	75	250	20
288	70	200	15
290	75	270	10
288	80	260	25
286	75	255	20
285	70	200	15
290	75	270	10
270	70	190	25
290	80	190	25

الملخص

الجبل الأخضر يمثل حوض معكوس في الجزء الشمالي الشرقي من ليبيا وهو عبارة عن حزام ترسيبي لفترة الكريتاسي المتأخر إلى الحقب الثلاثي على طول ساحل البحر المتوسط. منطقة الدراسة تقع في الجزء الأوسط من هذا الحزام (جردس الجراري) والذي تمثل منطقة ذات نمط تركيبي شديد الحدة ويعتبر احد أشكال تراكيب نهاية الكريتاسي المتأخر والمحاط بصخور الحقب الثلاثي. ولقد تركزت الدراسة على تحليل مفصل للتراكيب الجيولوجية المتواجدة بناءاً على دراسات حقلية معمقة وتحليل دلالات أنماط حركة القص المختلفة إلى جانب أنواع و سمك الطبقات الترسيبية المتواجدة في المنطقة.

رواسب حقب الكريتاسي الأعلى إلى الأوليكوسين تغطي كل المنطقة, وتمثلت بتكوينات من الأقدم إلى الأحدث بالتالي: تكوين المجاهير ووادي الدخان والعويلية ودرنة والبيضاء ويمثل السطح الفاصل بينها وبين الحقب الرباعي سطح عدم التوافق.

أثناء العصر الجوراسي إلي بداية العصر الكريتاسي, الجبل الأخضر كان جزء من الحافة القارية المستقرة, وكان عباره عن حوض رسوبي كبير في شمال ليبيا. عند نهاية العصر الكريتاسي (خصوصا عند السانتونيان), أظهر النمط التركيبي للمنطقة انعكاس للحركة بواسطة تكتونية اللي نتيجة لحركة ضغط أفقية بسيطة, والناتج كان ارتفاع رواسب نهاية الكريتاسي ضمن تكوينات درنة والبيضة (من العصر الإيوسيني إلي بداية الأوليكوسين) شكل ما يعرف بتركيب جردس الجراري. انعكاس نهاية الكريتاسي بدأ بتشوه قصي هش علي طول شرق غرب إلي غرب شمال غرب– شرق جنوب شرق قص يميني كبير وأنتهي بتشوه قصي لدن, وتمثلت هذه التراكيب بثلات مراحل من

الطيات إلـى جانب صـدوع ذو انـزلاق مضـربي وعاديـة ومعكوسـة. ويعتبر طـي جردس الجـراري الكبيـر المرحلة الأخيرة من الطي النهائي (ف3) والذي بدأ بحركة تكتونية شديدة أثناء فترة الكريتاسـي المتأخر تلتها حركات تكتونية أضعف نسبيا خلال فترات الباليوسين والايوسين وأخيرالاليكوسين.

الخصائص التركيبية وتحاليلها في منطقة جردس الجراري الجزء الأوسط من الجبل الأخضر, شمال شرق ليبيا.

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