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Structural Setting of the Jordan Northern Highlands

An Integrated Study using Surface and Sub-Surface Geological Data by Utilizing GIS Technology

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Professor Anton le Roex **Professor Zvi Ben-Avraham**

CAPE TOWN, REPUBLIC OF SOUTH AFRICA

DIDICATION

TO MY BELOVED FAMILY

MAHA

2011

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ABSTRACT

The Jordan Northern Highland (JNH) area represents one of the key geological provinces for the study of the influence of Arabian Plate motion and thus, compression and extensional tectonics along the Dead Sea Transform (DST) in Jordan. Therefore it has, for many decades, been the target of attention by many researchers and investigators as well as oil companies for its distinctive geological setting. However, integration and analysis using modern technology such as Geographic Information Systems (GIS) to identify the structural setting has not yet been applied.

This study was designed, for the identification of the General structural style of this part of Jordan by: (1) Definition of dominant structural styles in the JNH: such as the main structural elements, basins, and highs; (2) Inference of the structural setup and its tectonic significance, and (3) Identification of the influence of the Dead Sea Transform on the geological setting of the JNH area

The study involved interpretation and analysis of surface and subsurface geological data; Fifteen (15) 2D reflection seismic profiles, gravity anomaly maps, surface geological information, borehole data, topographic maps, and previous studies were used. Integration of the results was a key factor in accomplishing the study.

Integration revealed a complex structural style of major fault zones and fold belt systems. These faulting systems are of normal type; striking NW-SE, NE-SW, and intersected by E-W and N-S fault trends. General throw of the NW-SE faults orients eastward, while for those of NE-SW trend, it is southeastwards in the southeastern parts and northward in the northern parts of the area. E-W segments present northward throw. Several low and high magnitude structural elements were identified accompanying the major faulting systems with a major NNE and N strike. Basement across the western parts of the area are shallower than those across the north, northeastern, east, and southeastern parts

The seismicity information of the study area deduced that the majority of events located in the study area were of magnitudes between 1ML to 3.9ML.

The study includes four chapters. Chapter one is an introduction to the study area and the methodology. Chapter two displays the interpretation of all used data sets and their results.

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The interpretation involved rendering of the pre-existing surface geological maps to produce a geological base map for the area under consideration to clarify its surface geologic setting in terms of major stratigraphic sequences and dominant surface structural elements. A qualitative and quantitative interpretation of a corrected Bouguer anomaly map facilitated delineation of the dominant subsurface structural style across the area as well as identification of the depth to the basement. Borehole data provided much insight into the subsurface stratigraphic distribution as well as the subsurface structural style through stratigraphic and structural correlation between the key boreholes. Chapter three puts forward the outcome of the integration between analyses of all surface and subsurface geological information that were used to give much insight into the General surface and subsurface geological setting of the JNH area. Geographic Information System Technology was applied to conduct the analysis. Chapter four discusses the results in relation to previous studies in order to identify the relationship of the structural setting of the study area from regional perspective.

The study area is surrounded by significant tectonic elements; Rutba Uplift from the east, Palmyrides and Golan Heights from the northwest, Jordan Uplift from the west, which comprises along the eastern margins of the DST. DST is believed of a direct control on the structural setting of the study area. The tectonic origin of the JNH area is relative to the above-mentioned tectonic elements.

The study revealed much insight into what is considered the complex structural style of the JNH area. It is formed of complex structural zones of faulting and folding with major NW-SE, NE-SW, NNE-SSW, N-S, and E-W striking. The combination of faulting and folding has led to the formation of series of horsts, grabens, uplift, and domal structural elements.

Ramtha Sirhan Fault System is the dominant structural element in the area as well as Zarqa Fault System, Fuluq Fault System, Amman-Hallabat Structure, Wadi Shueib Structure, Ajlun Dome, the major NE-SW trends, Sirhan Basin, Irbid Ramtha Basin, and the DST.

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1. INTRODUCTION

1.1. THE STUDY AREA

The Jordan Northern Highlands (JNH) study area lies in northern Jordan abutting the Syrian border between 35˚45-36˚45 E and 32˚00-32˚45 N. It covers an area of around 5645 Km². The Jordan Valley bounds it from the west and the towns of As Safawi and Al Azraq from the east. The Yarmouk River and Syria bound it from the north while its northwestern corner abuts the Golan Heights. The Zarqa River borders the southern sections 30Km north of the city of Amman (Figure 1-1).

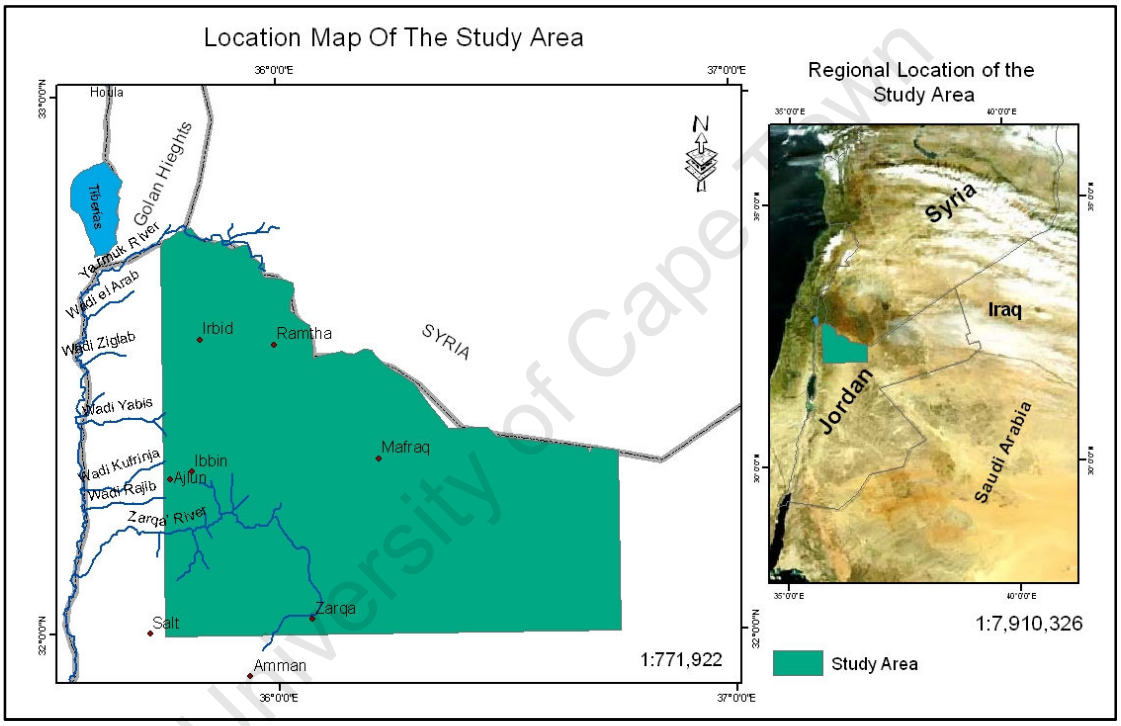

Figure 1-1 Location map of the study area

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4.2.1. GENERAL TOPOGRAPHY AND GEOMORPHOLOGY

The surface topography is characterized by hilly rugged mountains, which descend in altitude toward the north and northwest. The topography slopes steeply toward the Jordan Valley in the west and north-northwest, and gently slopes to the east and southeast. Variations in elevation reach the maximum in the central and western parts while they

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gently vary in the east and south-southeastern sides. Maximum elevation is about 1240m within the vicinity of Ajlun area. On the other hand, elevation falls into-60m below sea level (bsl) in the northwest. Figure 1-2 illustrates a Digital Elevation Model (DEM) of the JNH area as developed from the 1:50,000 topographic maps. To the north, toward the Syrian border, basalt sheets outcrop on the surface and become more extensive toward the north-northeast, forming a belt shape close to the Syrian territories toward Jabal Druze.

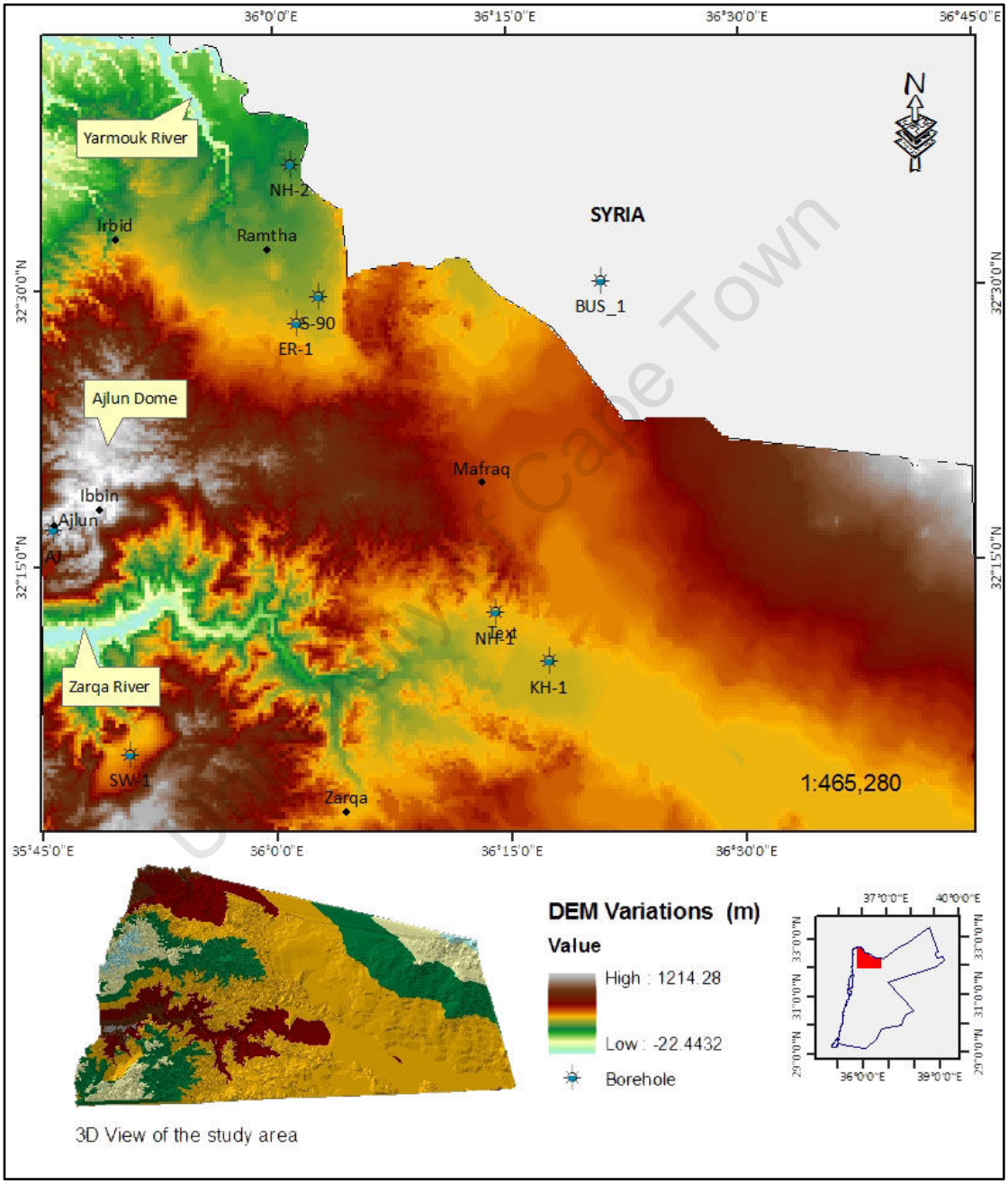

Figure 1-2 Digital Elevation Model (DEM) of the JNH area, showing its reief variations

1.1.2. PREVIOUS GEOLOGICAL STUDIES

1.1.2.1. GEOLOGICAL PREVIOUS STUDIES

The geology of Jordan has been studied since mid of the 19th century, and bibliographies of early geological work can be found in Lartet (1869), Blankenhorn (1914); Inoides and Blake (1939), Picard (1943), Quenelle (1951). Extensive description of the geology of Jordan are found in Burdon (1959), Bender (1968a &b, 1974, 1975), Abed (1982), Powell (1989 a and b), and in the Natural Resources Authority (NRA) published bulletins

Blake and Ionides (1939) produced a geological map at 1: 1000 000 scale covering the entire of east Jordan. The work was followed by a geological survey by Quenelle from 1946-1956 which published a 1:500 000 geological in 1951; this work formed the basis of a compilation of three sheets at scale 1:250 000 for east of Jordan, described by Burdon's (1959) handbook on the geology of Jordan.

Quenelle and Sir Macdonald mapped the area at scale 1:250 000 in 1964 and 1965 respectively. Weisman and Abdullatif in 1964 mapped the Yarmouk River area at scale 1:10 000 within the scope of engineering project, yet it was not available to access for this study.

The German Geological Mission (GGM) (1961-1966) produced 1: 1000 000 draft geological maps. Geological maps at scale 1: 1000 000 scale covering Jordan were compiled by Bender (1968a) and a few colored 1:100 000 geological maps were produced by Bender (1974).

The study area is covered by the 1: 250 000 geological map of Amman produced by the GGM in the sixties. This work is essentially a modification of a map at the same scale produced by Quenelle in the fifties.

The Natural Resources Authority (NRA) has published geological reports on some parts in the area attached with maps of 1:50 000 scale under the National Geological Mapping Project for the entire country. 10 sheets of scale 1: 50 000 cover the study area.

The Neogene and Quaternary basalts exposed in the northeast Jordan are part of the North Arabian Volcanic Province that covers an area of about 45000 km² of which 11000 km² are present in Jordan (Bender, 1974). The study area is covered by a distinctive Basaltic lava

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plateau that stretches over about 700 km in a NW-SE direction from Syria through Jordan to Saudi Arabia. The regional trend of the volcanic province is northwest-southeast, parallel to the Sirhan Fault Graben and the Red Sea axis (Guba and Mustafa, 1988).

The earliest studies in the North Arabian Volcanic Province were carried out by Lartet (1869) and Doss (1886) and the first geological map was published by Dybertret (1929). The first regional geological and petrological investigation of the basalt in north-east Jordan was carried out by the GGM (1965). Van Den Boon and Sawwan (1966) concluded that six different basalt flows could be recognized in this province.

Recent study by Ibrahim (1993) proposed that the history of Cenozoic basaltic volcanism in Jordan and adjacent areas could be explained in terms of the plate tectonic regime of the African and Arabian plates. He pointed out the close association of eruptive centers with regional faults and parallelism of volcanic fissures (dykes) to this regional fault trend.

Ibrahim (1993) subdivided the basaltic flows in north east Jordan into five volcanic-stratigraphic groups belonging to the newly defined Harrat Ash-Sham Basaltic Super Group. These five groups comprise the Wisad, Safawi, Asfar, Rimah, and And Bishriyya Groups Of Late Miocene to Holocene age.

Tarawneh *et al*., (2000) modified new classification based on K-Ar dating and subdivided the Harrat Ash-Sham Basaltic Super Group into three major volcanic phases; the first is of Oligocene age (26-22 Ma), the second is of late Miocene age (12-8 Ma) and the third phase is mostly of age break- Quaternary (6-<0.5 Ma)

1.1.2.2. GEOPHYSICAL PREVIOUS STUDIES

Detailed geophysical studies are rare and random in the JNH. Few magnetic and gravity traverses across the area were carried out. Knopoff and Belsha (1966) interpreted two gravity and magnetic profiles between Amman-Jerusalem and Nablus-Amman, and concluded that there is a thick sedimentary cover above the basement exists on either side of the rift, as well as there is a considerable thinning westward. Folkman (1981) interpreted the local negative gravity anomalies which occur within the transform zone by deep depressions which are separated by structural highs, while the local magnetic anomalies which occur in the northern part of the transform as basaltic flows. Kharabsheh, 1981

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indicated that magnetic anomalies within the Jordan valley have a dominant N-S direction, caused by local intrusions above the basement. Depth to the basement seems to be deepest in the Salt area with over 3km; it is about 2km in Ajlun area, and increases farther north.

Ginzburg *et al*., 1979, and Ginzburg *et al*., 1981 showed, as a result of deep sounding experiment along the western side of the Jordan Dead Sea Transform, that the thickness of the continental crust along the rift is about 35 km and thinning to some 20 km along the Gulf of Aqaba and westwards towards the Mediterranean associated with thickening of sedimentary cover. El Isa *et al*., 1987 carried out a crustal structural study of Jordan based on seismic refraction data, and concluded that the depth to the crystalline basement is at 2-2.5 km north of Amman city and not less than 5 km in central Jordan.

A geophysical study was carried out in the northwest Jordan during the year 1992 by the Geophysical Division at the Natural Resources Authority (NRA) to support the petroleum exploration activities in this region. Awni *et al*., 1992 conducted a qualitative and quantitative interpretation of the existed aeromagnetic and gravity data during this geophysical study. The aeromagnetic survey carried out by Geoterrex Ltd. in 1979 under contract to Phoenix Corporation. The gravity data was commenced in 1990 by the geophysical team of the NRA. The study concluded that the depth to basement increased towards the northwest and north-northeast (≈5.8 km north of Ajlun), and decreases to ≈4.16 km east of Aj-1 well, farther to the southwest it reaches to about 3km.

GSI recorded 296 km of dinosis data from 1975-1976 but most of the data were considered unreliable because it was very poor. However more data were acquired by INOC in 1983 and were processed by the GSI with some of the data reprocessed by CGG.

Various oil companies studied the JNH for the investigation of its hydrocarbon potential. Filon Exploration Corporation (1975) and Beicip (1975 and 1981) carried out a detailed structural study in order to identify the potential structures. Beicip produced a comprehensive structural maps at scale 1:250 000 that cover the whole country. In 1986, Elf Aquitaine evaluated the structural setting of the area, hence it was not recommended for further pursue. On the other hand, Trollinger (1986) carried out a comprehensive geomorphologic and structural study by which produced 5 geomorphic-structural maps of 1: 250 000 cover Jordan. In addition, Trollinger's concluded that JNH region is structurally adequate and suitable for hydrocarbon accumulation. The study also indicated that the

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eastern parts of the area have better chance to develop a source rock potentiality due to the additional thickness of the Mesozoic section. This agreed with the results of Marathon Oil Company (1988) study. Unlike Petrofina in 1987 which evaluated the area as an area of difficult tectonic style and the structures are of medium size with small closures. As a result of these conclusions, a joint committee of Petrocanada and OMV in 1988 reviewed the existed seismic data and concluded that there is no attractive prospect was mapped in the area. The only sustainable high is Ajlun Dome. Amoco Oil Company in 1988 emphasized that the mapped structures are small and limited in number.

1.1.3. REGIONAL GEOLOGICAL SETTING AND HISTORY OF JORDAN

Jordan comprises the northwestern part of the present Arabian Plate along the eastern flank of the Dead Sea Transform, which separates the African Plate to the west from the Arabian Plate to the east (Figure 1-3)

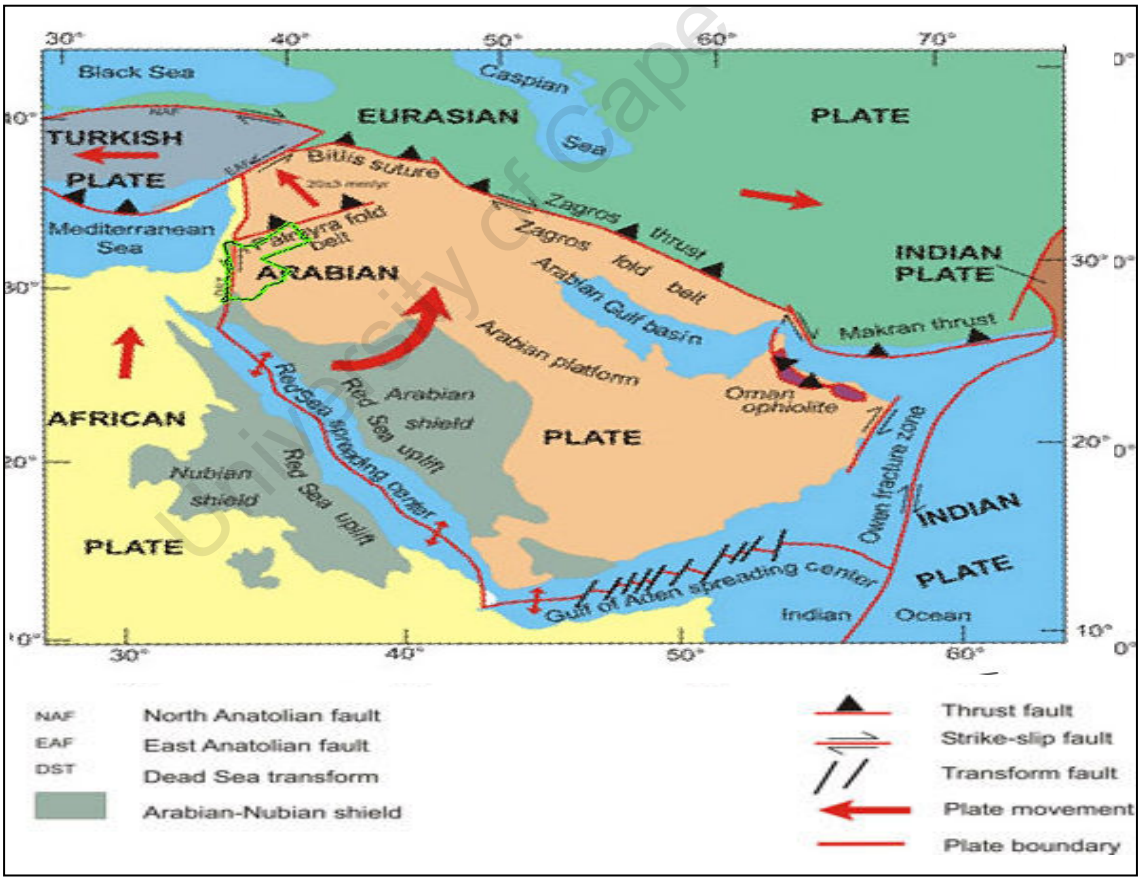

Figure 1-3 Regional geological location map of Jordan, after the Saudi Arabia Geological Survey

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The rock record in Jordan is characterized by stable shelf environments throughout geologic time with several periods of transgression and regression influenced by regional tectonics, eustacy, epeirogenic movements and taphrogenic activity that have subjected the Arabian Plate since the late Proterozoic time (Bender, 1975).

The Arabian Plate tectonic history can be subdivided into six tectonic phases that shaped its geology. These include:

1) Pre-Cambrian
2) Ordovician-Silurian Glaciation / de-Glaciation
3) Carboniferous (Hercynian Orogeny)
4) Early Triassic (Zagros Rifting)
5) Late Cretaceous (First or Early Alpine Orogeny)
6) Tertiary (Second or Late Alpine Orogeny)
7) Neogene Separation from Africa.

javascript:;The geological map of the Arabian Plate illustrates that divergent margins are forming in the spreading centers of Red Sea and Gulf of Aden to the west and southwest of the Arabian Plate. The South and southeast of the Arabian plate is bounded by the Owen-Sheba intra-oceanic transform fault. An active convergent margin lies to the north and northeast with Turkey (Bitlis sutures) and east within Iran (Zagros Mountains) where the Arabian plate is thrusting beneath the Eurasian plate. The Dead Sea represents a transform strike-slip fault zone to the northwest of the Arabian Plate (Figure 1-4)

Following is a brief description of the major tectonic events that formed the General geological history of Jordan through the Phanerozoic Eon. Global paleogeographic evolution impact on the evolution of the Arabian in General and Jordan in particular has been set forth through the incorporated paleogeographic maps (Stampfli *et al.*, 2008; Stampfli *et al.*,2002; Stampfli *et al.*,2002b; von Raumeri *et al.*,2002):

1.1.3.1. PRE-CAMBRIAN ERA

The oldest portions of the Arabian plate formed in the middle to late Proterozoic (800-650 Ma) when a series of island arcs and micro-continental fragments accreted against the northeastern margin of the Pan African craton to form the Gondwana super-continent. The

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primary crust of the Arabian shield is composed of a combination of several constructional units, each of which was formed by an intra-oceanic island arc terrain consisting of an andesitic assemblage of meta-volcanic rocks and a dioritic suite of plutonic rocks. Each closure and arc collision led to deformation and ophiolite obduction (north-south units) and was culminated with microplate and continental collision at about 640 Ma. The last Precambrian orogenic event was concluded with the development of Hormuz salt basin in eastern Arabia and is characterized by horsts and tilted fault blocks trending NNE-SSW (Beydoun, 1977).

Pre-Cambrian rocks form the basement in most of the Levant and Arabian Peninsula. The rocks represent episodes of plate collision and magmatism. During the pre-Cambrian, Arabia was part of the supercontinent of Gondwana. During the upper Pre-Cambrian, the plate was consolidated with the northeastern flank of the African Plate by a complex process of terrane accretion and plate collisions. Differential movements and compressions of the Arabian and Nubian shields relative to other North African shields outlined the initial lower Paleozoic structural framework of Arabia. Most probably the Najd and Zagros Fault Systems were developed around 640 Ma as shear zones in response to a highly compressive east-west trending stress associated with the continental collision. From approximately 620 Ma to 540 Ma, Arabia underwent drastic change from collision to extensional tectonics. This is reflected by the prominence of post-tectonic extensional alkali-rich granites and volcanic, as well as the development of extensional basins or rift grabens with intervening horst or highs (Grabowski and Norton, 1995, and Sharland *et al*., 2001). Figure 1-4 illustrates the ancient Paleogeography of Arabia during the Late Precambrian period

Pre-Cambrian igneous metamorphic rocks cover an area of approximately 1800 sq. km in south Jordan. These rocks are exposed from the area south of Aqaba for approximately 70 km towards north along the east side of Wadi Araba, dipping east of Wadi Rum underneath thick Paleozoic sandstones series. These rocks are intruded by numerous acidic, intermediate and basic dike rocks.

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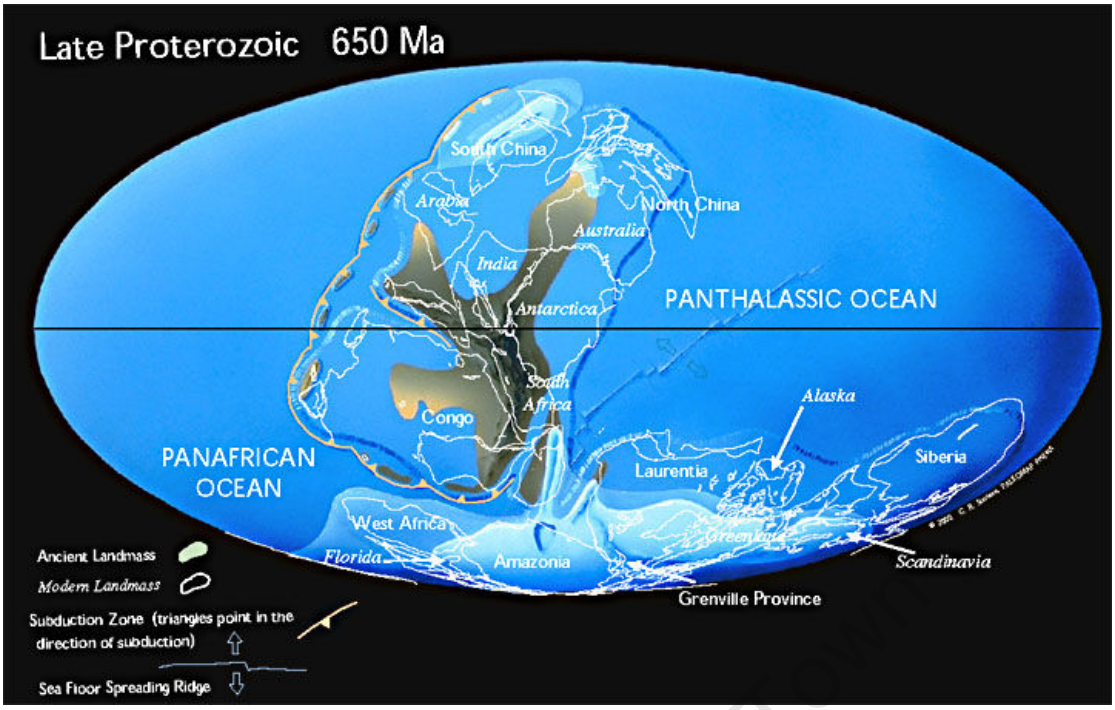

Figure 1-4 Paleogeography during Late Precambrian (650Ma), modified after Stampfli *et al.*, 2008

1.1.3.2. PALEOZOIC ERA

CAMBRIAN PERIOD:

Pannotia, the supercontinent that formed at the end of the Precambrian Era, approximately 600 Ma, had already begun to break apart by the beginning of the Paleozoic Era. A new ocean, the Lapetus Ocean, widened between the ancient continents of Laurentia (North America), Baltica (Northern Europe), and Siberia. Gondwana, the supercontinent that was assembled during the Pan-African orogeny, was the largest continent at this time, stretching from the Equator to the South Pole

Early Cambrian uplift led to widespread erosion and the subsequent Cambrian-Devonian sequences were mostly deposited on a peneplaned platform (Konert *et al.*, 2001). The stratigraphic record on the northeastern shelf of the Arabian plate indicates gentle subsidence in the Late Cambrian and Early Ordovician, followed by increased subsidence in the mid Ordovician (Sharland *et al.*, 2001) that led to transgressions in this area. Figure 1-5 illustrates the Global Paleogeography during the Late Cambrian (514 Ma)

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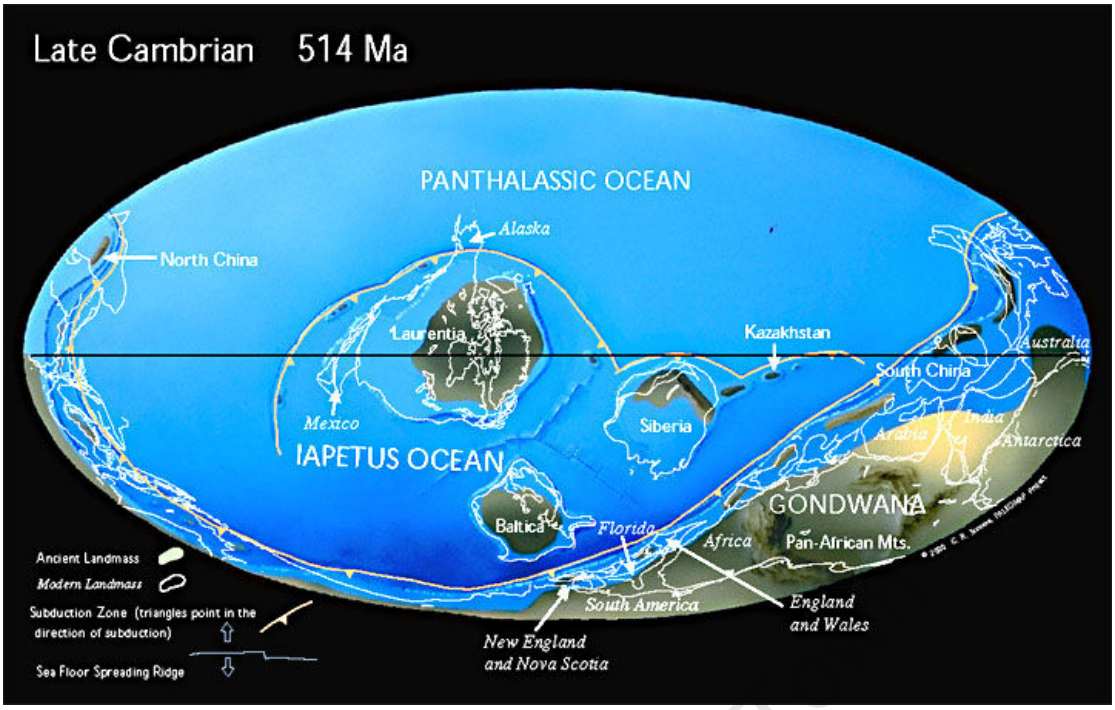

Figure 1-5 Paleogeography during the Late Cambrian (514 Ma), modified after Stampfli *et al*., 2008

In Jordan, An early transgression and regression of the Tethys ocean advanced to the eastern side of central Wadi Araba, and appears to have terminated along a shoreline running north-northeast during the Cambrian; this was indicated by continental sandstones above the Tethyan marine sedimentary rocks.

ORDOVICIAN PERIOD

javascript:;The Late Ordovician was characterized by the expanding of the polar glaciers across Gondwana and most of western parts of Arabia (Husseini, 1991). During Late Ordovician times (while the Arabian Plate occupied relatively high southern latitudinal location), a glacial episode occurred which affected the western part of the Arabian Plate, leaving behind evidence of glaciation on the Arabian Shield and broad and deeply cut sub-glacial valleys. (Haq *et al*., 2005). Figure 1-6 illustrates the ancient Paleogeography during the Middle Ordovician period

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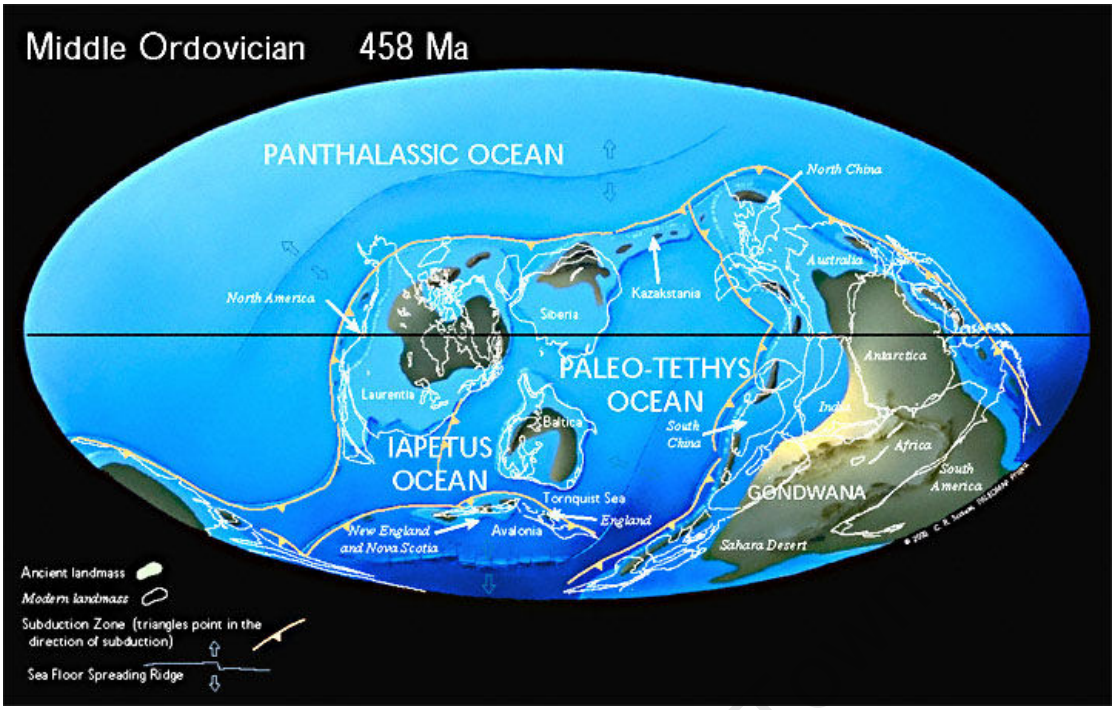

Figure 1-6 Paleogeography during the Late Cambrian (514 Ma), modified after Stampfli *et al.*, 2008

During the Ordovician there was another transgression in southeast Jordan and northwest Saudi Arabia indicated by sequences of shales and shallow marine facies, often graptolite-bearing sediments. A major event of regression and glacial deposition affecting the African and Arabian plates occurred during the Late Ordovician (Bender, 1975)

SILURIAN PERIOD:

By middle Paleozoic, approximately 400 Ma, Laurentia collides with Baltica closing the northern branch of the Lapetus Ocean and forming the "Old Red Sandstone" continent. Coral reefs expand and land plants begin to colonize the barren continents. It is also likely that by middle Paleozoic times, North and South China had drifted away from the Indo-Australian margin of Gondwana, and were headed northwards across the Paleo-Tethys Ocean (Figure 1-7) (Stampfli *et al.*, 2008).

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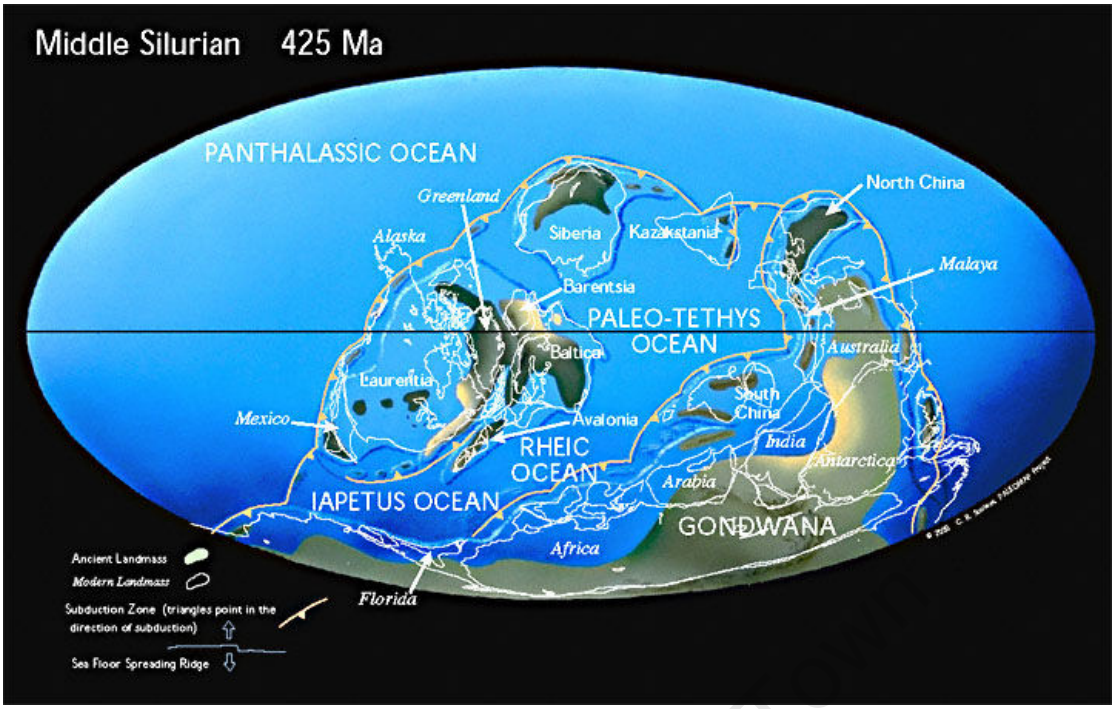

Figure 1-7 Paleogeography evolution during Silurian period (425 Ma); continents begin to collide as Paleozoic oceans close, modified after Stampfli *et al*., 2008

Early Silurian is characterized by regression and transgression, which caused a rise in the sea level in response to deglaciation (Mahmoud *et al*., 1992), which in turn resulted in a regional deposition of rich organic sediments across much of the African and Arabian plates (Masri, 1988). Silurian sediments comprised southeast Jordan and they appear to have been deposited in the same environment conditions during the Ordovician.

DEVONIAN PERIOD

The Plate continued to reside in relatively high latitudes until the Early Devonian and persisted as a promontory of Gondwana with passive margins. Thereafter, it started to drift northwards into lower latitudes, reaching tropical environments by Permian times (Konert *et al*., 2001). In Oman the Late Silurian saw an uplift, which may have been a precursor related to the eventual breakup of Gondwana. This led to a broad regression and stratigraphic gaps on the Platform (Sharland *et al*., 2001). The next major deformational event that widely influenced the Arabian Plate was the so-called Hercynian Orogeny. The Hercynian is a term commonly used for Late Devonian to Permian diastrophic movements in Europe and North America. The timing of this orogeny on the Arabian Plate is more restricted (Late Devonian

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through Late Carboniferous), when the Plate suffered multiple phases of compression and block faulting. The northern edge of the Plate saw initiation of back-arc rifting and basaltic eruption. The compression, uplift of central Arabia and the clockwise rotation of the Plate produced widespread inversion and erosion, leading to the removal of several kilometers of sediment from the uplifted areas (Konert *et al.,* 2001). The Plate then tilted gently towards the northeast and fluvial to alluvial clastics dominated over much of the peneplaned Hercynian relief (Ziegler, 2001). Figure 1-8

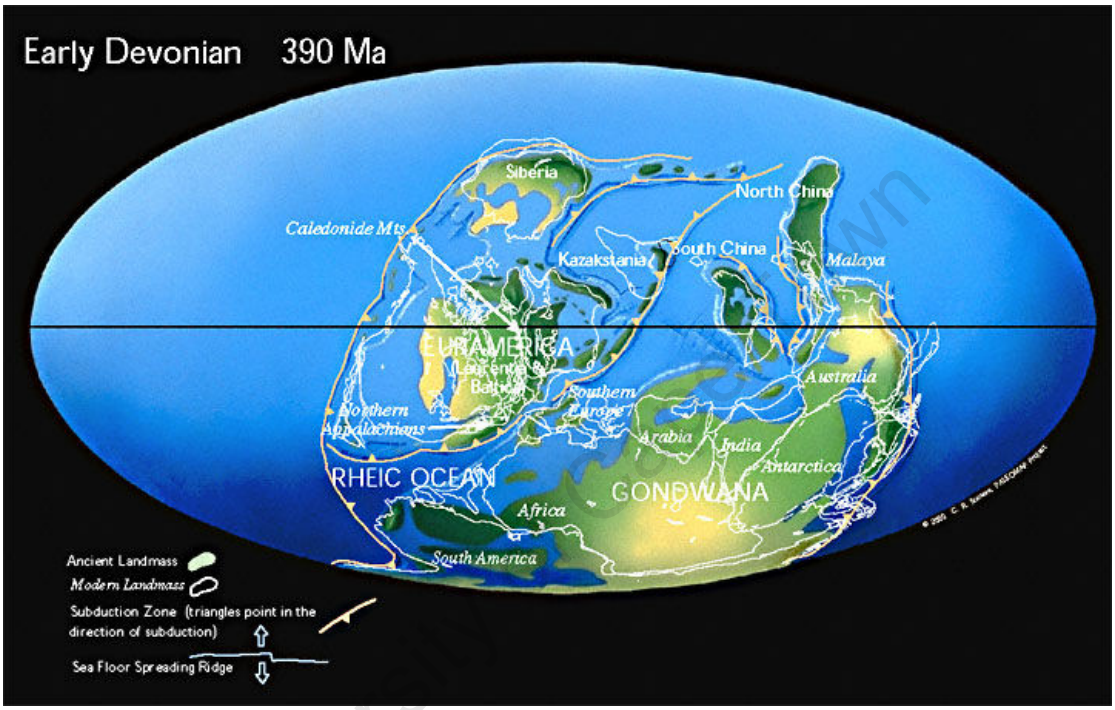

Figure 1-8 Paleogeography during Early Devonian period (390 Ma), modified after Stampfli *et al.*, 2008

CARBONIFEROUS PERIOD

During the Late Carboniferous and Permian the Arabian Plate moved from the relative high latitudes to lower latitudes, but not before another episode of glaciation near the Carboniferous-Permian boundary that affected the southernmost part of the Plate. The early Permian saw another phase of major crustal extension that weakened the crust enough to allow sediment load alone to drive subsidence and aid in the accumulation of thick carbonate sediments in subtropical latitudes (Haq *et al.*, 2005). (Figures 1-9 and 1-10)

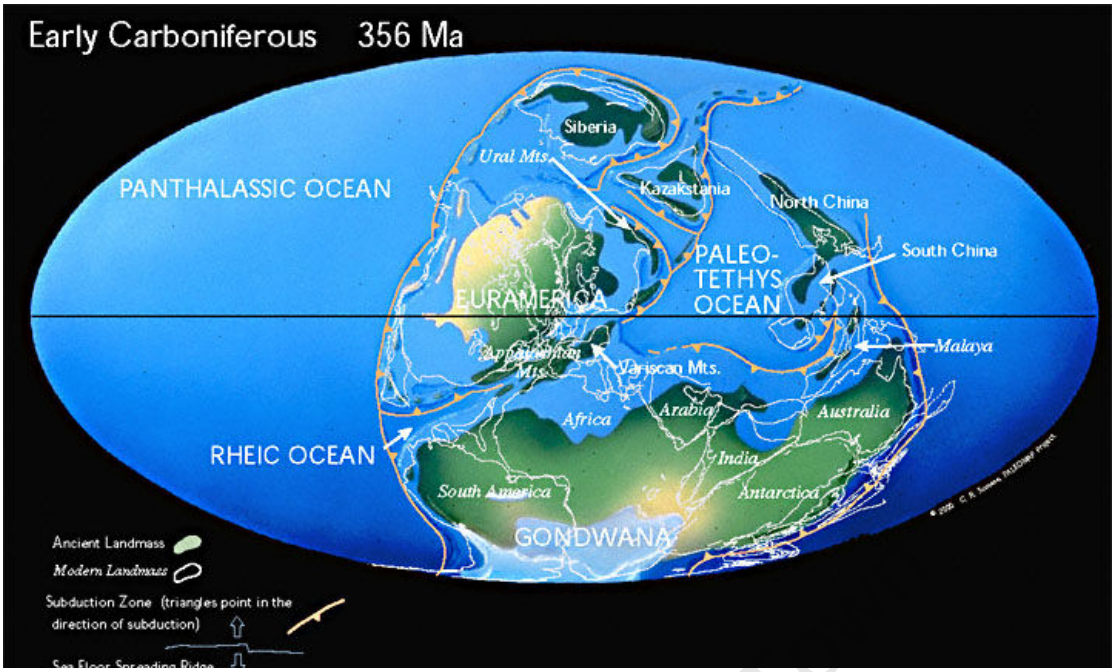

Figure 1-9 Paleogeography during Early Carboniferous (356 Ma); Pangaea began to form, modified after Stampfli *et al*., 2008

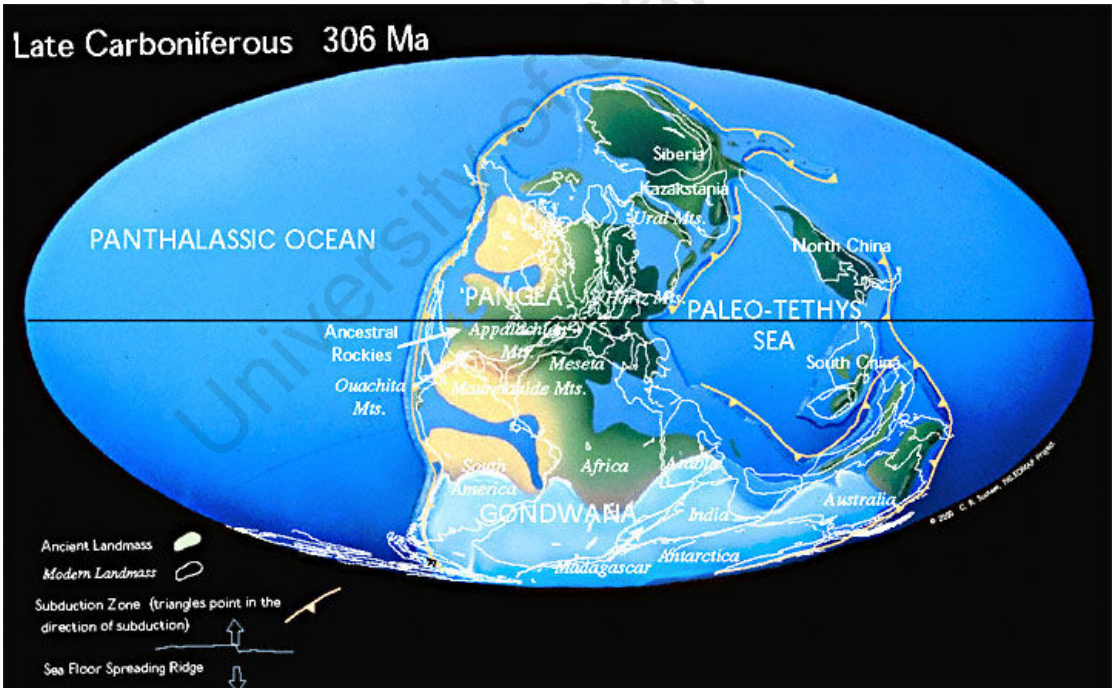

Figure 1-10 Paleogeography during Late Carboniferous period (306 Ma); a time of great coal swamps, modified after Stampfli *et al*., 2008

Vast deserts covered western Pangea during the Permian as reptiles spread across the face of the supercontinent. 99% of all life perished during the extinction event that marked the end of the Paleozoic Era (Figure 1-11) (Stampfli *et al*., 2008).

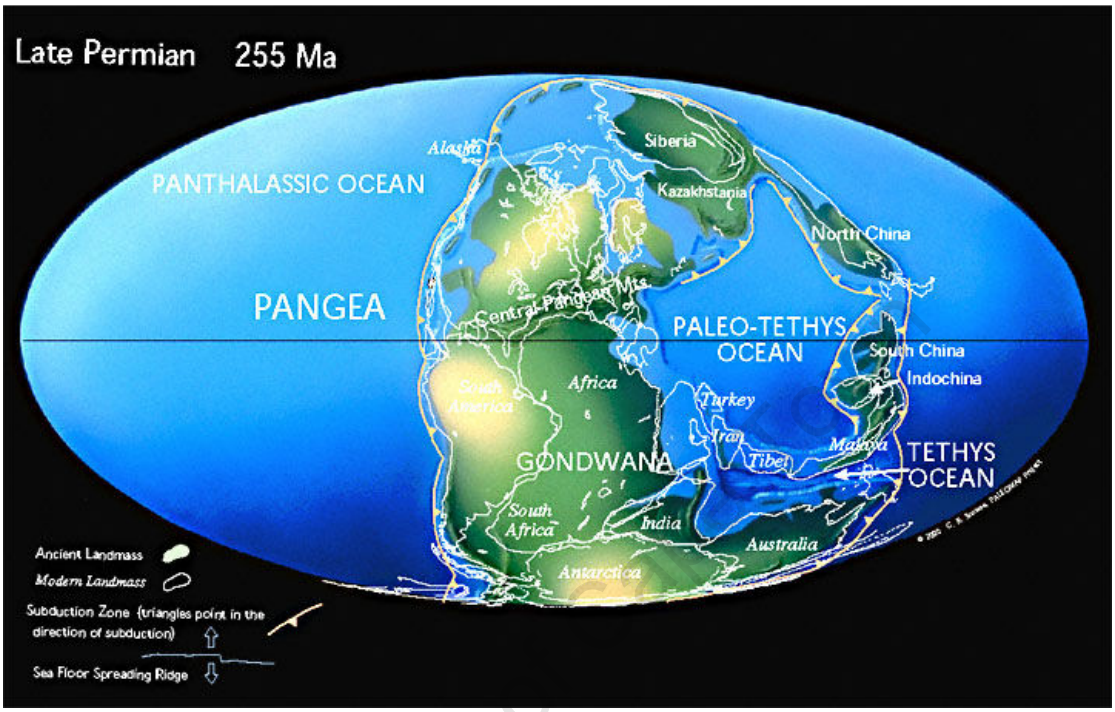

Figure 1-11 Paleogeography during Permian period (255 Ma), modified after Stampfli *et al*., 2008

In the Late Permian further rifting and block faulting along the northeastern front of the Plate, as well in Syria, Iraq and India initiated the splitting of this part of Gondwana. It may also have reactivated the Precambrian Najd Rift system creating north northeast-trending ridges separated by broad valleys (Wender *et al*., 1998; Sharland *et al*., 2001). Thus, the Late Permian not only saw the initiation of the continental breakup of this region, but also the creation of a passive margin along most of the northeast boundary of the Plate fronting the newly opened Neo-Tethys Ocean after the Iranian terranes had split and drifted away. This was also the beginning of the dominantly carbonate sedimentation on the Platform over a breakup unconformity. The subsidence at the northeastern passive margin was initially largely post-rift thermal, to be replaced by dominantly due to sediment loading (Bishop, 1995).

In Jordan, Makhlouf *et al.,* 1990 documented exposures of Permian siliclastics along the eastern parts of the Dead Sea to the south of Zarqa River.

1.1.3.3. MESOZOIC ERA

TRIASSIC PERIOD

The supercontinent of Pangea, mostly assembled by the Triassic, allowed land animals to migrate from the South Pole to the North Pole. Life began to re-diversity after the great Permo-Triassic extinction and warm-water faunas spread across Tethys (Stampfli *et al*., 2008). Figure 1-12

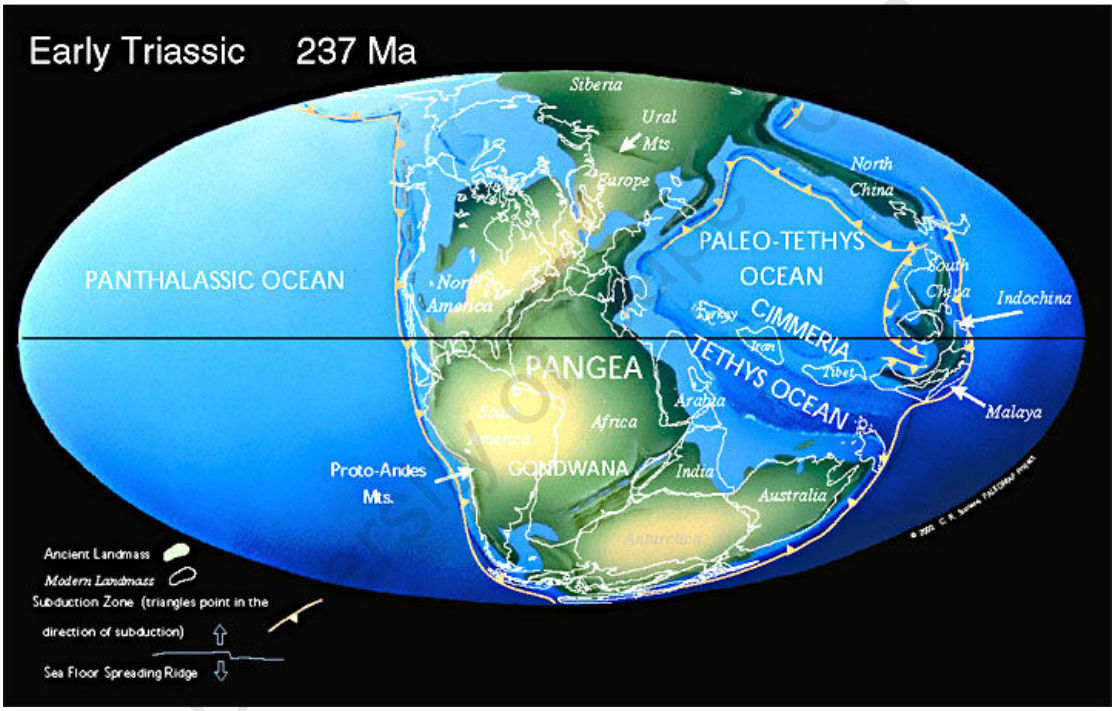

Figure 1-12 Paleogeography during Triassic period (237 Ma); a time Pangaea began to drift apart, modified after Stampfli *et al*., 2008

In lower Triassic hot arid conditions prevailed over the Arabian Peninsula and a clastic influx the western hinterland increased relative to the upper Permian times. Near the close of Triassic there was a marked change and climate became less arid. Tectonic uplift of the shield areas and local highs may have led to erosion prior deposition of younger strata (Haq *et al*., 2005). At the end of Triassic, Orogenic movements affected central and southern Arabia as well as the area of the Dead Sea Rift System and a significant unconformity is

indicated. The discordance is not clearly in Iraq and Syria where Jurassic follows the Triassic without a break in sedimentation (Haq *et al*., 2005)

During the Lower-Middle Triassic, transgression of the Tethys advanced from the west and northwest to Jordan east of the Dead Sea, where Triassic siliclastics and carbonates disconformably overlie Lower Paleozoic sediments.

JURASSIC PERIOD

By the Early Jurassic, south-central Asia had assembled. A wide Tethys ocean separated the northern continents from Gondwana. Though Pangea was intact, the first rumblings of continental break up could be heard (Figure 1-13) Stampfli *et al.,* 2008.

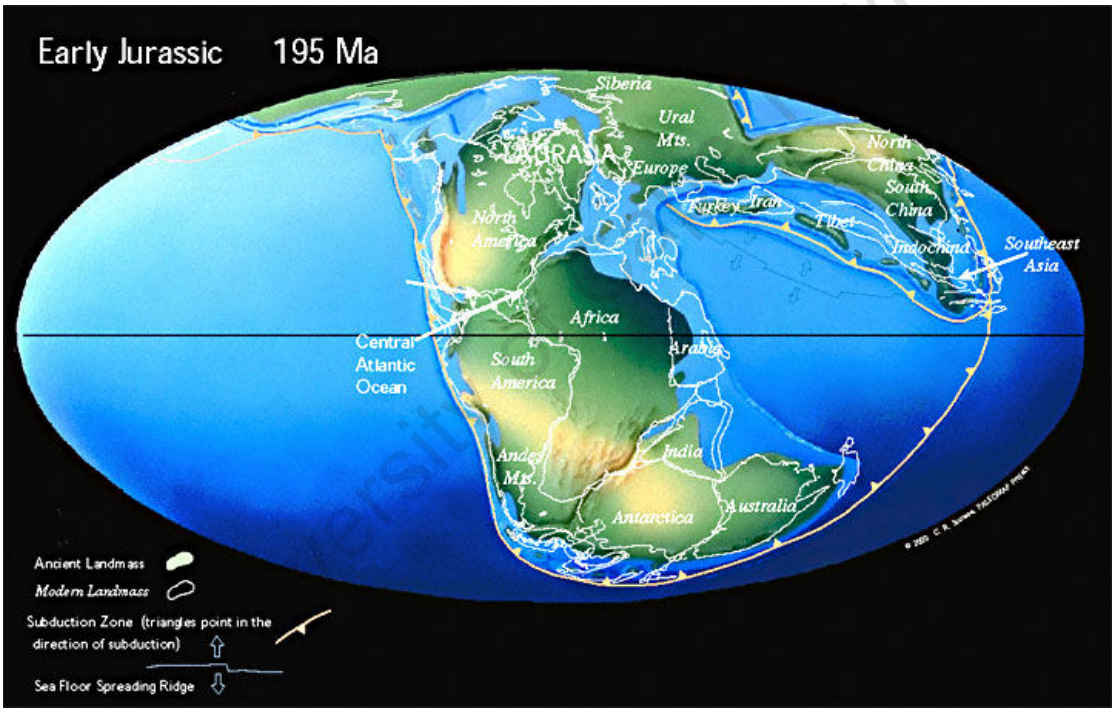

Figure 1-13 Paleogeography during Early Jurassic period (195 Ma), modified after Stampfli *et al*., 2008

The supercontinent of Pangea began to break apart in the Middle Jurassic. In the Late Jurassic the Central Atlantic Ocean was a narrow ocean separating Africa from eastern North America. Eastern Gondwana had begun to separate from Western Gondwana (Figure 1-14) Stampfli *et al*., 2008.

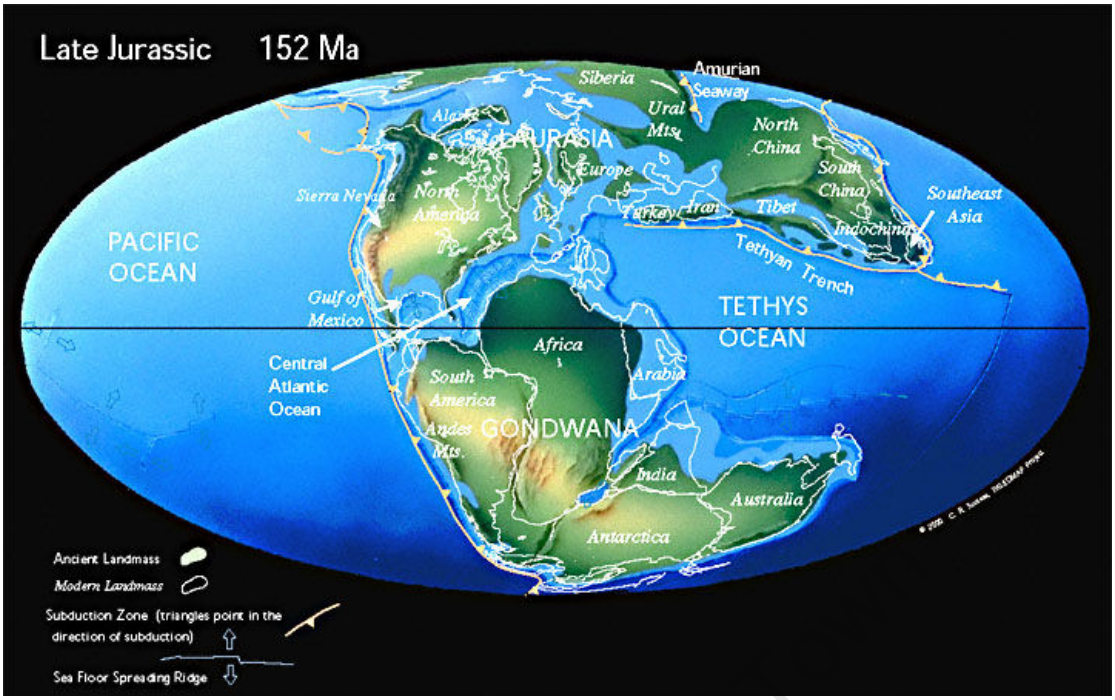

Figure 1-14 Paleogeography during Late Jurassic period (152 Ma), modified after Stampfli *et al.*, 2008

The next major tectonic event was initiated in the Early Jurassic when the Indian Plate first began to split from Gondwana (Grabowski and Norton, 1995), completing its separation from Arabia in the Late Jurassic. Rifting in the central Mediterranean also began in the Early Jurassic, affecting the northern part of the Arabian Plate. Late Early Jurassic rifting at the northwestern boundary of the Plate led to later development of a new passive margin and new accommodation space along this subsiding shelf (Sharland *et al.,* 2001).

After a period of regression associated with tectonic activity, a major unconformity and absence of lower Jurassic, the Jurassic ocean invaded the Jordan. Renewed uplift and erosion, epeirogenic movements and local volcanism during the upper Jurassic preceded the deposition of Lower Cretaceous sandstones (Bender, 1975). The eastern borders of the marine depositional environment and the thickness of the deposited sediments were remarkably influenced by a structural weakness zone.

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CRETACEOUS PERIOD

During the Cretaceous the South Atlantic Ocean opened. India separated from Madagascar and raced northward on a collision course with Eurasia. Notice that North America was connected to Europe and that Australia was still joined to Antarctica, (Stampfli *et al*., 2008).

The second phase in the breakup of Pangea began in the early Cretaceous, about 140 million years ago. Gondwana continued to fragment as South America separated from Africa opening the South Atlantic, and India together with Madagascar drifted away from Antarctica and the western margin of Australia opting the Eastern Indian Ocean. The South Atlantic did not open all at once, but rather progressively "unzipped" from south to north. That is why the South Atlantic is wider to the south, (Stampfli *et al*., 2008).

Other important plate tectonic events occurred during the Cretaceous Period. These include: the initiation of rifting between North America and Europe, the counter-clockwise rotation of Iberia from France, the separation of India from Madagascar, the derivation of Cuba and Hispaniola from the Pacific, and the uplift of the Rocky Mountains, (Stampfli *et al*., 2008).

Shallow seaways covered the continents because sea level was 100 - 200 meters higher than today. Higher sea level was due, in part, to the creation of new rifts in the ocean basins that, displaced water onto the continents. The Cretaceous was also a time of rapid sea-floor spreading. Because of their broad profile, rapidly spreading mid-ocean ridges displace more water than do slow spreading mid-ocean ridges. Consequently, during times of rapid sea-floor spreading, sea level will tend to rise, (Stampfli *et al*., 2008).

The Mediterranean rifting continued into the Early Cretaceous, which may have been partially responsible for uplifting in western Arabia (Grabowski and Norton, 1995). Also by the Early Cretaceous, separation of India from Arabia had been accomplished and a new ocean had begun to open between the two Plates. The southern Oman margin was now also a subsiding passive margin, open to transgression. The far-field opening of the central and south Atlantic at this time may have also contributed to the uplift of the western part of the Arabian Plate and changed the gentle northeastward tilt of the Plate to the east. This shifted the dominant sediment transport direction, i.e. eastward from the uplifted area that supplied large volumes of sediments to the Platform (Al-Fares *et al*., 1998; Sharland *et al*., 2001).

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In the mid Cretaceous a new short-lived spreading ridge system formed off the northeastern margin of the Arabian Plate, most likely related to changes in the motion of the Indian Plate. (Haq *et al*, 2005)

In the early Late Cretaceous, accelerating convergence between the Arabian and Asian Plates led to the obduction of this new Neo-Tethyan oceanic crust as ophiolites along the northeastern margin of the Arabian Plate. This convergence also exerted compressive stresses over the Plate and caused uplift and erosion over many of the re-activated arches and anticlines (Figure 1-15). (*Haq et al., 2005*)

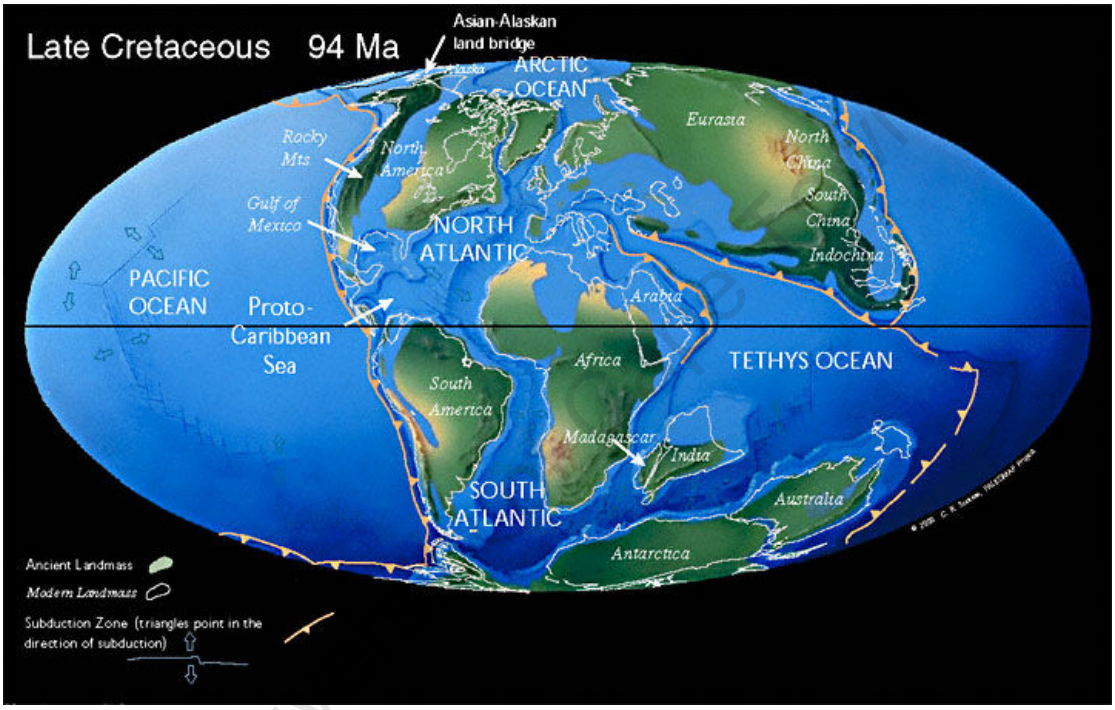

Figure 1-15 Paleogeography during Late Cretaceous period (94 Ma), modified after Stampfli *et al*., 2008

Early Cretaceous siliclastics rocks unconformably overlie the Triassic and Jurassic rocks in northwestern Jordan. This unconformity is angular due to the late Jurassic epeirogenic movements. A gradual transgression occurred throughout the Lower Cretaceous and spread clastic continental sediments across the Jordan Valley to the east, while a marine platform environment dominated northwest Jordan (Bender, 1974). During the early Cretaceous, the Middle East was characterized by broad regional Paleo-highs, basement controlled north-

northeast to south-southeast trending horst, and tilted blocks and salt domes (Murris, 1980).

A regional transgression and regression movements are localized to a great extent in the beginning of the Late Cretaceous (Cenomanian), as well as the Post-Cenomanian age (Nuweihed, 1982). Significant tectonic movements took place during the Late Cretaceous which led to folding, uplift, erosion and tilting of fault blocks which also accompanied several volcanic activities (Coleman, 1993; GSI, 1985; Nuweihed, 1982; Bender, 1975).

Upper Cretaceous Orogenic activity aided the formation of a fore deep along the Tethys margin, which contributed to the accumulation of deep marine bituminous limestone and cherts under anoxic conditions (Bender, 1975).

1.1.3.4. CENOZOIC ERA

During the Early Cenozoic, India began to Collide with Asia. 50 - 55 million years ago India began to collide with Asia forming the Tibetan plateau and Himalayas. Australia, which was attached to Antarctica, began to move rapidly northward (Stampfli *et al*., 2008).

The third and final phase in the breakup of Pangea took place during the early Cenozoic. North America and Greenland split away from Europe, and Antarctica released Australia which like India 50 million years earlier, moved rapidly northward on a collision course with southeast Asia. The most recent rifting events, all taking place within the last 20 million years include: the rifting Arabia away from Africa opening the Red Sea, the creation of the east African Rift System, the opening of the Sea of Japan as Japan moved eastward into the Pacific, and the northward motion of California and northern Mexico, opening of the Gulf of California, (Stampfli *et al*., 2008).

Though several new oceans have opened during the Cenozoic, the last 66 million years of Earth history are better characterized as a time of intense continental collision. The most significant of these collisions has been the collision between India and Eurasia, which began about 50 million years ago. During the Late Cretaceous, India approached Eurasia at rates of 15 - 20 cm/yr - a plate tectonic speed record. After colliding with marginal island arcs in the Late Cretaceous, the northern part of India, Greater India, began to be subducted beneath Eurasia raising the Tibetan Plateau. Asia, rather than India, has sustained most of the

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deformation associated with this collision. The collision zones, or sutures, between these fragments are still warm, and hence, can be easily reactivated. As India collided with Asia, these fragments were squeezed northwards and eastwards out of the way, along strike-slip faults that followed older sutures. Earthquakes along these faults continue to the present-day. The collision of India with Asia is just one of a series of continental collisions that has all but closed the ocean great Tethys Ocean. From east to west these continent-continent collisions are: Spain with France forming the Pyrenees mountains, Italy with France and Switzerland forming the Alps, Greece and Turkey with the Balkan States forming the Hellenide and Dinaride mountains, Arabia with Iran forming the Zagros mountains, India with Asia, and finally the youngest collision, Australia with Indonesia.(Stampfli *et al*., 2008).

This phase of continental collision has raised high mountains by horizontally compressing the continental lithosphere. Though the continents occupy the same volume, their area has decreased slightly. Consequently, on a global scale, the area of the ocean basins has increased slightly during the Cenozoic, at the expense of the continents. Because the ocean basins are larger, they can hold more water. As a result, sea level has fallen during the last 66 million years. In General, sea level is lower during times of continental collision (early Devonian, Late Carboniferous, Permian, and Triassic, (Stampfli *et al*., 2008). Figure 1-16

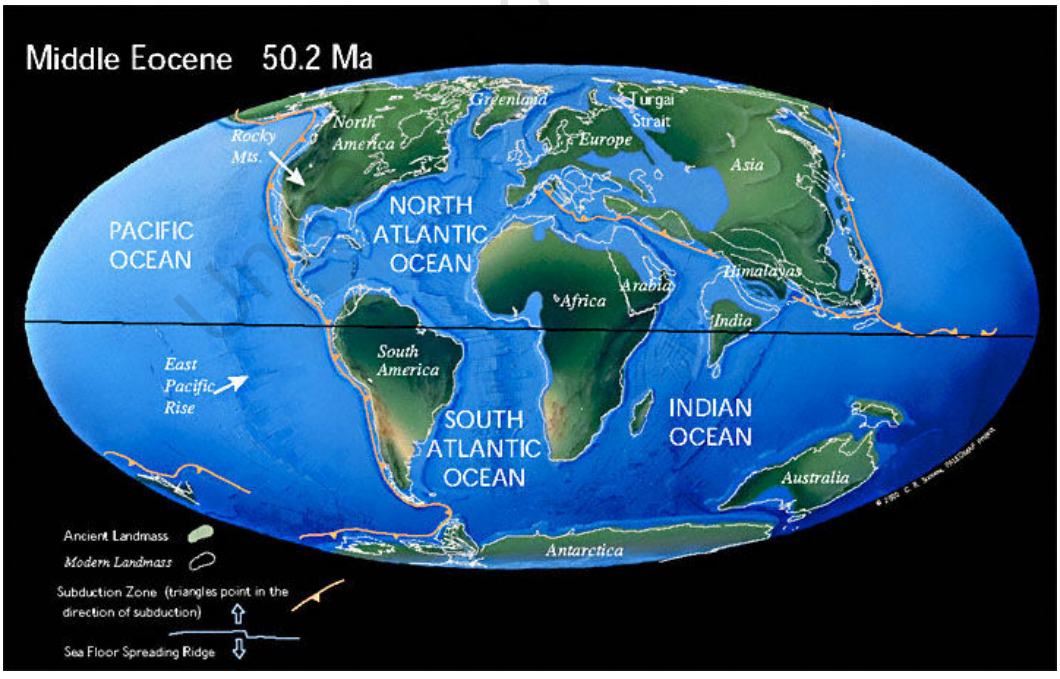

Figure 1-16 Paleogeography during Middle Eocene period (50.2 Ma), modified after Stampfli *et al*., 2008

MIOCENE PERIOD

20 million years ago, Antarctica was covered by ice and the northern continents were cooling rapidly. The world has taken on a "modern" look, but notice that Florida and parts of Asia were flooded by the sea (Stampfli *et al.*, 2008).

During the last half of the Cenozoic the Earth began to cool off. Ice sheets formed first on Antarctica and then spread to the northern hemisphere. For the last 5 million years the Earth has been in a major Ice Age. There have been only a few times in Earth's history when it has been as cold as it has been during the last 5 million years (Stampfli *et al.*, 2008). Figure1-17

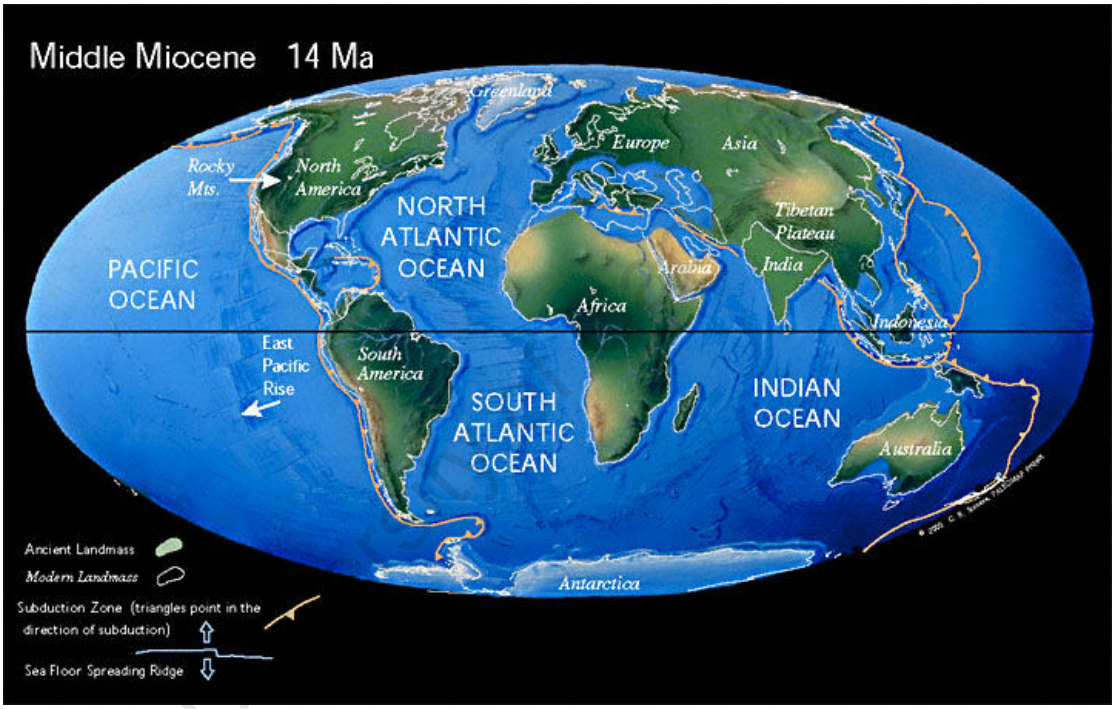

Figure 1-17 Paleogeography during Middle Miocene period (14 Ma), modified after Stampfli *et al.*, 2008

The Cenozoic tectonic history of the Arabian Plate is largely of continued rapid convergence between the Plate and Eurasia and the closure of the eastern part of the Neo-Tethys seaway. Much of this convergence was accommodated by subduction along the northern margins of the shrinking Tethys seaway, under the Iranian terranes and the Makran subduction zone of Pakistan. In the late Eocene the Plate began to collide with Asia and the closure of the Neo-Tethys was essentially complete by the late Oligocene. The Plate once

again was tilted to the northeast due to rifting along the western margin and structural loading in the northeast. Rifting in the Gulf of Aden and Red Sea may have been initiated in the late Oligocene (Hughes *et al*., 1991), but it manifested itself fully in the mid to late Miocene, most likely aided by loading of the eastern part and flexing of the Plate (Sharland *et al.,* 2001).

Several phases of volcanic activity during the Neogene erupted in the northern and eastern parts of the Jordan (Bender, 1975, Burden, 1959). Taphrogenic structural movements started during the Oligocene on the southeast side of the Wadi Araba Jordan Geo-suture and resulted in uplift, emergence, and continental erosion (Bender, 1975). During the Mid – Tertiary folding and later regional arching occurred in the west and northern areas of Jordan simultaneously with the early stages of the Jordan Rift taphrogenesis. Erosion occurred over emergent areas adjacent to the Rift Valley and southern shield. During the Pliocene and Pleistocene several phases of major faulting took place (Bender, 1975).

1.1.4. GENERAL LITHO-STRATIGRAPHY OF JORDAN

1.1.4.1. REGIONAL PALEOFACIES OF JORDAN AND THE ARABIAN PLATE REGIONS

The Paleofacies evolution of Jordan since the beginning of the Cambrian is believed to be influenced by the following factors (Bender, 1975):

1. The Tethys-Ocean, which occupied the area in the west and northwest and transgressed several times over parts of, or over the whole country.
2. The Wadi Araba-Jordan geo-suture between the Palestine and East Jordan blocks.
3. The Nubo-Arabian Shield in southeast and south, from where mechanical and chemical weathering products were trans-ported into the shelf of the Tethys.

Bender, 1975, Trollinger, 1985, and Beicip 1974 studies about the Paleofacies of Jordan since the Early Cambrian formulated the General litho-stratigraphic distribution as well as Ziegler, 2001 and Jawzi, *et al*., 1994 study about the hydrocarbon accumulation of the Arabian Peninsula since the Late Permian. These studies revealed to the followings:

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PALEOFACIES OF THE PALEOZOIC ERA

CAMBRIAN PERIOD

During Lower Cambrian to Middle Cambrian, the first transgression of the Tethys reached the eastern-rim of Central Wadi Araba. To the east and southeast of the limit of the transgression the continental deposition of sandstone continued in epeirogenic basin during a dominantly dry climate period. In middle Cambrian a regression occurred since continental sandstones were deposited in northern Wadi Araba, on top of the marine sandstones.

ORDOVICIAN PERIOD

In the Lower Ordovician the ocean invaded the flat hinter-land and covered the entire southeast of Jordan. Marine shallow water type sediments dominant by fine sandstones and sandy shales were deposited during Middle and Upper Ordovician until the Llandoverian. During Upper Silurian continental deposition of the clastics resumed, as observed in the southeast corner of the country.

DEVONIAN PERIOD

Lower Devonian sediments equivalent to the Tabuk Formation of Saudi Arabia may exist beneath Mesozoic sediments in the Jafr, Wadi Sirhan and Azraq Troughs.

Paleontological studies carried out by Olexcon 1967 on material collected from Safra Well (44 Km east of Amman) indicate that sedimentation persisted at least locally in the area into the carboniferous period.

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LATE PALEOZOIC-MESOZOIC ERA

Ziegler, 2001 studied the Paleofacies evolution of the Arabian plate during the period Late Permian to Holocene, and constructed Paleofacies maps.

PERMIAN TO MIDDLE TRIASSIC PERIOD

During the Late Permian to Middle Triassic (Figures 1–18 to 1-201) a new passive margin developed with Neo-Tethys. The Arabian Plate is interpreted as an essentially peneplaned ENE-dipping platform. With the northward drift of the Plate, low-latitude warming occurred.

Shallow-marine and arid-evaporate environments developed and a regional carbonate regime spread over the eastern Arabian Platform. In Jordan, During the Permian, the Paleozoic rocks were tilted east-wards and eroded. Sedimentation resumed during the Lower Triassic. Outcrops of these sediments were seen to occur in the lower reaches of wadies which breach the rift escarpment between Wadi Hisban and north of El Lisan Area, while further east and southeast erosion prevailed on the continent.

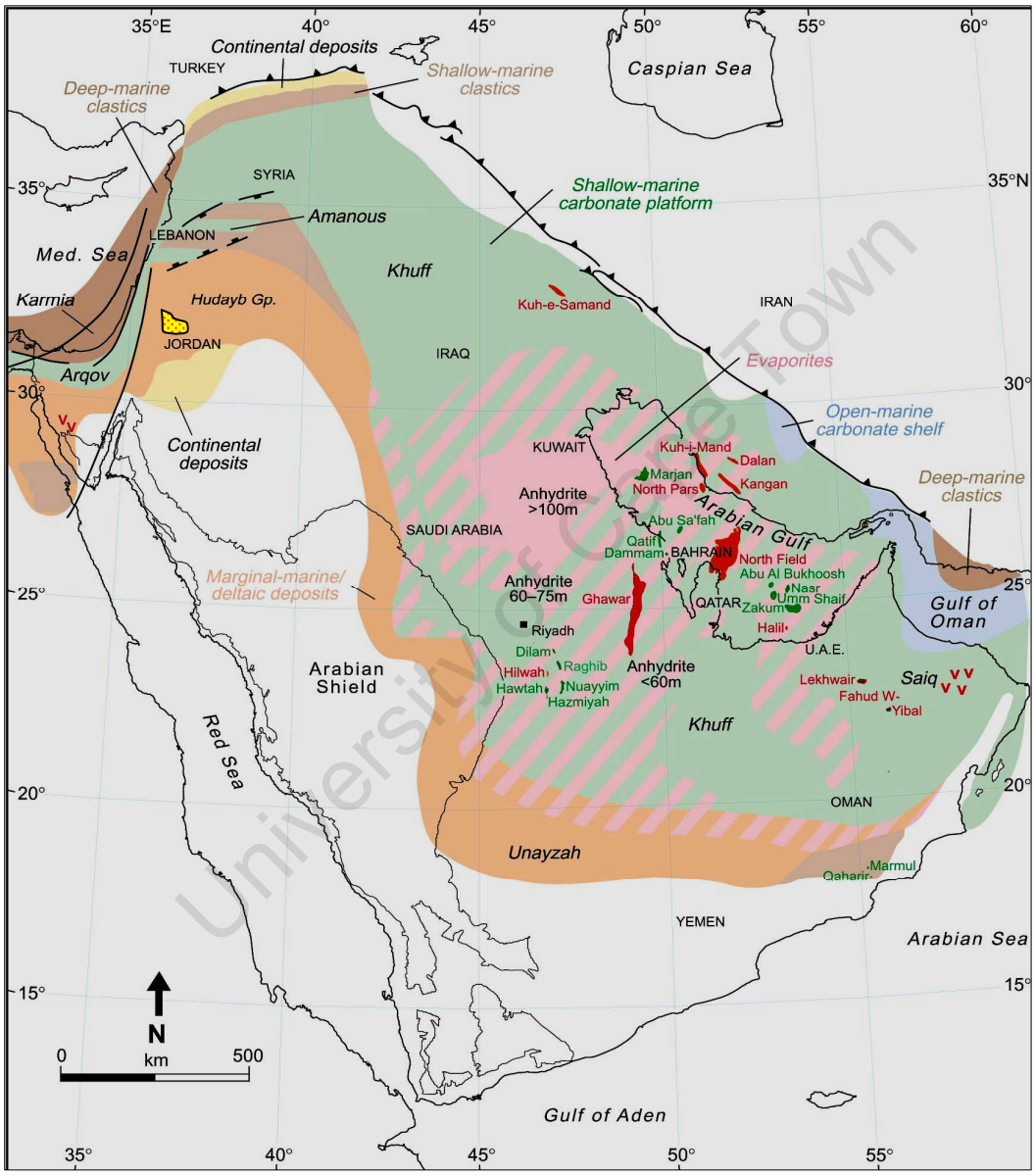

Figure 1-18 Paleofacies of Late Permian Kazanian to Tatarian (256–248.2 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

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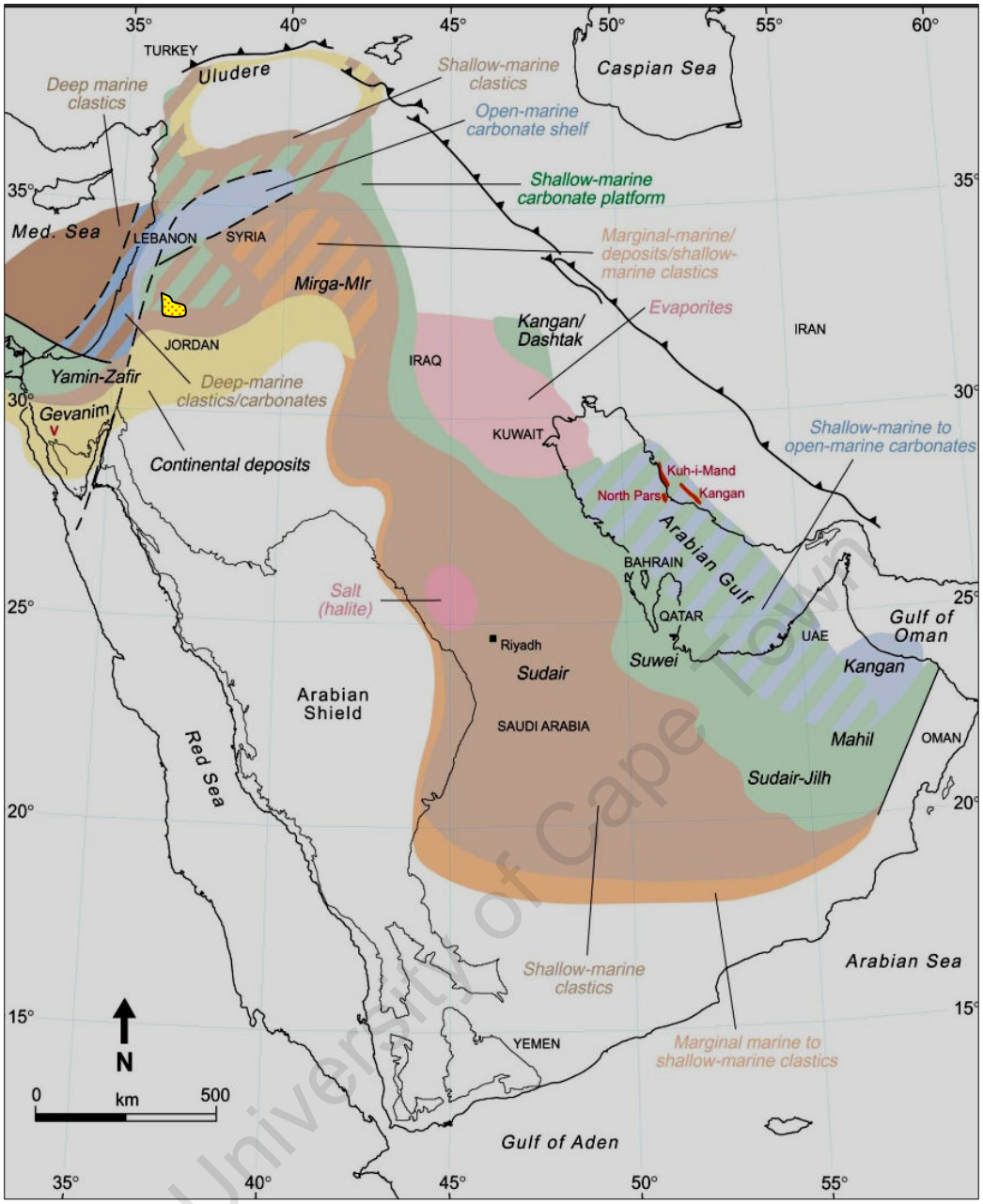

Figure 1-19 Paleofacies of Early Triassic: Scythian (248.2–241.7 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

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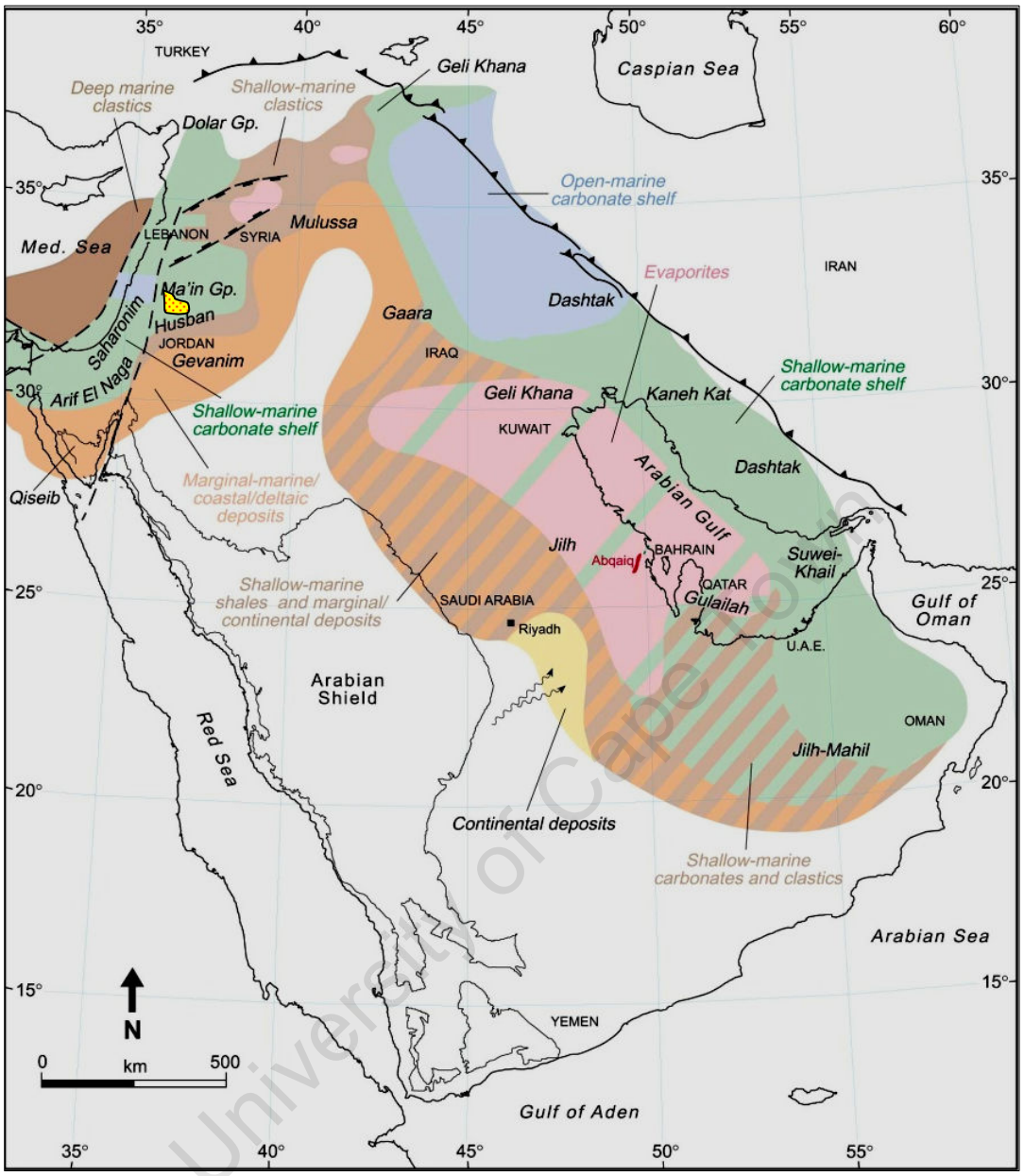

Figure 1-20 Middle Triassic: Anisian to Ladinian (241.7–227.4 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

LATE TRIASSIC TO EARLY JURASSIC PERIOD

During the Late Triassic to Early Jurassic, (Figures 1-21 to 1-26), rifting occurred at the northern end of the Plate. A new northern passive margin with Neo-Tethys was created. The southern part of the Plate and the southeastern edge of the Arabian Shield were uplifted

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and contributed massive floods of terrigenous clastics toward the northeast. It is probable that the Hercynian horst-blocks and grabens channeled the sands into southern Iraq and as far as Khuzestan in Iran. West of the Summan Platform, an N-trending seaway developed, possibly a successor of the Paleozoic Widyan Basin.

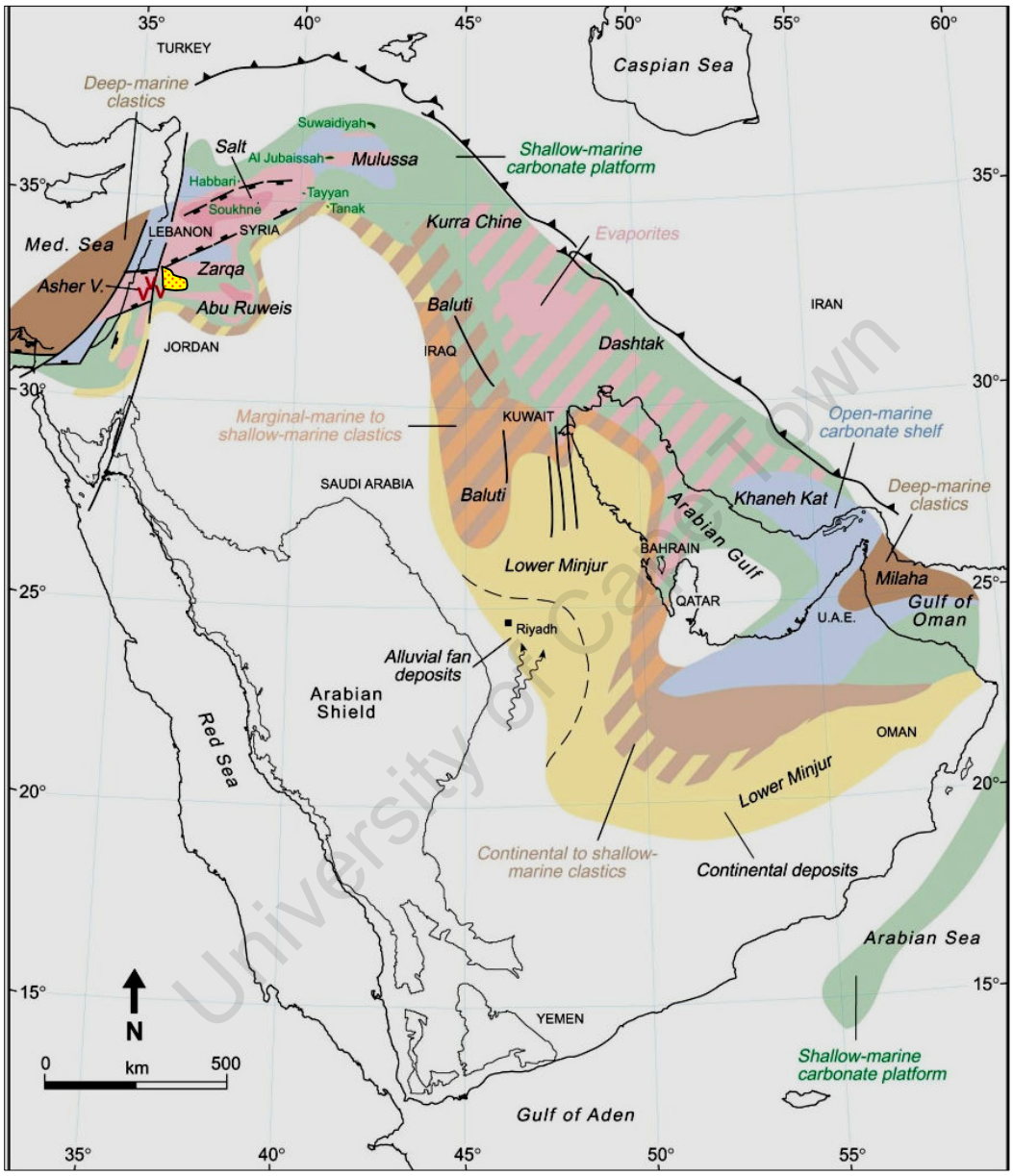

Figure 1-21 Late Triassic: Carnian to Norian (227.4–209.6 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

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At the end of the Triassic the sea regressed and the whole area was subjected to erosion. During the Triassic phase of sedimentation a sequence of, argillaceous and carbonate deposits accumulated.

EARLY TO LATE MIDDLE JURASSIC PERIOD

During the Early to late Middle Jurassic, the N-trending Gotnia Basin became established across the head of the Arabian Gulf, possibly separated by the 'Rimthan Arch' from its southern extension, the Arabian Basin. The Gotnia Basin allowed direct access for the open marine Neo-Tethys far across the Arabian Platform. The Rimthan Arch has a northwesterly Najd trend, or an even older trend relating to the Rayn Micro plate (Al-Husseini, 2000).

In the late Middle Jurassic, a carbonate regime was dominant throughout the region, and even the western shelf of the Arabian Basin hosted reefal limestones.

In the Middle Jurassic (Bajocian-Bathonian), incipient graben systems with a northwesterly Najd trend developed at the southern margin of the Arabian Plate. They began as a terrestrial to continental infill of erosional lows or pre-rift structural depressions, and culminated in the Late to Middle Jurassic (Callovian-Oxfordian) as rift troughs containing shallow-water carbonates. In the Levant, limited Palmyrides-trend rifting occurred and the extrusion of the Devora volcanics was concurrent with the tectonic activity. In the Middle Jurassic the sea regressed again. Outcrops of Jurassic sediments were restricted to the Jordan Valley side wadies in a region extending southwards for about 20 kilometers from Wadi Zarqa. During this period, sandstones, clays and dolomitic limestones accumulated. Erosion on the continent continued in the South and East.

It has been noticed that Jurassic and Triassic shorelines run more or less in parallel. Jurassic-Triassic sediments were seen to occur beneath the lower Cretaceous sandstones (Kurnub Sandstone) in many drilled wells in the northern and north-eastern parts of Jordan.

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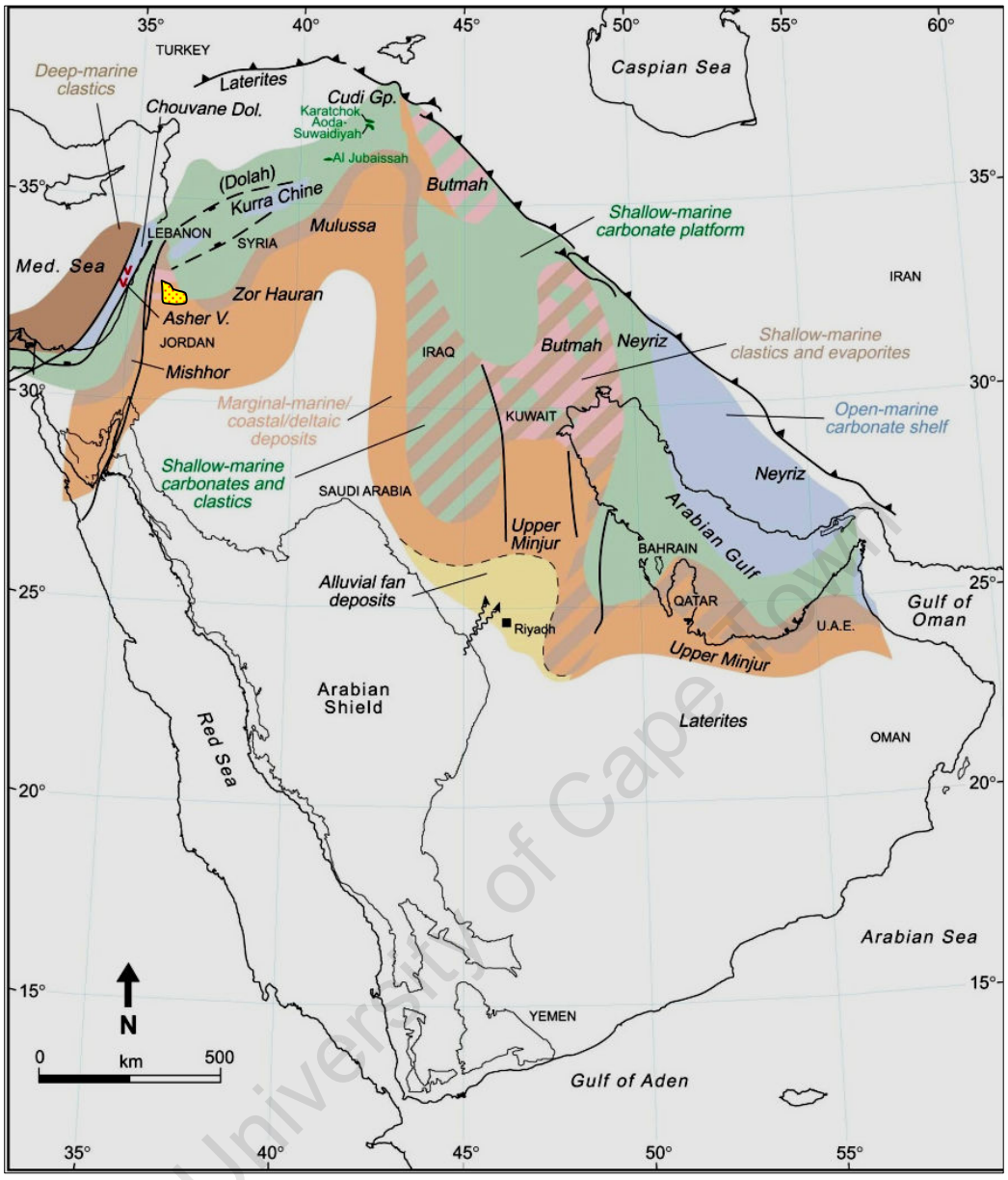

Figure 1-22 Triassic to Jurassic Transition: Rhaetian to Hettangian (209.6-201.9 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

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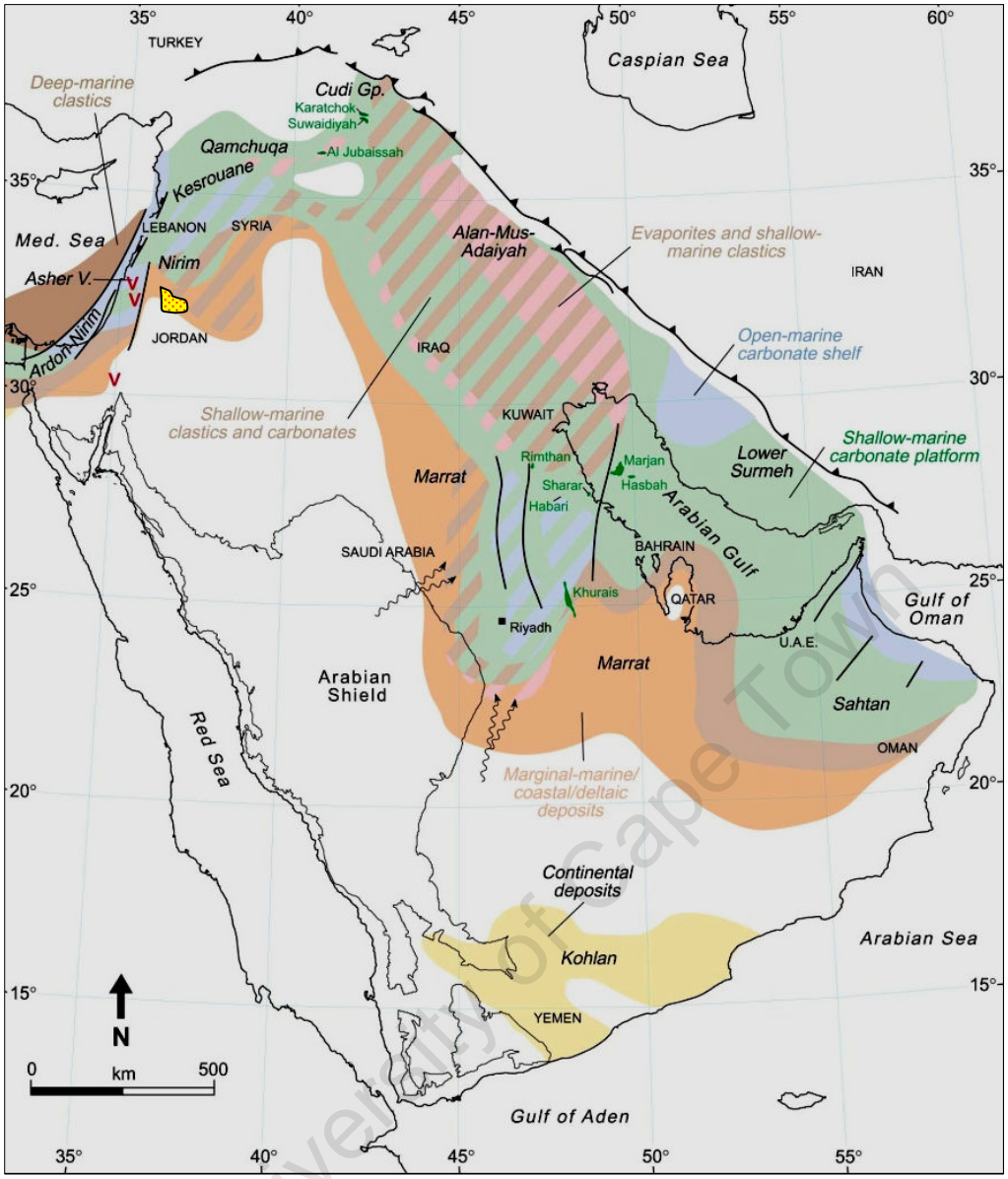

Figure 1-23 Early Jurassic: Sinemurian to Aalenian (201.9–176.5 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

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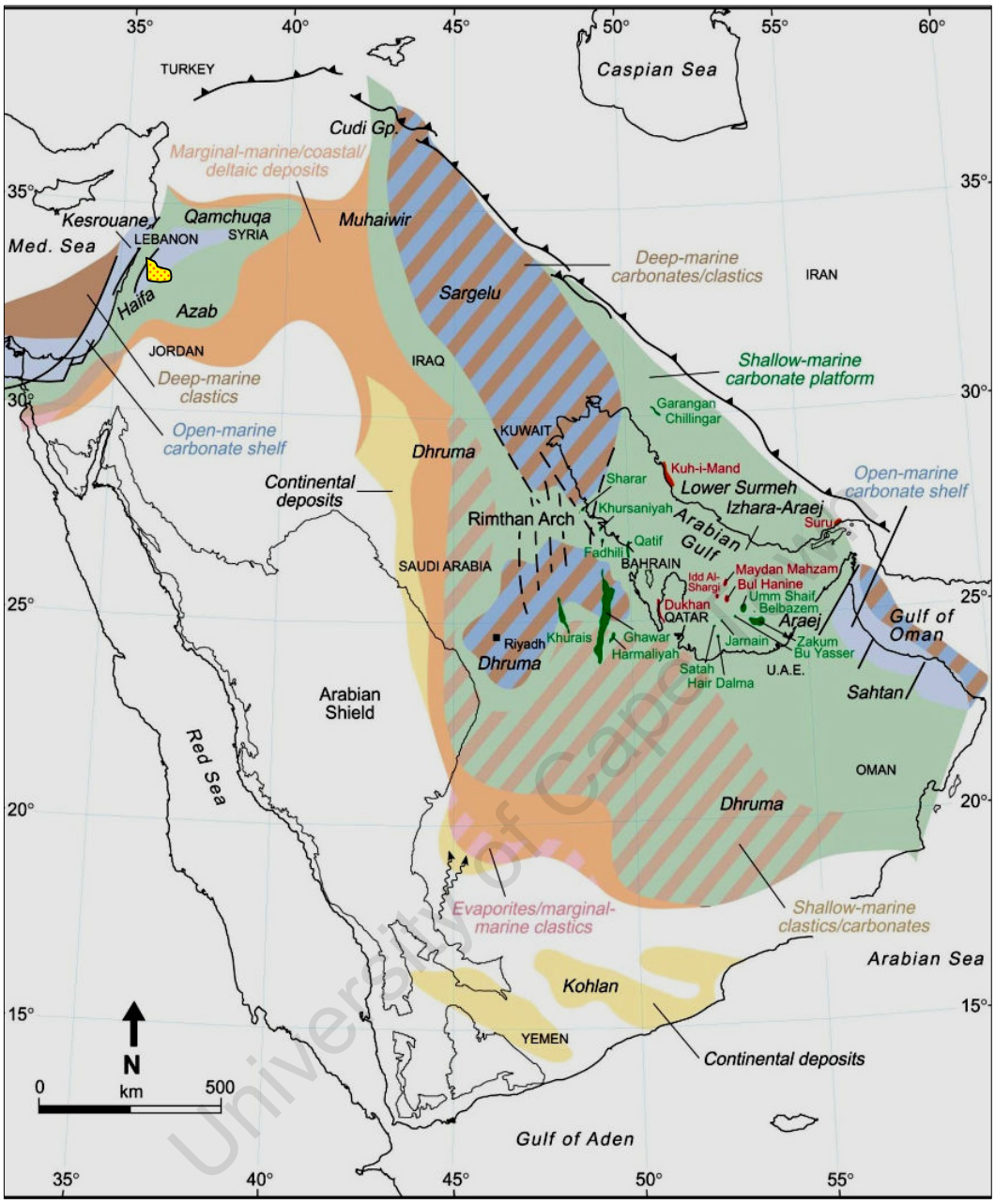

Figure 1-24 Middle Jurassic: Bajocian to Bathonian (176.5–164.4 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

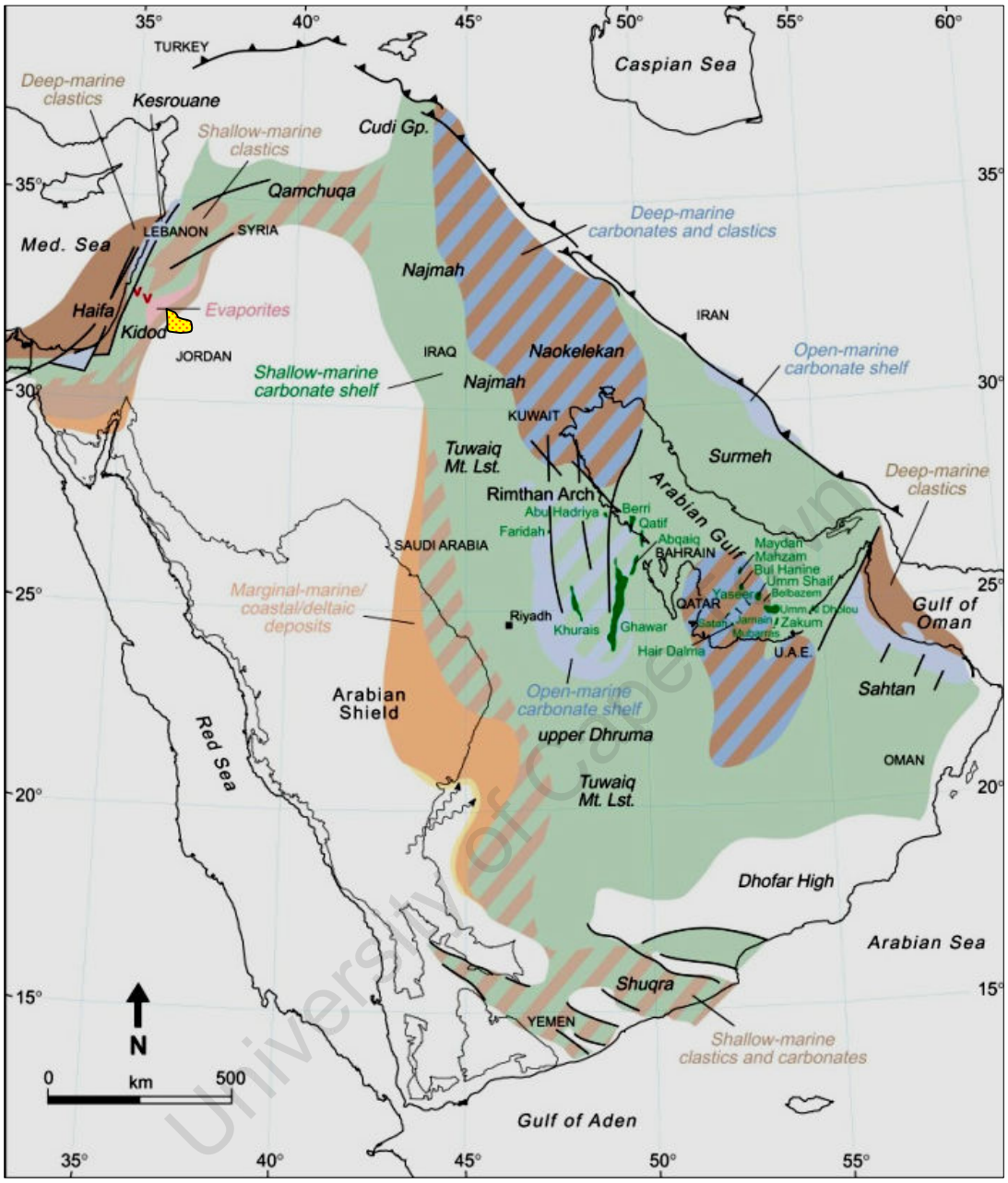

Figure 1-25 Late Middle Jurassic: Callovian to Oxfordian (164.9–154.1 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

The Late Jurassic (Figure 1-26) was a tectonically active period in southern Yemen, with clearly expressed rifting related to the separation of India from the Afro-Arabian Plate. Significant rift shoulder uplift characterized the southeastern continental margin of Oman, whilst the northeastern margin remained remarkably stable and accumulated typical shelf-

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margin carbonate sediments. In central Arabia, slow but progressive infill of the intra-shelf basins took place through repetitive shoaling-upward carbonate cycles. These cycles usually culminated in exposed evaporate flats (sabkha). The Gotnia and Arabian basins may have been intermittently connected by Najd- and Hercynian-trending seaways across the southern Gotnia rim. The Levant region also shows uplift and rifting coincident with massive Tayasir volcanism. The Arabian-Nubian Shield was to a considerable extent exposed and eroded.

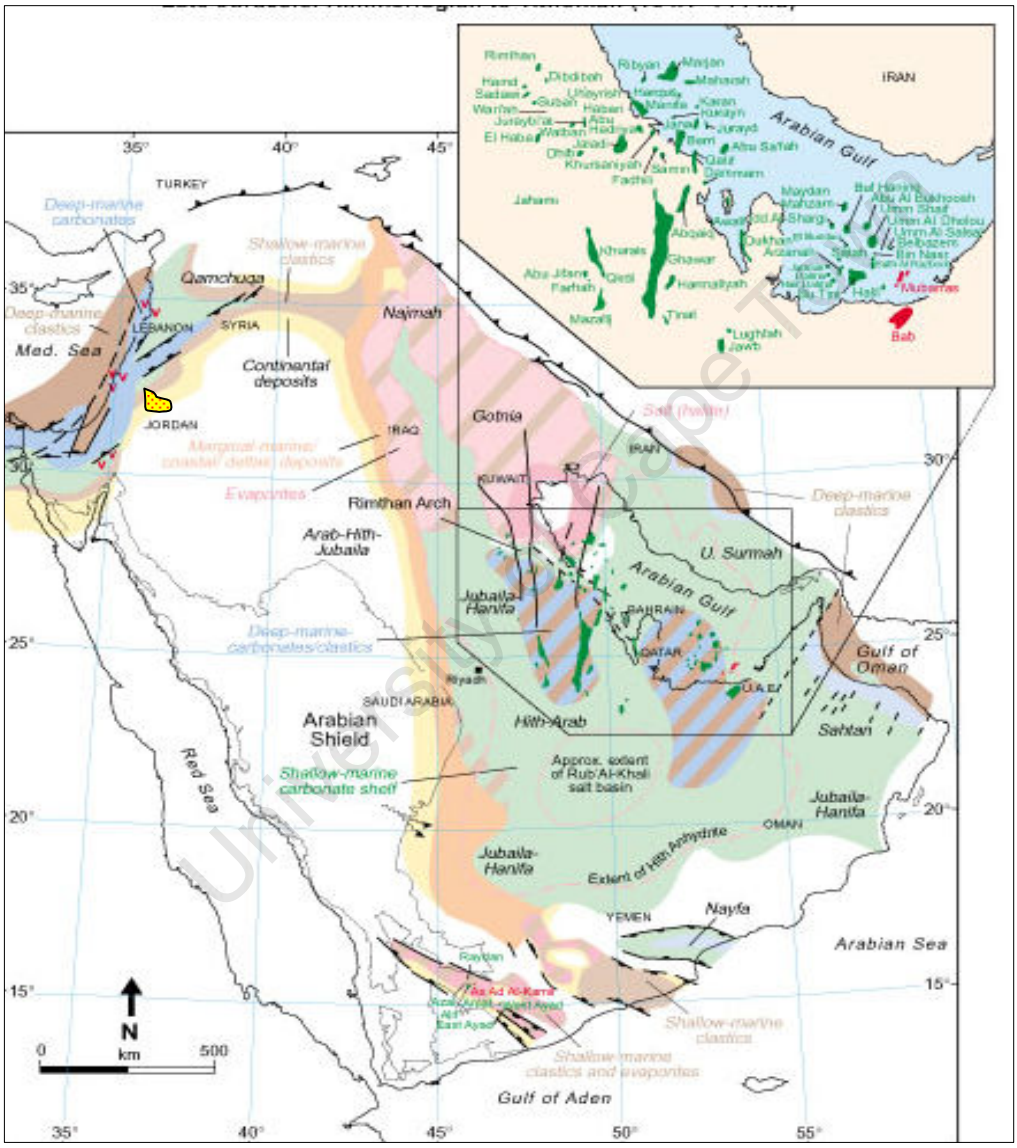

Figure 1-26 Late Jurassic: Kimmeridgian to Tithonian (154.1–144 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

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EARLY CRETACEOUS-EARLY PALEOCENE PERIOD

At the beginning of the Cretaceous (Figure 1-27 to 1-29), global sea level was relatively high and consequently most of the Arabian Plate accumulated almost exclusively shallow-marine carbonates. The major exception was the remnant of the Gotnia Basin that underwent rapid subsidence in the eastern part along Hercynian lineaments to form a narrow deeper-marine intra-shelf basin in which the Balambo shales of Iraq and the Garau of Iran accumulated. The Arabian Basin was rapidly in filled, first by carbonates and later by terrigenous clastics .The southeast Oman plate-margin segment was foundering accompanied by the establishment of open-marine, deep shelf deposits.

In Jordan region, the Lower Cretaceous sandstones are neritic to littoral north and northwest of the Jurassic shoreline. South and southeast of this shoreline, the lower part of the Lower Cretaceous succession, both marine and brackish influences have been encountered in Southeast Jordan. The Lower Cretaceous sandstones of the continental origin extend to the east and to the extreme southeast where they become diachronous and their top became younger from west to east.

In the late Early Cretaceous (Figure 1-30), extensive rudist banks colonized the shelf breaks to the intra-shelf basins, such as the Shilaif Basin in the southern Gulf, and in the Levant. Following the opening of the central Atlantic Ocean, a distinct change in motion of the Arabian Plate has been postulated by Al Fares *et al*. (1998). Far-field stresses are thought to have resulted in the uplift and erosion of the western part of the Arabian Craton and the supply eastward of large amounts of terrigenous clastics and shallow-marine sands. The plate stress, combined with sufficient sediment loading, served to trigger the growth of salt structures in the area of the southern Arabian Gulf over which numerous rudist banks developed.

Neo-Tethys became compressive and began to close during the Late Cretaceous (Turonian) to Early Paleocene (Figure 1-31). Ophiolites that were obducted onto the Arabian Plate margin may be observed in Oman, at many places along the northeast Zagros margin, and in the Troodos Mountains of Cyprus. Hercynian-trend lineaments extended northward from the Central Arabian Arch into the Zagros fore-deep. Early Senonian uplift and inversion of older structures occurred in the Levant. This caused deformations along the Syrian Arc and the onset of faulting in the Azraq Graben in Jordan. Shallow marine carbonates were

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deposited southward across Sinai into the depression that marked the proto-Red Sea rift. The deposition of shallow-water and lacustrine sediments occurred as far south as the Jeddah region.

In Jordan region, The Cenomanian-Turonian sediments are fully marine and thick in the west, northwest and north. On the contrary in the south, southeast and east, they wedge out, calcareous contents decrease and the arenaceous facies prevail. The Late Cretaceous Santonian-Maestrichtian marine sediments have been developed into two different characteristic sedimentary successions:

1. Chalky limestones, sandy limestones, silicified limestones, sandstones, chert, phosphate and Tripoli deposits were originated in what is called "Gentle Swells System" (Nuweihed, 1981).
2. Thick bituminized marls, marly limestone, compact dolomites and limestones, interbedded with black brown chert layers were deposited in basins and troughs with local euxinic environments.

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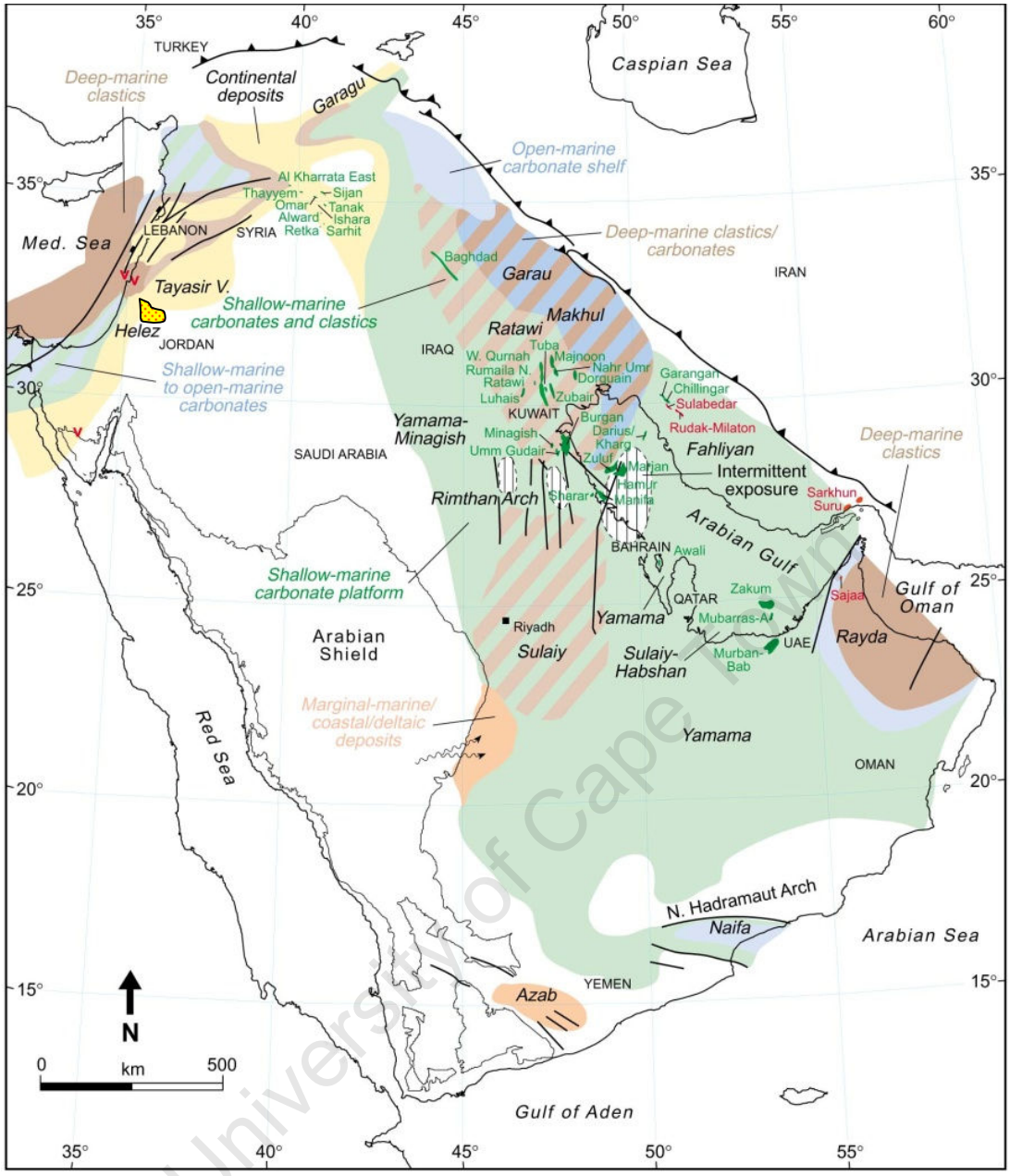

Figure 1-27 Very Early Cretaceous: Berriasian to Valanginian (144–132 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

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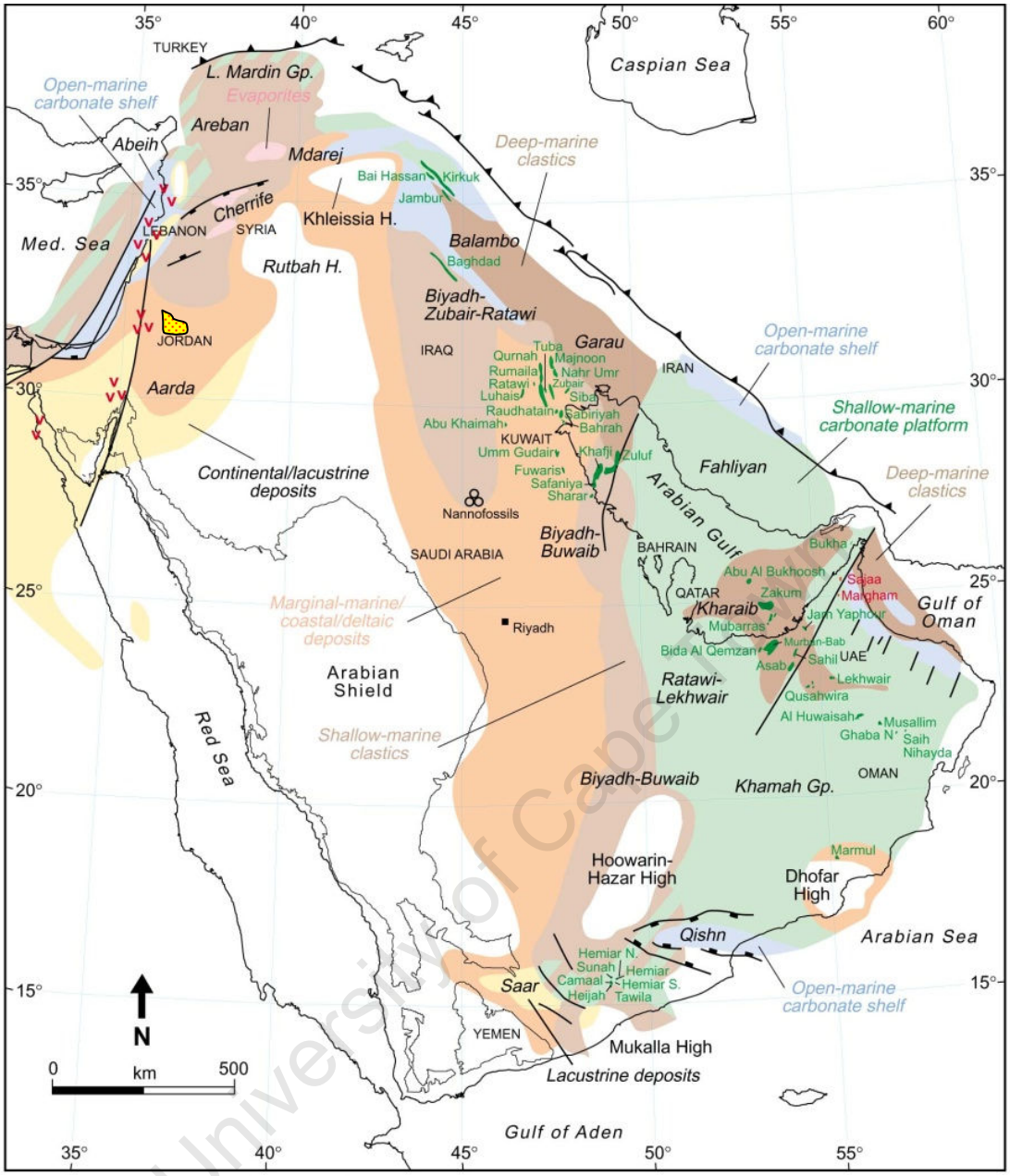

Figure 1-28 Early Cretaceous: Hauterivian to Barremian (132–121 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

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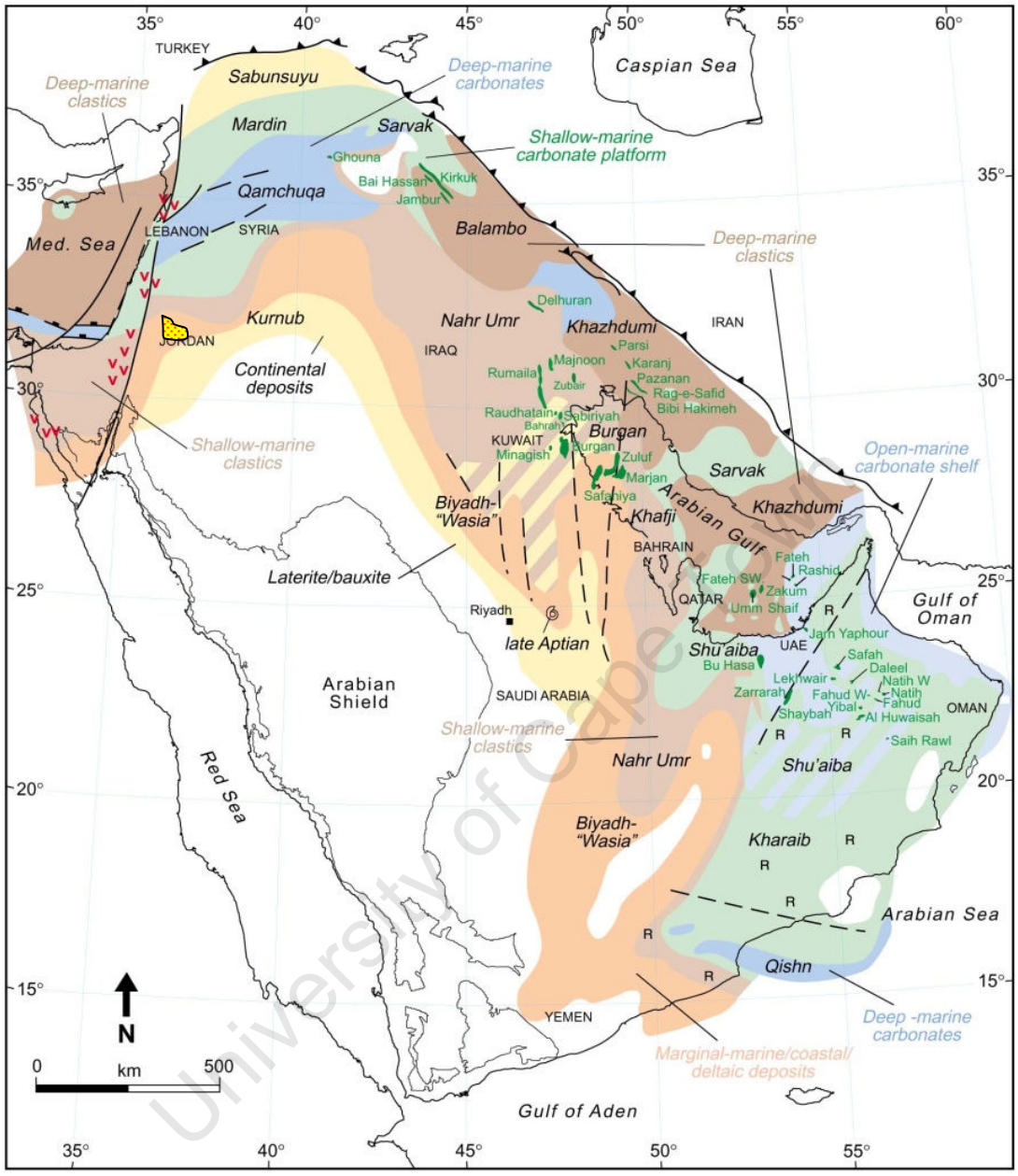

Figure 1-29 Late Early Cretaceous: Aptian to Albian (121–98.9 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

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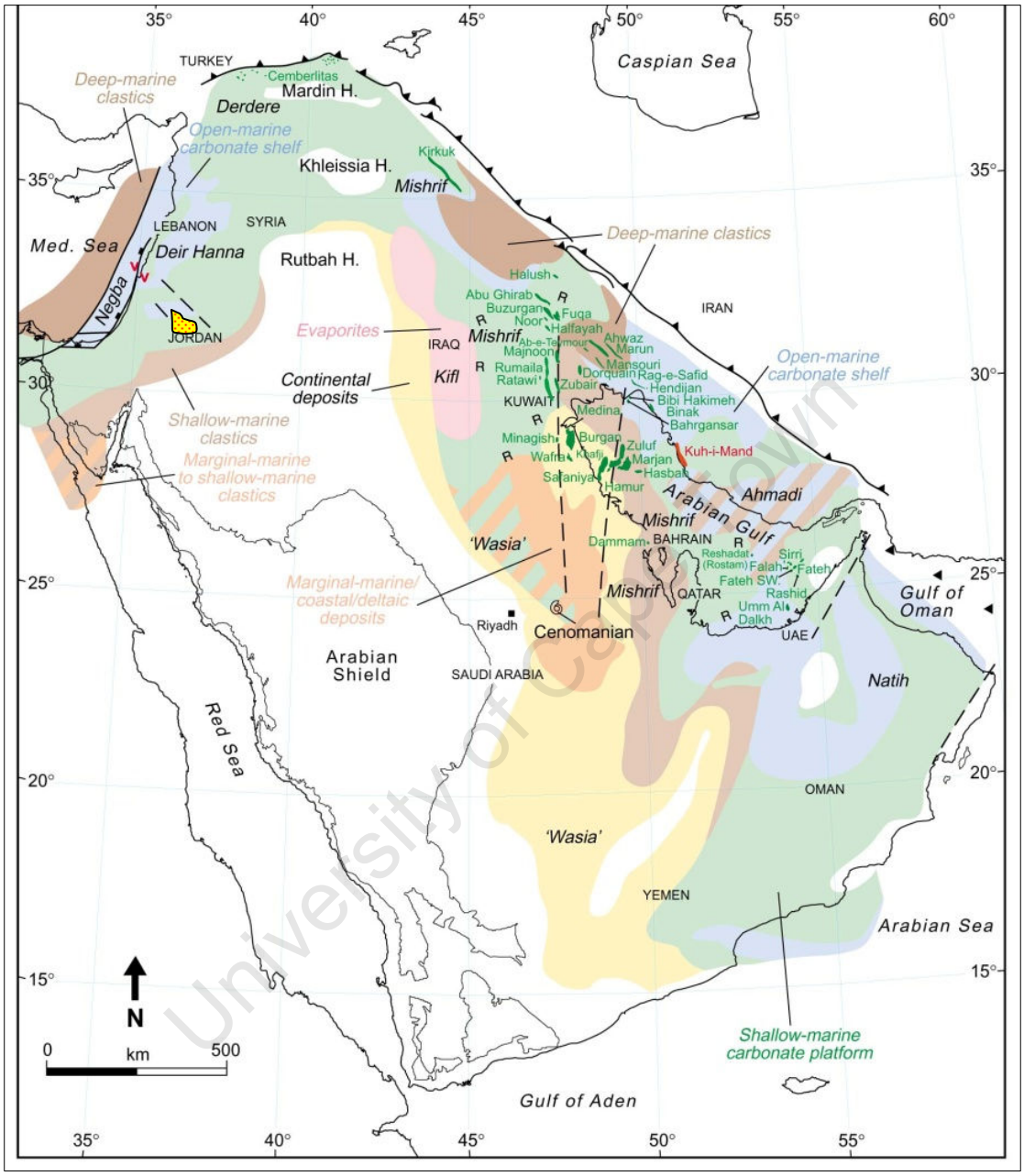

Figure 1-30 Early Late Cretaceous: Cenomanian to Turonian (98.9–89 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

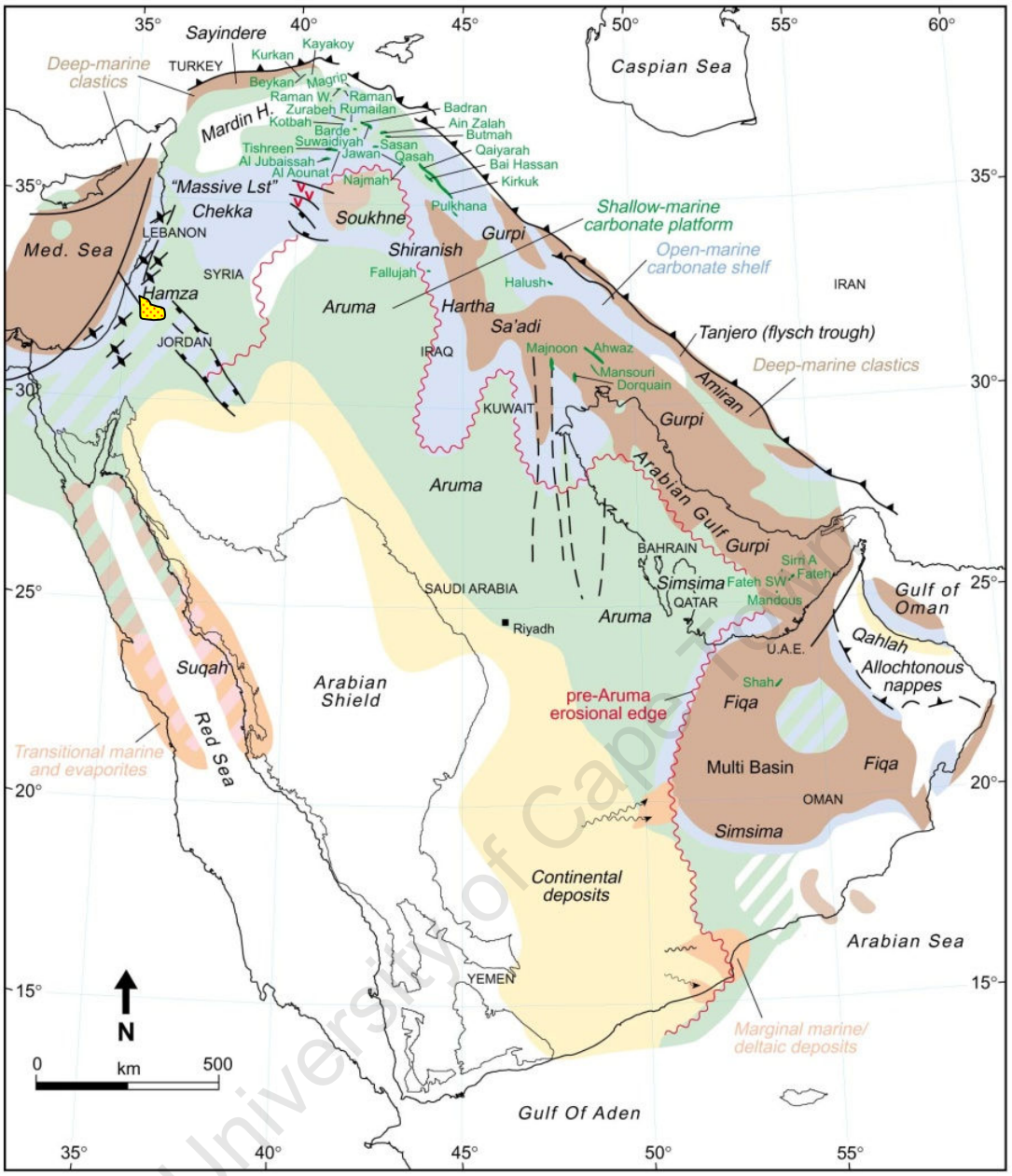

Figure 1-31 Late Cretaceous to Early Paleocene: Senonian to Danian (89–60.9 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

CENOZOIC ERA

LATE PALEOCENE TO EARLY OLIGOCENE PERIOD

Global sea level during the Late Paleocene to Early Oligocene (Figures 1-32) was relatively high and only in the Late Oligocene there was a marked drop (Haq *et al*., 1988). At the time

of high sea level, a shallow epeiric sea inundated the eastern platform of the Arabian Plate. The sea periodically shoaled to emergence, which caused the formation of transitional coastal sabkha. The Hercynian structural trends of the Central Arabian Arch continued to modify the morphology of the foreland basin. This became progressively narrower as it was filled in, until it became structurally neutralized.

Jordan Tertiary marine sediments of the Paleocene and the major part of the Eocene were deposited in a similar "gentle swells and basins system".

Along Wadi Araba – Jordan rift, coarse clastic weathering products from the bordering, uplifted areas were deposited at the same time together with Taphrogenic tectonics in the Oligocene. Locally, in the central part of the graben, thick rock salt was deposited in the Oligo-Miocene to Pliocene.

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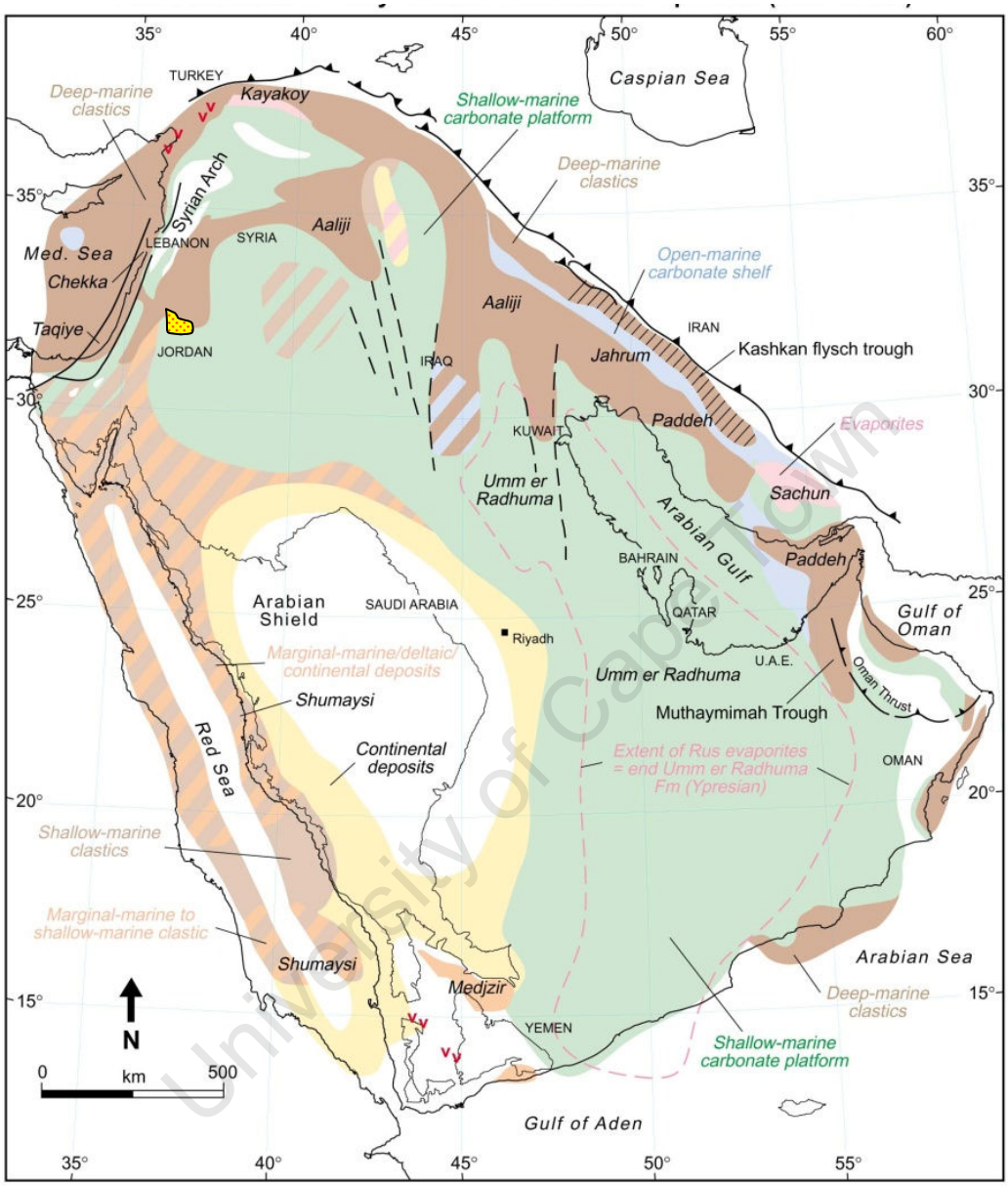

Figure 1-32 Late Paleocene to Early Eocene: Thanetian to Ypresian (60.9–49 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

LATE MIDDLE EOCENE TO EARLY MIOCENE PERIOD

From the late Middle Eocene to Early Miocene (Figures 1-33–1-34), the Arabian Plate began to impact southern Asia, and the Zagros Orogeny began. The western part of the Plate was

emergent and only on the subsided margins (e.g. the Gulf of Aden), did marine sedimentation continue.

The Priabonian and Oligocene-Miocene deposits of southern Dhofar and the Hadramaut record the early stages of rifting and progressive opening of the Gulf of Aden. Western Yemen at this time was part of the thermally doming Afar Triangle. As a consequence, vast amounts of volcanic rocks were erupted in the hinterland of Aden and the southern Red Sea. Although early rifting in the Red Sea region has been dated as Early Oligocene, the first phase of sea-floor spreading did not begin until the Early Miocene, and lacustrine to continental sedimentation prevailed in the pre-rift depressions.

On the northern margin of the Arabian Plate, molasse and flysch-type clastics were discharged into the fore-deep of the Taurus Orogenic belt (the Aslantes-Iskenderun Basin) and onto the shallow shelf of the Mardin High.

In the Levant, clastic detritus from the Arabian Craton was discharged onto the Sinai plains and indicates that the Dead Sea Transform Fault was not yet active, although basaltic extrusive are present along and adjacent to the incipient fault; volcanics were also extruded in the eastern Mediterranean. A new tectonic phase affected the Syrian Arc and Galilee, and the Palmyrides and Sinjar inversion structures.

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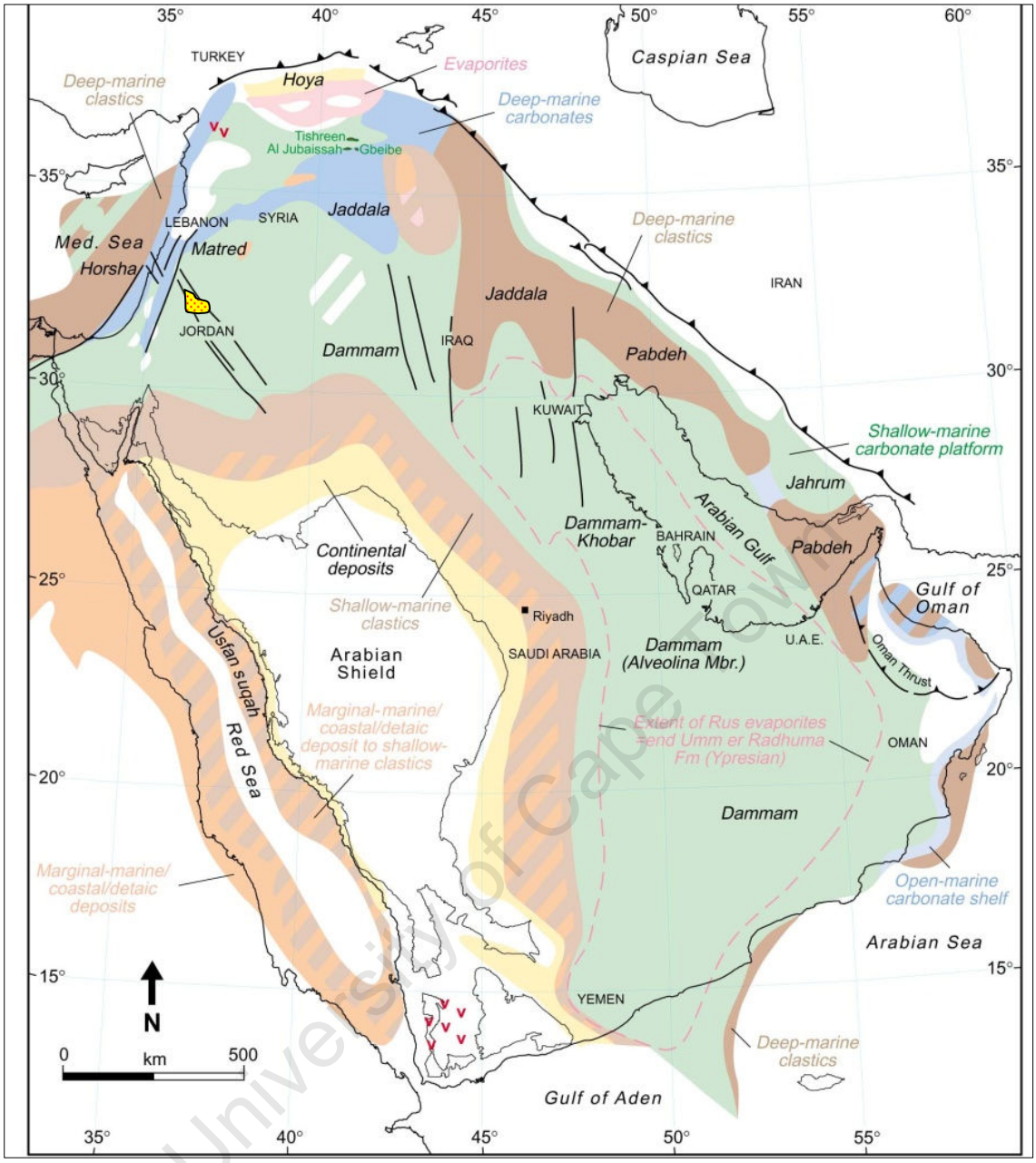

Figure 1-33 Middle to Late Eocene: Lutetian to Priabonian (49–33.7 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

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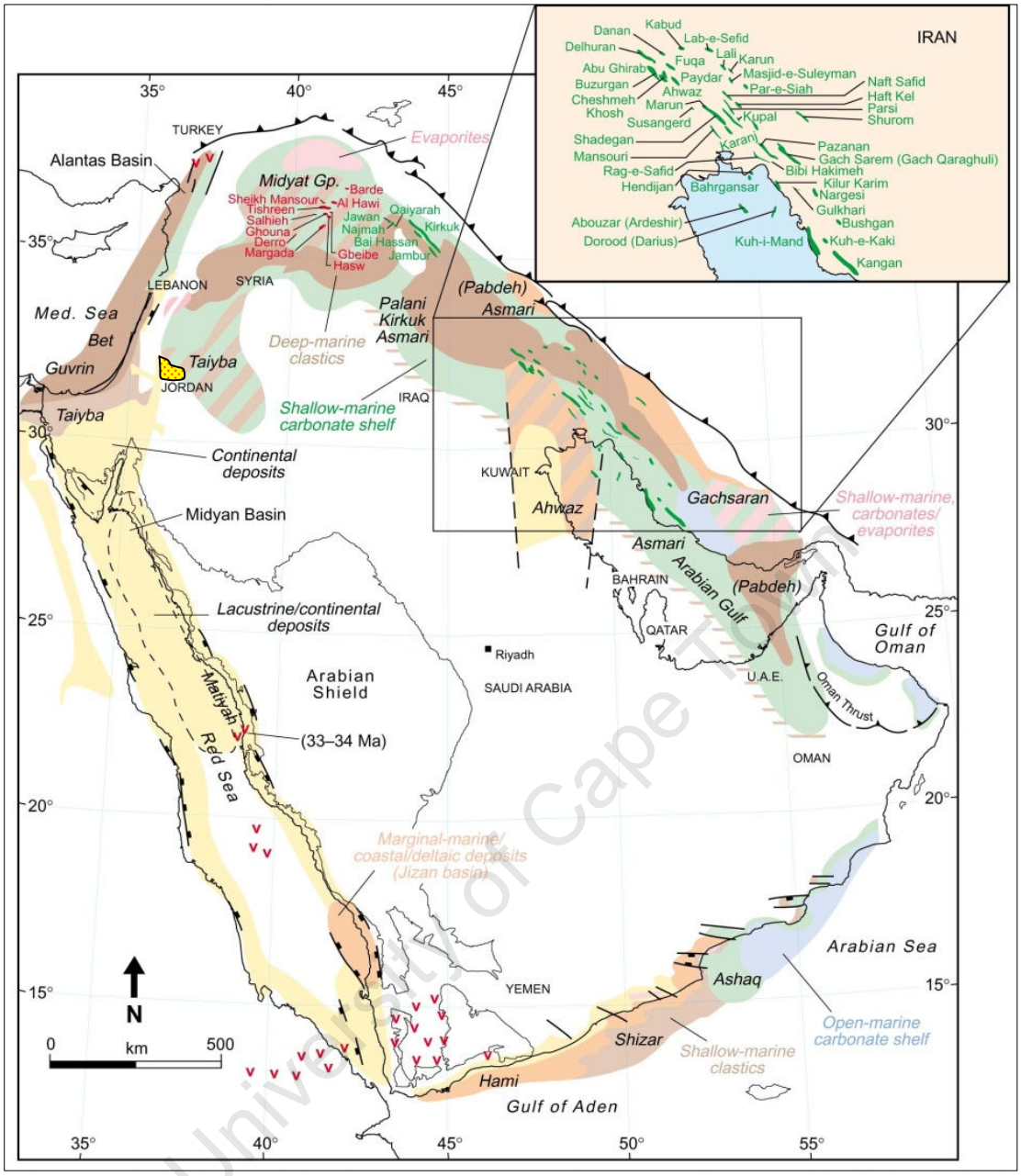

Figure 1-34 Oligocene: Rupelian to Chattian (33.7–23.8 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

MIOCENE TO PLIOCENE PERIOD

The Miocene to Pliocene (Figures 1-35 to 1-36) was the time of maximum compression between Arabia and Asia, coeval with the Late Alpine Orogeny in Europe. During this period,

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the Arabian Plate began to separate from Africa, the Gulf of Aden opened, and the Dead Sea Transform Fault acted as a complex sinistral strike-slip fault.

The second phase of sea-floor spreading in the Red Sea began about 10 Ma and is continuing. The Syrian Arc, through collision of the Arabian Plate with Eurasia, continued to undergo inversion. Along the Red Sea margin of the Plate, basaltic lavas were extruded to form a series of large lava fields (*Harrat*). Major N-trending faults appear to have controlled the emplacement of these volcanics. Where this fault zone meets the Red Sea the character of the rift sediments changes from constricted marine saline evaporites in the north to globigerinid, deep-marine shales in the south. The N-trending Hercynian lineaments occur as far north as the Zagros Fore-deep, on the western side of which a great thickness (>4,000 m) of continental sediments was discharged into the rapidly subsiding Lurestan (fore-deep) Province of Iran. To the east, salt marsh evaporites and shallow-marine carbonates and shales were deposited. The eastern Mediterranean was cut off from open-marine circulation at this time, and the Late Miocene saline evaporites are proof of the resultant 'salinity crises.

During the Pleistocene, sea level was low (Haq *et al*., 1988) and, as a consequence of uninterrupted collision and erosion along the northern Arabian Plate margin, a large thickness (>1,000 m) of conglomerates and sands were deposited at the northeastern edge of the Craton. Inversion and uplift continued in the Palmyrides and the Sinjar basins. East of the Arabian Arch, the shallow epicontinental Arabian Gulf began to take its present shape. Initially, shallow-marine shales were deposited but, as changes to more arid conditions took place, the Gulf established itself primarily as a carbonate province, particularly on the shallow shelf along its southern and southwestern coasts.

At the end of the Pliocene, sea level stood about 150 m higher than today and the subsequent drop in sea level to that of the present day has made visible old strandlines and erosional terraces. Kassler in 1973 reported high-level terraces in Oman.

During the Late Pleistocene glaciation, the sea-level drawdown was such that the entire Gulf basin became exposed as far as the Gulf of Oman. The axis of the Gulf changed from a central position in its Western Basin (toward the head of the Gulf), to a northward-skewed position in the Eastern Basin (Purser and Seibold, 1973). This axial shift was due to the southward bulge of the Zagros fold belt, east of the Kazerun strike-slip fault**.** The western axis is situated in front of the Zagros belt, whereas the axis in the Eastern Basin is part of the

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Zagros fold belt. Along the Iranian coast and at the head of the Gulf, ongoing vertical movements of the Zagros Mountains have been observed in the form of elevated river terraces and renewed incisions by younger drainage systems; also canals and other artifacts have been affected by rising anticlines**.** The Gulf of Aden continues to open and is underlain by oceanic crust. It reaches bathyal depths and is rimmed by a narrow marine shelf. The Red Sea is also a spreading center and now forms a 1,900-km-long trench that has a maximum depth of 2,220 m in the Discovery Deep. For the most part, an extremely narrow shelf parallels the rift. Sub-alkaline basalts are accumulating in the southern part of its inner trench. The Dead Sea Transform Fault is active and several 'rhomb chasms' have formed, some of which became isolated basins, as evidenced by lacustrine and hyper saline depositional environments. The Mediterranean reestablished normal marine conditions following the Messinian salinity crisis, with bathyal depths close to the Levant shore. A striking feature has been the progressive desertification of much of the region during the Pleistocene-Holocene. Most parts of the Arabian Peninsula are strongly affected by wind erosion and the accumulation of wind-blown sand. Large areas are rock deserts or deflation plains. Elsewhere, huge volumes of loose sand are being piled up by the prevailing winds in the deserts of the Rub' Al-Khali of eastern Arabia, An Nafud of northern Saudi Arabia, and Ad Dahna desert of eastern Saudi Arabia. In southeastern Arabia, monsoon influences result in sediment transport by seasonal flow in wadies. Ephemeral lacustrine conditions prevail in parts of the eastern Rub' Al-Khali and Yemen are due to monsoonal flow from the mountains. The Levant is influenced by seasonal winter rainfall. Under hot, arid conditions, and in wind-sheltered locations with a relatively stable sea level, the shorelines of the Arabian Gulf are prograding, and saline super-tidal flats (sabkha) are spreading basin ward

During Cenozoic the Jordan rift was either occupied by fresh water lakes draining west to the Tethys, or it formed an inland depression with terrestrial or lacustrine sediments. Also marine deposits during Miocene extended for 100 km east of the rift into El Azraq – Wadi Sirhan depressions and even east of the Jebel Ed-Drouz area. A major phase of Taphrogenic movements took place in the Plio-Pleistocene. The major graben movements ended at the time of the Middle Pleistocene basalt volcanism. More likely a fresh water lake (Samra Lake) covered the northern part of the rift. This lake slowly changed to the brackish Lisan Lake, Lisan Maris extends from approximately 50 km south of the Dead Sea to the north almost as far as Lake Tiberias. Not before the Upper Pleistocene did the Lisan Lake change into the

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present Dead Sea. Throughout the Quaternary detritus was transported into the Rift Valley, and the extension Azraq-Wadi Sirhan and El-Jafr depressions of East Jordan. These depressions were partly covered by fresh and brackish water lakes during fluvial periods of the Pleistocene, while fluviatile conglomerates of the same age spread over wide areas along the eastern slopes of the mountain ridges bordering the east side of the Wadi Araba – Jordan Rift.

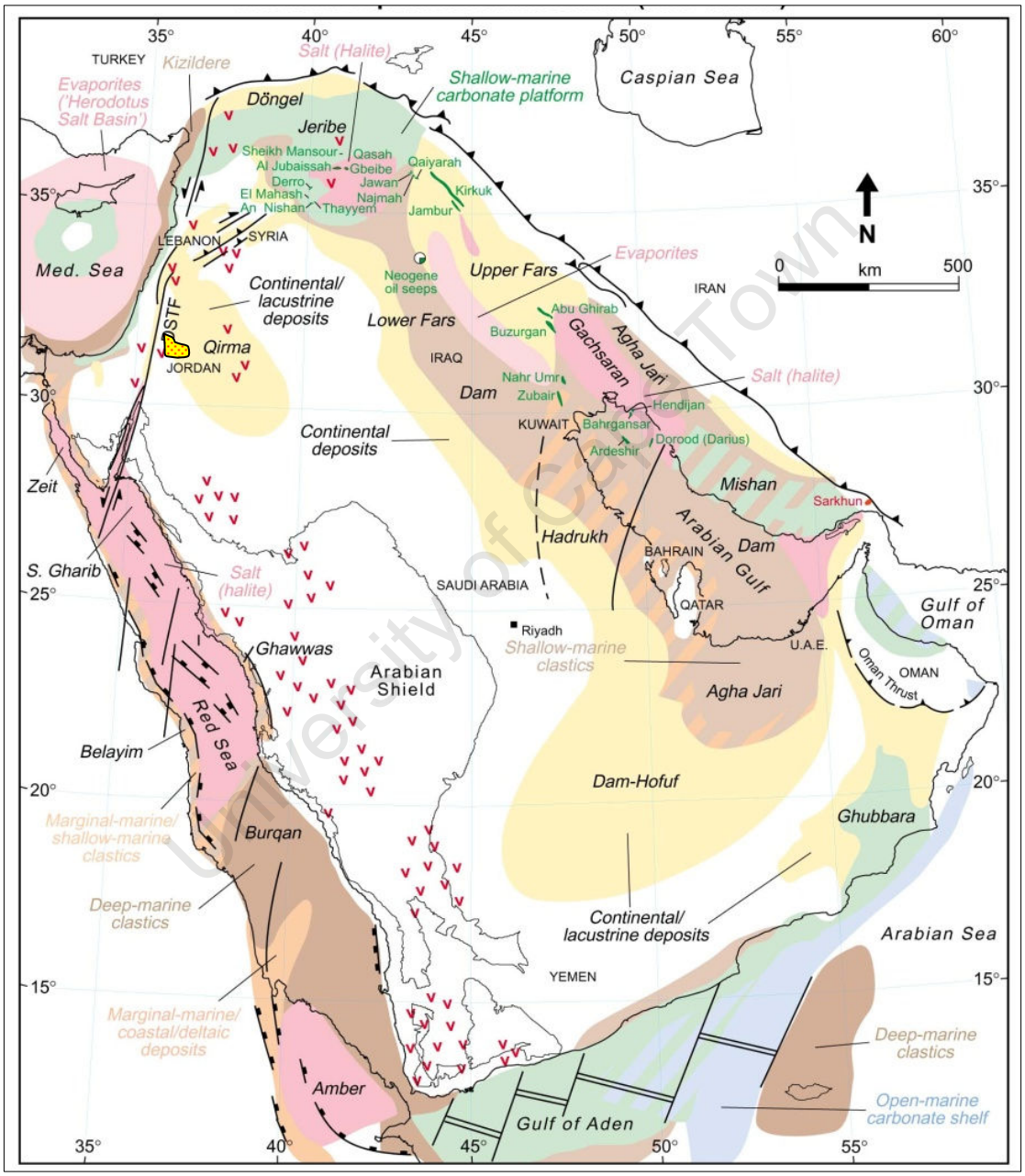

Figure 1-35 Miocene: Aquitanian to Messinian (23.8–5.3 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

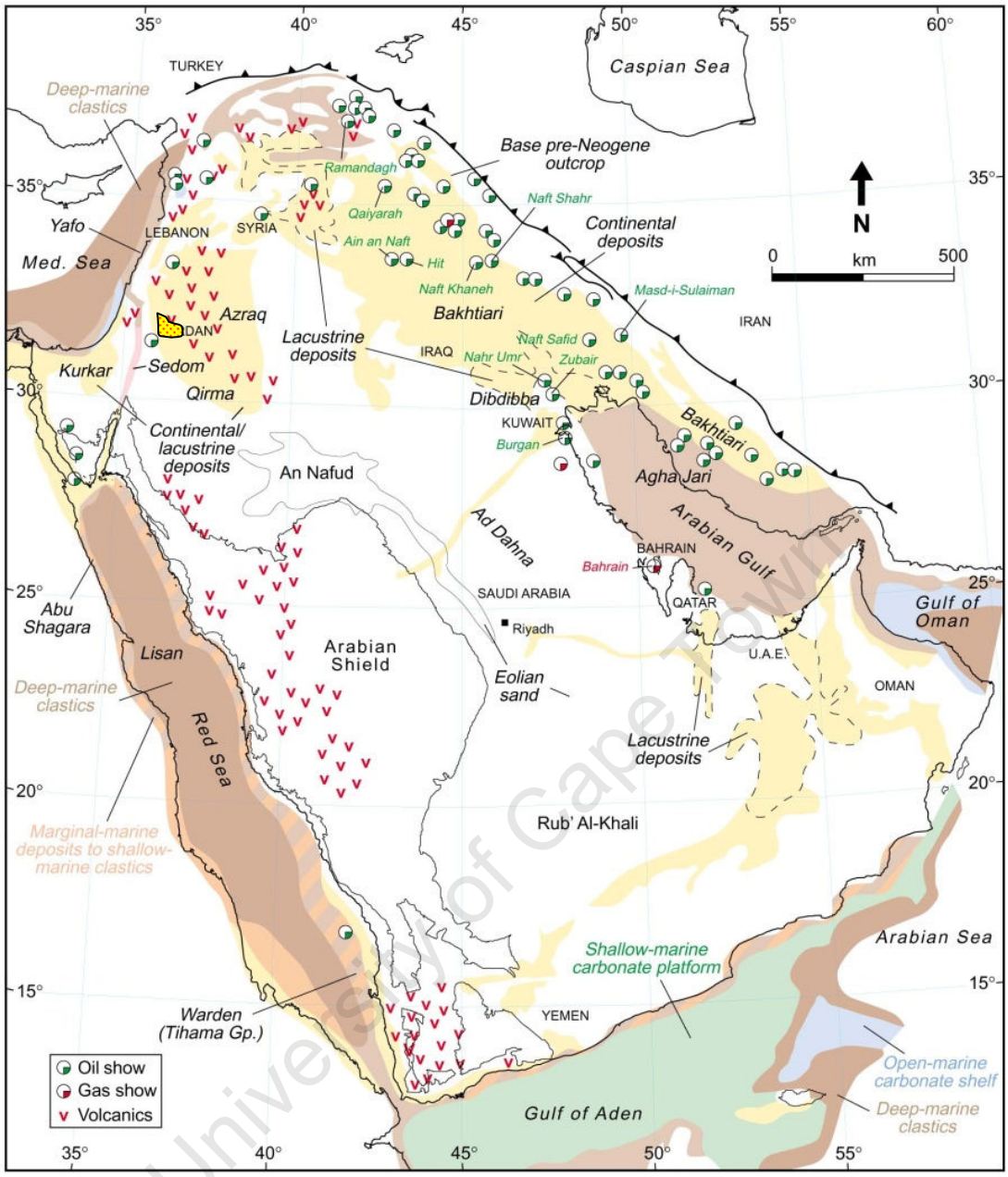

Figure 1-36 Pliocene to Quaternary: Zanclean to Present Day (5.3–0 Ma), modified after Ziegler, 2001 (study area is shown in yellow polygon)

1.1.4.2. GENERAL STRATIGRAPHY

The lithostratigraphy of Jordan is represented by Paleozoic siliclastics, Mesozoic siliclastics and mixed carbonate siliclastics. A regional angular unconformity between Paleozoic and

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Mesozoic truncated deeply and eroded most of the Paleozoic sediments. Three major facies characterized the Mesozoic in Jordan (Selly, 1978): (1) Deep marine limestone and dolomite; (2) Grain stones and packstones; and (3) Pelletoidal limestone, microcrystalline dolomite and evaporites. Marine platform carbonates with near shore clastic deposits comprise most of the known stratigraphic rocks in Jordan.

The Paleozoic section can be divided into Infra-Cambrian to lower Ordovician, dominantly subaerial clastic sequence, and a Middle Ordovician to Silurian clastic marine sequence. Within the overlying carbonates, regional facies and transgressive and regressive trends indicate that open ocean condition were to the northwest (Occidental, 1991)

Tertiary sediments are represented by deep pelagic chalk and shallow marine chert, phosphate and limestone (Abed, 2000). Volcanic activity in Jordan is significant and represented by basalt flows at the surface and emplacement of dykes and plugs. Most volcanic rocks comprise northeast and central Jordan; Figure 1-37 illustrates a generalized vertical litho-stratigraphic columnar section with related geologic events subjected Jordan Region according to Occidental (1991) studies. The litho-stratigraphic subdivisions and nomenclature are related as follows: Tertiary and Cretaceous Formations are according to the Natural Resources Authority Petroleum nomenclature, while Jurassic and Triassic are according to Bandel and Khoury (1989) nomenclature. Figure 1-38 illustrate a simplified geologic map of Jordan modified after Bender 1975.

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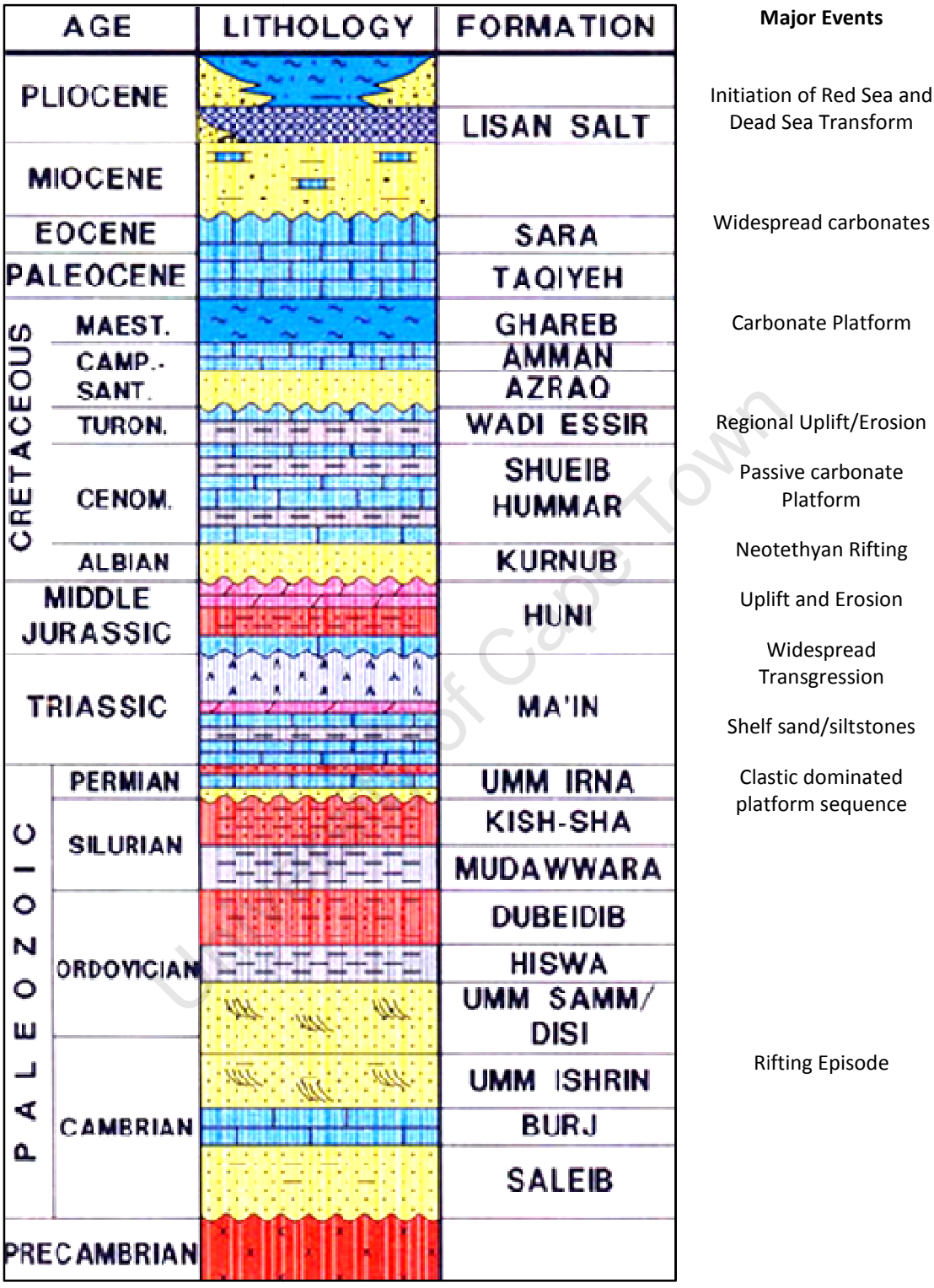

1-37 Generalized litho-stratigraphic columnar section of the major rock sequences in Jordan with major geologic events

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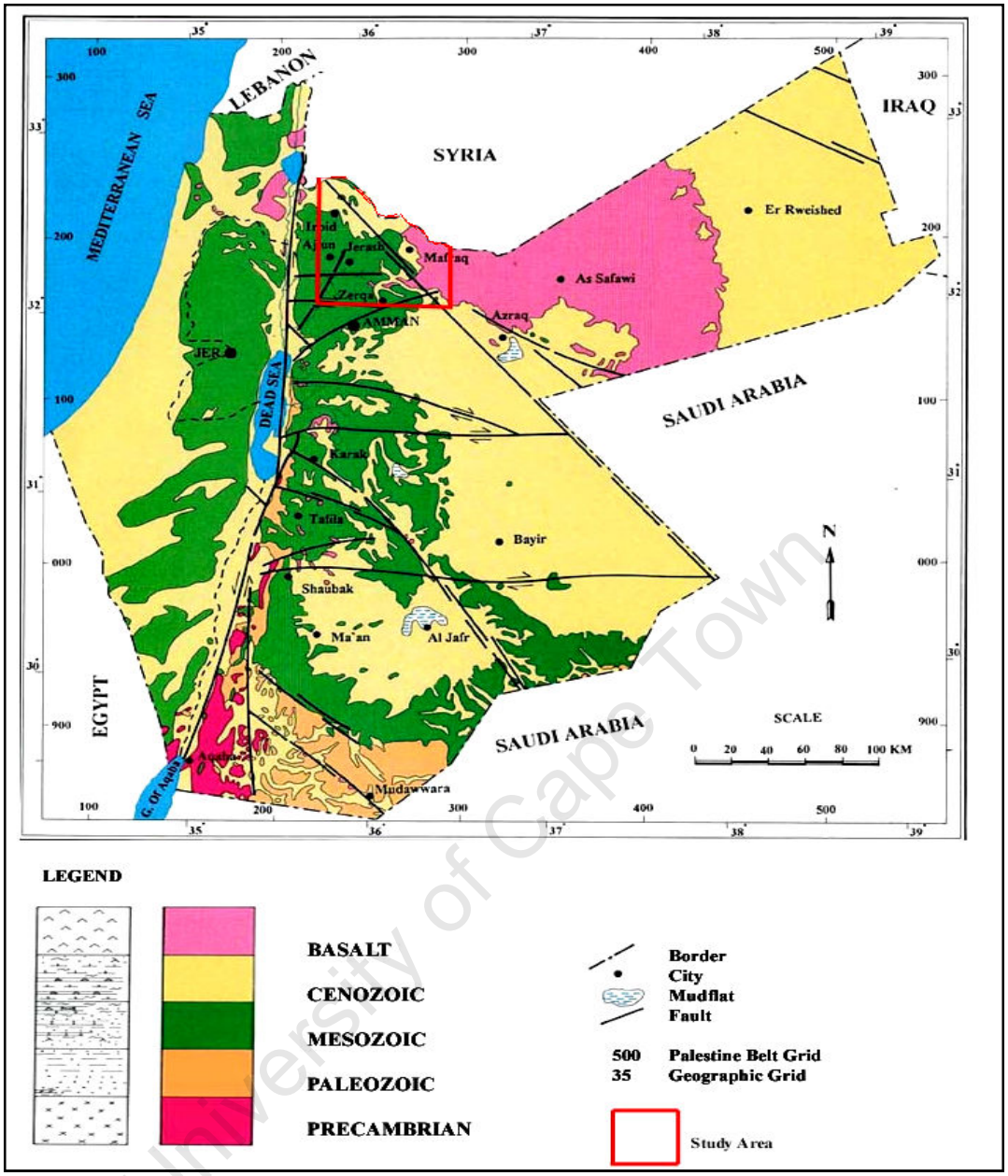

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Figure 1-38: Simplified geological map of Jordan, modified after Bender 1975

A BRIEF DESCRIPTION OF THE MAJOR STRATIGRAPHIC ROCK UNITS

PRE-CAMBRIAN ROCKS

The basement rocks of south and southwest Jordan, which form the northernmost portion of the Arabian Nubian Shield (ANS), have been classified into two complexes separated by a regional unconformity. The basement rocks are comprised almost exclusively of Late

Proterozoic meta-volcano sedimentary sequences, plutonic calc-alkaline granitoids, andesitic, and rhyolitic volcanic (McCourt and Ibrahim, 1990), cut by numerous dykes, and overlain to the north and east by Lower Paleozoic Sandstones.

The Saramuj Conglomerates represent the oldest sediments found in Jordan, although they have been slightly metamorphosed. Approximately 200m are seen in outcrop along the eastern side of the Wadi Araba and at the southeastern and of the Dead Sea

PALAEOZOIC ROCKS

Paleozoic sedimentary rocks lie disconformably above basement rocks (late Proterozoic) and outcrop in the southern desert in a southeast direction. Sediments from the Cambrian, Ordovician and Silurian are well exposed in southern Jordan. Cycles of fluvial siliclastics, marine siliclastics and marine sediments characterize the sequence of the Paleozoic rocks (Powell, 1989).

Permian rocks are 60 m thick in central Jordan and consist of a thick sequence of siliclastics sediments, which can be subdivided into two fluvial sedimentary facies consisting generally of sandstone, siltstone, silty shale, abundant carbonaceous plant material and abundant ferruginous glaebules (Makhlouf, *et al.,* 1990).

MESOZOIC ROCKS

Triassic sediments crop out along the northeastern margin of the Dead Sea and consist of an over 1000m thick sequence (Bandel, 1981; Bandel and Khoury, 1981). Lower Triassic deposits of ~70m (Scythian age) are exposed along the eastern side of the Dead Sea. To the south, the Triassic deposits pinch out, while in the north and northeast the sequence contains thick deposits of evaporitic facies. Near the Zarqa river in the study area, Triassic sediments of Scythian – Anisian, and Ladinian (?) age are >280m thickness and contain gypsum (Bender, 1975; Basha, 1981). In northeast Jordan, upper Triassic evaporitic facies are 900-1300m in thickness, and are comprised of alternating dolomite, limestone, anhydrite and salt. Some argillaceous facies are also present, traces of bituminous material, pyrite and glauconites are also found. In the study area, upper Triassic sediments of Carnian age represent the oldest outcrops with a total thickness of 220 m in surface sections and from 55 m to 570 m in deep wells (Abdelhamid *et al*., 1991).

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Jurassic rocks unconformably overlie Triassic rocks in the study area. The upper boundary is marked at the base of the Lower Cretaceous. It consists of thick beds of limestone (70m) at the base, overlain by plant fossil bearing sandstone (70m), interbedded limestone and sandy marl (220m). It is believed that they are from the Bathonian age and are of littoral to neritic origins (Bender, 1975; Abdelhamid *et al*., 1991). In the northeast of Jordan, a sequence of alternating limestone, dolomite, and some argillaceous limestone, as well as traces of pyrite, bituminous material and glauconite, are present (Khalil and Muneizil, 1992).

Lower Cretaceous rocks rest with a regional angular unconformity on Paleozoic and Mesozoic rocks. This unit is up to 300m thick and generally distinguished by white to varicolored sandstone interbedded with silty and clayey sediments, mottled horizons, levels of iron crusts, and some soil horizons. The depositional environment was predominantly fluvial to marginal marine (Powell, 1989; Moumani, 2002).

Throughout most of Jordan, a major transgression of the Tethys Ocean deposited carbonate facies of the Cenomanian-Turonian (Powell, 1989). This package disconformably overlies the Lower Cretaceous.

The Cenomanian-Turonian package overlies disconformably the Lower Cretaceous (Powell, 1989), and consists of alternating marl and limestone. A prominent gypsum horizon with red and green clays is present toward the top of the formation. Thickness of the depositional environment narrows upwards toward a coastal sabkha (salt flat) represented by the gypsum horizon (Powell, 1989; Abed, 2000).

The Turonian rock formation ranges in thickness from 80 to 200 m. It marks the top of the middle Cretaceous sequences with fractured fossiliferous and medium hard to hard marl portions. These portions contain chert nodules at top.

The Coniacian rock formation ranges in thickness from 30 to 87m (Sunna, 1994). It consists mainly of marl and sandstone.

The Santonian is dominated by bedded chert with alternating limestone and chalk overlain by phosphorite facies with minor chert and limestone of the Campanian. This package is deposited in a shallow marine environment (Powell, 1989).

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The Maestrichtian – Paleozoic formation is essentially a chalk-marl unit. In central Jordan, its thickness reaches more than 100m whereas in the north-300m (Powell, 1989). The lower part of this formation is characterized by an oil shale horizon, which is distinctive in central Jordan.

TERTIARY ROCKS

The Eocene sedimentary unit consists of alternating thin beds of chert with thick horizons of white chalk that is in excess of 200 m thick (Powell, 1989). A pronounced erosional unconformity truncates its top and marks the contact with the overlying Oligocene conglomerates (Abed, 2000).

Late Oligocene-Miocene sediments consist of reddish conglomerates, calcarenites, and minor calcilutites. These facies are arranged in four major cycles superimposed on many smaller cycles. The thickness is around 250 m.

Neogene volcanism is exposed in north, northeast and central Jordan. It forms part of the regional continental volcanic province "North Arabian Volcanic" which extends from Syria in the north to Saudi Arabia in the south crossing Jordan and covers an area of about 11,000 km² (Bender, 1974, Ibrahim, 1993). The rocks of these volcanic outcrops belong to the Alkali Olivine Basalt series. Based on recent K-Ar dating, the volcanics of northeast Jordan have been subdivided into three major volcanic phases; 1) 22-26 Ma, 2) 12-8 Ma and 3) 6-< 0.5 Ma (Tarawneh, *et. al*., 2000).

QUATERNARY SEDIMENTS

Quaternary sediments cover broad areas in Jordan. Poorly sorted fluvial and lacustrine Pleistocene sediments overlie the older rocks. The sediments are very thick in the Rift Valley. Lacustrine, alluvial fans, alluvium and wadi sediments, Aeolian sand, sand dunes, mudflats, calcrete and soil cover broad areas of Jordan.

1.1.5. REGIONAL STRUCTURAL SETTING

Jordan has remarkable tectonics for its distinctive geological setting in the northwestern portion of the present Arabian Plate, which is separated from the African plate by the Dead Sea Transform (DST). The DST forms the western border of Jordan (Figure 1-39).

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Consequently, the DST is considered to be the major obvious tectonic feature that affected the overall tectonic setting of Jordan.

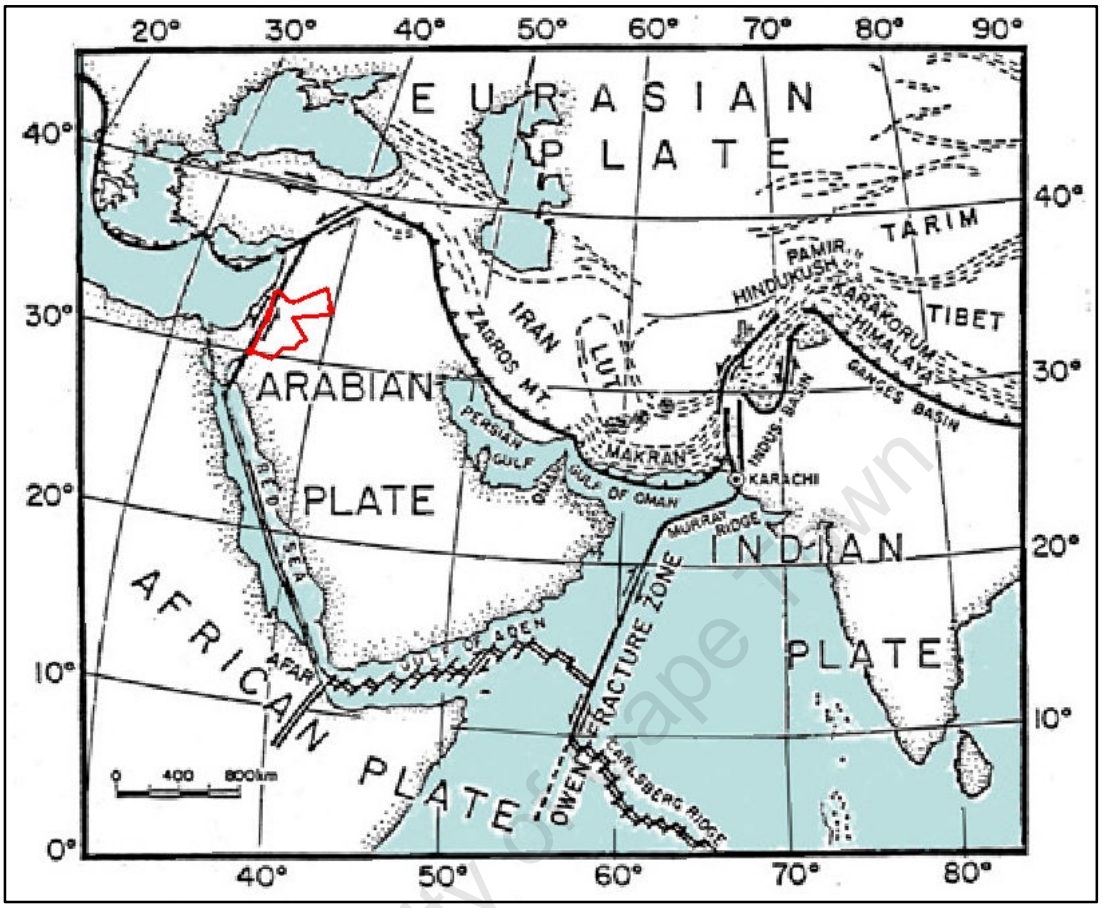

Figure 1-39: Regional structural setting of Jordan, modified after NASA; http://eol.jsc.nasa.gov 2008

A comprehensive structural study carried out by Beicip in 1981 and 1976 showed that Jordan is formed by two main geologic units; each is characterized by different structural features; the Dead Sea Transform Fault (DST) region and the Jordan Platform. The Jordan Platform consists of two parts; the western part along the DST which comprises an elongated hinge zone along the west margins and a Plateau unit to the east. This conforms to Bender's geological subdivisions.

He subdivided Jordan into four major physiographic structural provinces (Figure 1-40). This subdivision was based on structural evolution, type of deformation, and pattern. Those provinces are (Figure 1-40):

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(1) The Wadi al Araba-Jordan Rift (Dead Sea Transform); is a narrow depression that extends from the Gulf of Aqaba for approximately 360 Km north to Lake Tiberias; it is part of the East African-Asia Rift System

(2) The Nubo-Arabian Shield in southern Jordan or the Southern Mountainous Desert; it occupies the area south of west-northwest striking escarpment of Ra's an Naqab and extends southward into Saudi Arabia.

(3) Block Faults in Central and Southeastern Jordan; it is bordered on the west by slopes that rise westward to the Mountainous Ridge province; in the north and in the east, the Central Plateau falls to the flat, wide southeast striking Al Azraq-Wadi as Sirhan Basin, which includes the oasis of Al Azraq in its northeastern part., and

(4) The Up Warping, Tilting, and Block Faulting in Northern Jordan, and the Anticlinorium, Up Warping, Blocks Faulting West of The Jordan River; it is a coherent physiographic feature, in spite of its varied geologic character. It stretches north-northeast to north about 370 Km from the Gulf of Aqaba for approximately 360 Km north to Lake Tiberias. In General it slopes gently towards the Central Plateau in the east, whereas it slopes very steeply towards the Rift province in the west

1.1.5.1. MAJOR DEFORMATIONAL PHASES IN THE REGION

Burdon, 1959; Quenelle, 1956; and Bender, 1975 categorized the main structural events, which took place during the structural evolution of Jordan into: (1) normal and lateral movements in the DST, associated with an important subsidence and (2) rejuvenation and readjustments of large fault blocks on the Jordan Platform, which have had compressive or tensile effects. In addition, Quenelle, 1959; Beydoun, 1977; and Isa, 1991 addressed a presence of three major deformational phases in the region which are mainly formed the present structural setting of the country:

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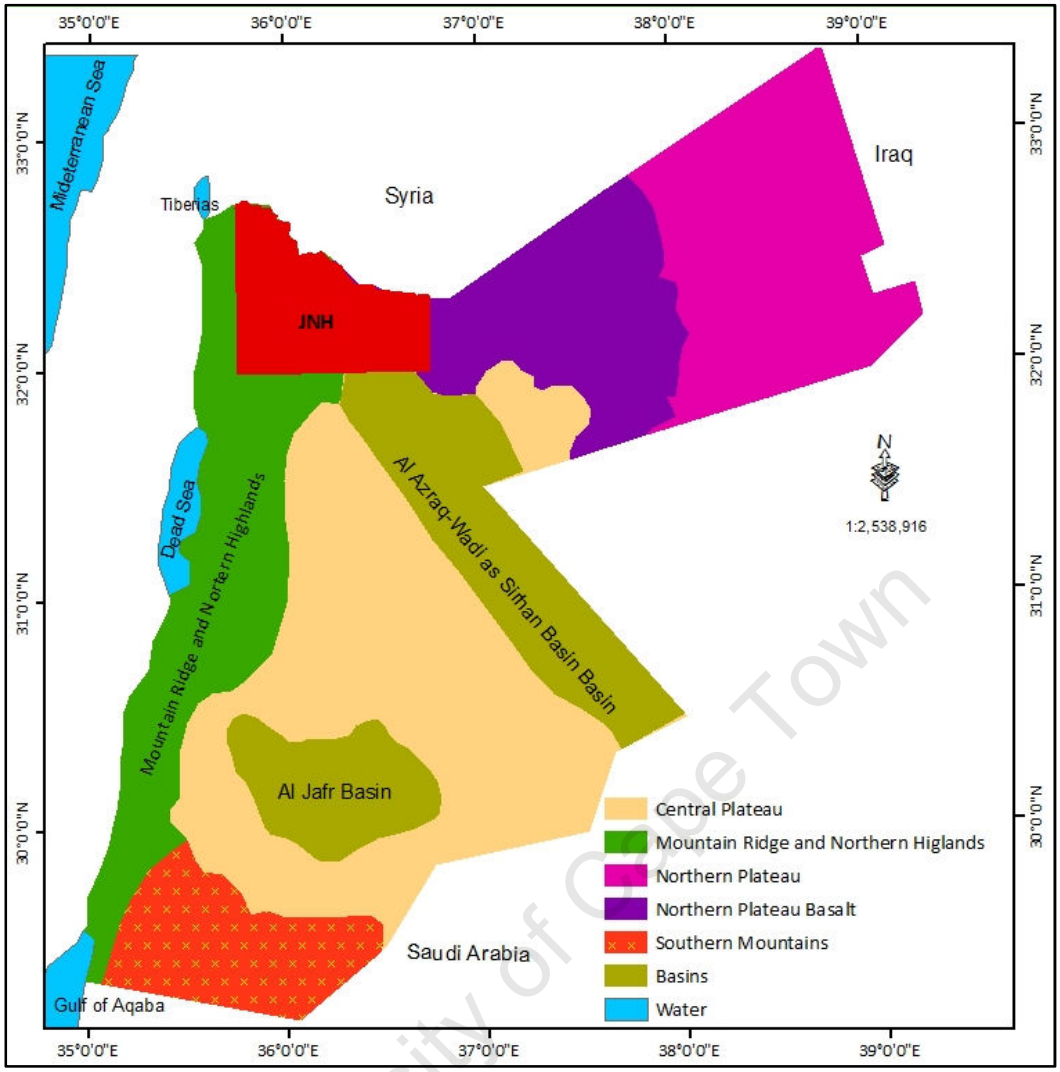

Figure 1-40: Physiographic structural provinces of Jordan, modified after Bender 1975

THE FOLDING EPISODE ALONG THE SYRIAN ARC; THE OLDEST

A system of en-echelon arranged , NNE and NNE oriented fold-thrust structures extends in S-shaped belt runs from central Syria (Palmyra Fold Belt), through Jordan to the Levantine Fold Belt, forming a series of anticlines and synclines, most asymmetrical and faulted locally by normal and strike-slip faults (Figure1-41). The development of this belt, known as the Syrian Arc System, is controversial and several models have been suggested to explain the mechanism of its formation (El Motaal *et al*., 2003).

Tectonic evolution of the fold-thrust belt seems to have passed through an extensional tectonic style followed by contractional tectonics. The extensional style coincided with the

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global opening of the Neo-Tethys and comprises Late Permian-Early Triassic initial rift, early Middle Triassic extensional rift, late Middle Triassic quiescent rift, Late Triassic thermal subsidence and Jurassic- Early Cretaceous rejuvenated rift stages. Major angular unconformities separate these stages from each other. The main pattern of the extensional tectonic style is half grabens rotating in a clockwise direction along NE (in Farafra-Sinai and Palmyra) and NNE (in Levant) oriented listric normal faults. This structural framework is responsible for the S-shape of the study belt. The half grabens are transversely broken by NW oriented right-lateral wrench transfer fault zones. The contractional tectonic style coincided with the Late Cretaceous closing of the Neo-Tethys and the convergence of The African-Arabian plate with the Eurasian plate. The new NNW oriented compressive stress led to a reverse rotation of the pre-existing fault blocks along the NE oriented listric faults and to a tectonic inversion of the rift basin. This rotation caused flexuring of the strata forming a number of anticlines with their southeastern limbs much steeper than the northwestern ones. Reverse and/or thrust faults are often associated with the steep limbs of the anticlines. The underlying fault blocks govern the orientation, areal distribution and the size of these structures. The separation of the Arabian plate from Africa that initiated in Oligo-Miocene time through the Red Sea rift enhanced the intensity of folding and thrusting of the study belt. More shortening and left-lateral offs*et al*ong the almost N-S oriented Dead Sea transform fault began in the Miocene and is still active at present (El Motaal *et al*., 2003).

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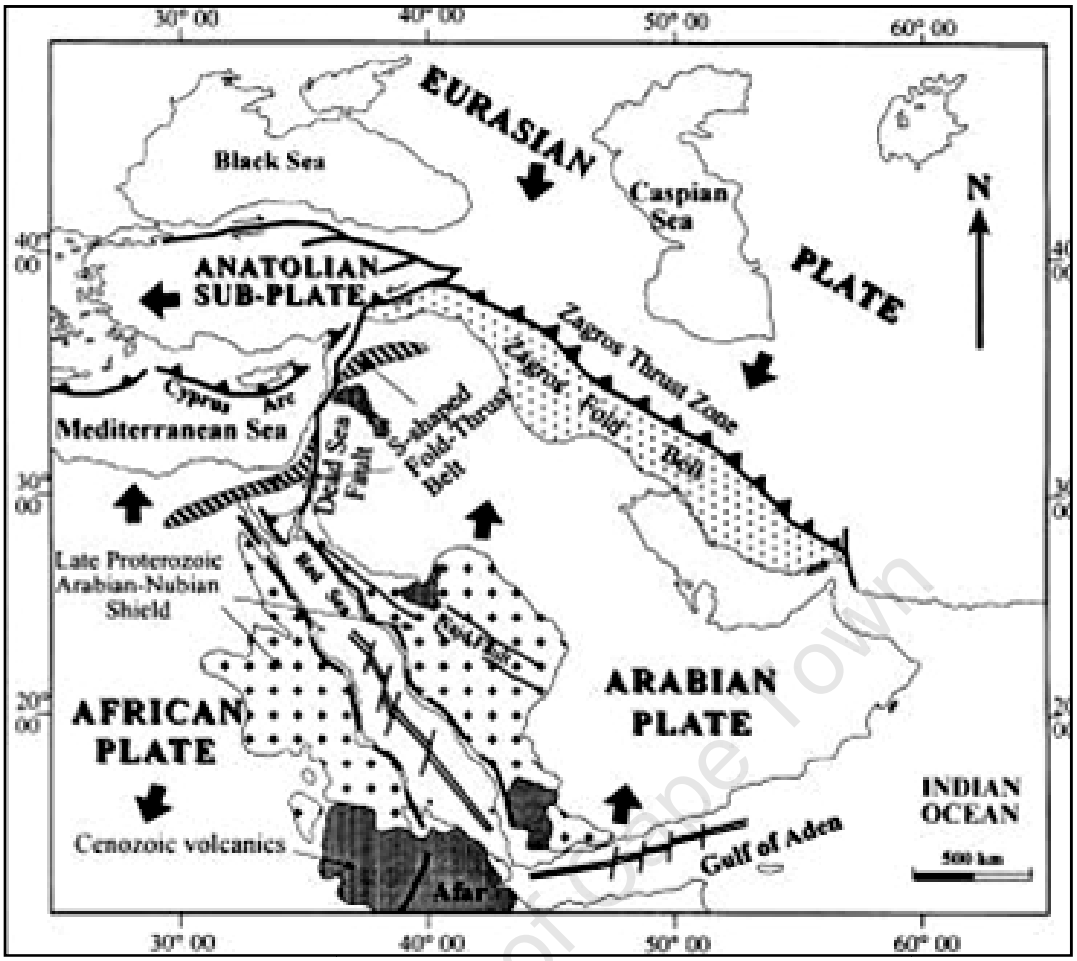

Figure 1-41: Structural mao showing the extension of the S-Shaped Syrian Arc element , modified after El Motaal *et al*., 2003

THE ERYTHREAN FAULT SYSTEM PHASE

The Erythrean Fault System Phase extends over hundreds of kilometers parallel to the Red Sea with normal and strike slip faults striking northwest-southeast and east-west. It was formed during the Late Miocene-Early Pliocene. It is mainly characterized by large Quaternary Basaltic flows.

THE DEAD SEA TRANSFORM PHASE

The DST was formed in the Cenozoic because of the break-up of the Arabian Plate from the African Plate (Rothstein and Garfunkel, 1983; and Basha and Mikbel, 1983, 1986). It is characterized by large strike-slip faults that are arranged en echelon, which contributed to the formation of pull- apart basins along the trend of the main fault (Quenelle, 1959). About

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107 km of left-lateral motion has occurred along the transform since Post Cretaceous time (Quenelle, 1958, 1959; Freund *et al*, 1970; Garfunkel, 1981; Quenelle, 1984; Walley, 1988; and Girdler, 1990). The main feature formed by this movement is the Dead Sea Transform. The development of the structures on both flanks of the DST resulted from a northward anticlockwise rotational movement of the Arabian Plate which occurred in several phases during Post Cretaceous to Pleistocene times (Freund, 1965). Mikbel and Atallah, 1983; Mikbel and Zacher, 1984; and Mikbel, 1985 suggested that the eastern flank of the DST in the Jordan region is totally controlled by this movement as expressed by landslides, local earthquakes and rock movements.

1.1.5.2. MAJOR STRUCTURAL FEATURES IN JORDAN AND VICINITY

THE DEAD SEA TRANSFORM (DST)

The most obvious structural feature in the region of the Middle East in General and Jordan in particular is the DST (Quenelle, 1958; and Garfunkel, 1981). It forms the southern part of a major system that extends approximately 1100 km northward linking the Red Sea, where crustal spreading occurs, along Wadi Araba, the Dead Sea, the Jordan Valley, Lake Tiberias, and Lebanon toward the Taurus Mountains in Turkey. The southern section between the Gulf of Aqaba and the Red Sea is trending toward the north-northeast, but toward the Lebanese border the trend swings to the north on a global scale. The DST is part of the continental boundary between the African Plate and the Arabian Plate which probably started formation during the Pliocene-Late Miocene because of interactions between several stresses. These stresses may be linked to the opening of the Red Sea during the Late Cretaceous (Quenelle, 1959; Beydoun, 1977; Bayer, 1988; Ginat *et al*., 1988; Girdler, 1989; Ben Avraham and Ten Brink, 1989; Mart, 1990) and the left lateral motion between the Arabian Plate and the Sinai sub-plate.

Horizontal and vertical movement along the DST caused the development of the deep Dead Sea Basin and uplift of the Arabian Plateau. The above mentioned movement is believed to have taken place during two phases (Quenelle, 1959; Beydoun, 1977; and Dewy and Sengor, 1979):

The first phase; horizontal displacement of about 62 km (strike-slip) on the west Arabian transform and uplift of the Arabian Platform during the Lower Miocene (Quenelle, 1959;

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Freund, 1970; and Bayer *et al*., 1989). This slip movement to the northern margin of the Arabian Plate and the Sinai sub-plate was hived off. In the Late Neogene, the Syrian Platform was forced eastwards with dextral shear acting on the Lebanon Palmyra Fold Belt with uplift and faulting, which produced the tectonic landform of the Lebanon Palmyra Belt and the Arch uplift of Judean and Northern Jordan. During the second phase of movement, a horizontal displacement of about 45 km during the Pliocene-Pleistocene occurred (Quenelle, 1983, 1985; and Bayer *et al*., 1989).

Thickness and facies changes in Triassic, Jurassic, Cretaceous and Lower Tertiary rocks on both flanks of the transform in the Jordan vicinity, indicate continued structural influence of the DST. Estimates of the slip rate along the Transform vary between 10 and 1mm/year (Garfunkel *et al*., 1981; Justin *et al*., 1994; and Ginat *et al*, 1998). A study of the slumped sediments of the Jordan River delta in the Dead Sea, produced evidence that the earthquake in Jericho in 1927 was caused by rupture of a fault segment beneath the northern basin of the Dead Sea (Niemi and Ben Avraham, 1994).

The DST is associated with a series of offset, overlapping, left lateral transform faults with a series of tensional rhomb-shaped grabens (Mart, 1990, Girdler, 1989, and Garfunkel *et al*., 1981) associated with stepping of sinistral strike-slip fault zone. These rhomb-grabens are recognizable now as the Gulf of Aqaba, the Dead Sea, possibly Lake Tiberias and the Hula Depression near the Lebanese border. The major fractures associated with the rift trend north-south, with north-west transverse faults and east-west faults resulting from a regime of transpressional stresses directed initially east south east-west North West (Mikbel and Zacher, 1981, and Quenelle, 1956). This led to a deformation process in the region throughout geologic time (Mikbel, 1986).

On both sides of the DST there are two broad northward plunging Arcs, belonging to the Syrian Arc System, or the belt of folded structures known as the Levantines. To the east, the Jordanian Arc and the Judean Arc (Filon, 1975; Beicip, 1976; and Trollinger, 1981), both are asymmetrical inward toward the rift; however, the structural aspects of the two arcs are quite different

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THE JORDANIAN ARC

Another significant structural feature, which influences the tectonic setting of Jordan is the Jordanian Arc, which is part of the up warping, tilting block faulting province.

The Jordanian Arc is defined as a regional structure that generally plunges northward and forming a complex faulted anticline trend characterized by a gentle eastern flank and a steep, complex western flank formed by faults and flexures along the eastern limb of the Transform.

The northern part of the Arc is known as the Northern Highlands Region which comprises the study area. South of the Northern Highlands Region, the Jordanian Arc is represented by a number of irregular trending anticlines, often aligned en echelon toward the northeast and separated by block faults and other fault associated structures. To the south of Jordan, near the Nubian-Arabian Shield, the axis of the Arc is paralleled by numerous long, north-northeast trending faults associated with the dominant rift movements. Regional structures in central and southeast Jordan are associated with broad epeirogenic swells and basins, which dominantly strike northwest and west-northwest such as the Al Jafr basin, Al Azraq, and the As Sirhan depressions (Beicip, 1976). The pattern of faulting along the east-west axis suggests a possible dextral (right-lateral-transcurrent) movement such as that found in the Zarqa River, Swaqa, and the Zakimat al Hisa faults (Figure 1-42)

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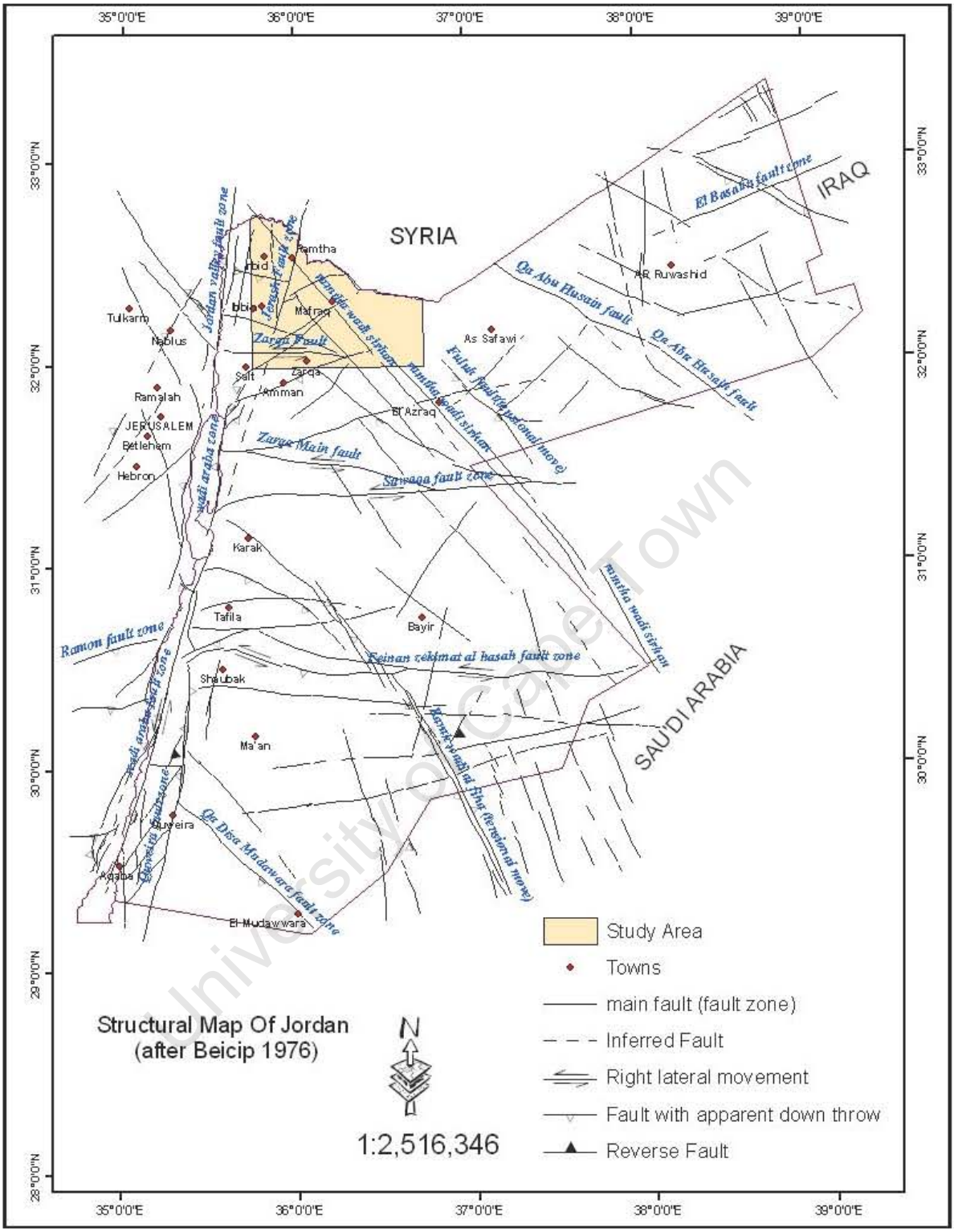

Figure 1-42: Major structural setting of Jordan after Beicip, 1976

1.2. RESEARCH OUTLINES

1.2.1. OBJECTIVES

The JNH area represents one of the key locations for the study of the influence of compression and extensional tectonics along the Dead Sea Transform (DST) in Jordan. The distinctive geological setting of the JNH is manifested by the presence of different structural styles-strike slip movements, intense deformation, and Syn-sedimentary folding and faulting. A considerable number of geological studies have already been conducted by previous researchers on this area, beginning in the seventies. The surface geology was studied by different means in order to define the structural style and its relation to the subsurface. However, integration and analysis using modern technology such as Geographic Information Systems (GIS) to identify the structural setting has not yet been applied.

As a result, this study has the potential to generate an analyzed structural framework that will lead to better understanding of the deformational styles in the study area. This certainly will convey a new regional geological vision for Jordan and its vicinity. To achieve the main goal, an integrated geological and geophysical analysis was combined together with a compilation of other published data utilizing modern Geographic Information technology (GIS).

To generate an analyzed structural framework, the work focuses on the following objectives:

1 Definition of dominant structural styles in the JNH: such as the main structural elements, basins and highs, deformation development throughout geologic time, origin, patterns, and trends.

2 Inference of the structural setup and its tectonic significance

3 Identification of the influence of the Dead Sea Transform on the geological setting of the JNH area

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1.2.2. DATA SETS

A bundle of surface and subsurface geological data were utilized for interpretation and analysis, the following is a brief description of the used information:

1.2.2.1. SEISMIC DATA

The Natural Resources Authority of Jordan (NRA) provided the research with a set of 2D seismic reflection profiles. This set consists of 15 migrated seismic profiles, which were selected from among 30 for their degree of quality and distribution across the area under consideration. However, none of these profiles was available in digital format. The selected profiles were collected by the Iraq National Company in 1984 and GSI-Cairo in 1986. Almost all the profiles are located in the eastern part of the study area and are about 270 km in length.

1.2.2.2. AERO MAGNETIC DATA

The data used in this study is part of a total Aero magnetic field data survey of Jordan which was carried out by the Phoenix Corporation in 1979.

1.2.2.3. GRAVITY DATA

The Natural Resources Authority collected the gravity data between May 1990 and April 1991 from 1500 gravity stations in northern Jordan (the Ajlun area)

1.2.2.4. GEOLOGICAL DATA

A set of various geological maps was utilized for surface geologic interpretation:

10 Geological maps (1:50,000), a recent survey by the NRA conducted between 1993-2004; Az Zarqa', Al Hababiya, Qasr Al Hallabat, Irbid, Jarash, Al Mafraq, Suwelih, Er Ramtha, Um Qutein, and Um Jimal.

Geological Map of Jordan by F. Bender, 1968 (1:500,000).

Structural Map of Jordan by Beicip, 1975 (1:750,000).

Preliminary Geological Map of Northwest Jordan (1:100,000) by Abdelhamid, *et al*., 1991.

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Geomorphic-Geologic Map of Jordan by Trollinger, 1981 (1:750,000).

1.2.2.5. TOPOGRAPHIC DATA

Ten Topographical maps (1:50,000) were utilized to produce a Digital Elevation Model (DEM). The DEM was used for surface structural analysis.

1.2.2.6. BOREHOLE DATA

The study used data from six boreholes, which were drilled for the purpose of oil exploration in the Northern Highlands Block in Jordan: NH-2 (1987), NH-1 (1987), SW-1 (1959), S-90 (1970), KH-1 (1971), and ER-1A (1970). In addition, another borehole from southern Syria was used for correlation with the previous boreholes. This borehole, Busra-1, was drilled in 1995.

SEISMICITY Data

Seismicity data from earthquakes that took place in the region during the period 1903-2003 by the National Jordanian Observatory at the Natural Resources Authority.

1.2.3. SCOPE OF WORK: METHODOLOGY

To achieve the main goal, an integrated geological and geophysical analysis was combined together with a compilation of other published data utilizing modern Geographic Information technology (GIS).

Inferring the structural setting of the area and its tectonic significance, manifested the need to design a peculiar approach for interpretation, integration, and analysis of the various data sets mentioned in previous section. This approach involves data collection, pre-processing, interpretation, integration, and analysis techniques respectively. The adopted techniques are as a result of the experience of existed geological studies in similar objectives; section 1.1.2. Kumar *et al*. in 2010 conducted a study for hydrocarbon exploration in Yemen; the study adopted an approach of integration of surface and subsurface data using GIS and Remote Sensing techniques. In addition to that, several studies such as but not limited to that used similar approach and achieved remarkable results in understanding the geological

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setting were referred to : Jurkun A. and Zielke J a and b., 1995; Zouaghi *et al*., 2005; and Tearpock *et al*., 2002. Waldemar *et al*., 1996

For data interpretation the researcher referred, mainly , to the several text books such as : Basin analysis and seismic stratigraphy after Fisher *et al.,* 1983; and Earth structure after van der Pluijm *et al*., 1997; Computer modeling of geologic surfaces and volumes after AAPG, 1992; Understanding GIS after ESRI, 2005.

Geographic Information Systems technology (GIS) was used to prepare baseline information like geological maps, structural maps, and geological cross sections. These help in providing information on the regional geological settings of the study area (Kumar *et al*., 2010)

On the other hand, using sub-surface information like gravity, magnetic and 2D seismic data provide relative subsurface information for the sub-surface geological setting, when integrated with the surface geological and structural information, provides valuable information about the dominant structural style. Therefore, the approach focused on integration of GIS methodologies to geology which was related to previous studies (refer to section 1.1.2). This involves an integration of GIS software programs together with those which are capable of interpretation the subsurface. An easily accessible geo-database helps to store, categorize and access data in GIS environment. According to ESRI definition , ''A geo-database in GIS is composed of spatial locations and shapes of geographic features which are stored as points, lines, polygons, pixels etc as well as their attributes'' (Zhou *et al*. 2007).

Visualization of geological structures is a very efficient way to create a good understanding of geological features. It is not only an illustrative way for common people, but also a comprehensive method to interpret results of the work. Geologists, geophysics engineers and GIS experts sometimes need to visualize an area to accomplish their researches. It can show how sample data are distributed over the area and therefore they can be applied as suitable approach to validate the result. (Tavakoli, 2008).

For JNH, three main steps to identify the structural style and its relevant to the regional setting are developed. Starting from data collection from the available various resources, an appropriate geospatial database for geological data is developed and finally generation of geological base line maps to cover both surface and subsurface created to visualize the

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characteristics of the JNH setting. Following the three steps of methodology, interpretation of results will take place. Tables 1-1 and 1-2 briefly visualizes the systematic approach of interpretation and integration of the data sets.

Implementation of these tasks required special software. As a result, ARC GIS, ERDAS IMAGINE 8.7, Surfer V8, GRAVCADW, and AutoCAD 2000 were used. Geo-spatial database was constructed.

Existing surface geological maps were utilized to produce a geological base map for the area under consideration to clarify its geologic setting in terms of major stratigraphic sequences and dominant surface structural elements. A qualitative and quantitative interpretative approach was carried out for a corrected Bouguer anomaly map in order to delineate the major structural framework and depth to the basement across the area. Study of the available borehole data provided much insight into the subsurface stratigraphic distribution and the structural style of the study area.

A set of fifteen 2D time-migrated seismic reflection profiles was used, on which five marker horizons were identified: Top of the Paleozoic, Top of the Triassic, Top of the Jurassic, Top of the Lower Cretaceous, and Top of the Cenomanian. Scarcity of deep boreholes that penetrated the Precambrian rocks and insufficient seismic coverage across the study area made identification of the top of the Precambrian difficult. Therefore, it was discarded from the interpretation to avoid ambiguity. In addition, seismicity of the area was taken into consideration. The results of interpretations for all available data sets and known studies were correlated to understand the dominant structural style and the stratigraphic distribution of the area.

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Table 1-1 Sub-Surface Geological studies which were adopted

Data Set	Pre-Interpretation Operations	Interpretation Operations	Output
Seismic	(1) Picking marker horizons. (2) Produce time and velocity maps (3) Generate depth maps (3) Generate structural	(1) Identification of structural elements. (2) Identification of stratigraphic setting; thinning, thickening, dips…etc (3) Correlation with all	(1) Spatial structural analysis maps (2) Stratigraphic distribution trends in terms of age and thickness
Gravity & Aeromagnetic	(1) Produce Bouguer and Aeromagnetic anomaly maps. (2) Preliminary investigation of the Bouguer and Aeromagnetic anomaly maps	(1) Qualitative and quantitative interpretation (2) Delineation structural elements (3) Correlation	(1) Structural framework maps for deep elements. (2) Depth to basement map (3) Dominant structural trends
Seismicity	(1) Generate earthquake events maps for the region as well as study area	(1) Study seismicity activity (2) Correlation with the structural maps produced from surface and	(1) Analyzed seismicity maps (2) Magnitude versus time of reporting events
Boreholes logs	(1) Definition the tops of the main of stratigraphic units (2) Set data base for the stratigraphic model (2) Develop stratigraphic and structural correlation	(1) Generate thickness distribution maps for the marker horizons (2) Study vertical and horizontal stratigraphic distribution (3) Correlation with other	(1) Structural and stratigraphic correlation profiles (2) 3D stratigraphic model

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Table 1-2 Surface Geological studies which were adopted

Data Set	Pre-Interpretation Operations	Interpretation Operations	Output
Geological Maps	(1) Digitization (2)Registration with attribute	(1) Identification of surface structural setting; major trends, dip …etc (2) Identification of stratigraphic setting (3) Generate geologic cross Sections (4) Correlation with sub-surface geological data	(1)Modified surface geological map (2) Cross sections
Topographic Maps	(1) Digitization the topographic maps (2) Generate DEM	(1) Definition the main terrain units (2) Generate topographic profiles (3) Correlation with surface and sub-surface geological data	(1) Topographic terrain map illustrating relation to the surface and subsurface geology

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2. GEOPHYSICAL INTERPRETATION AND STRUCTURAL ANALYSIS

ABSTRACT

A scientific interpretation approach based on the integration of various data sets (surface and subsurface geological data) as well as geophysical data was adopted to enable the extraction of the existing spatial relations among these data sets. Accordingly, the interpretation involved three systematic tasks: Pre-interpretation, interpretation, Integration, and Analysis. Pre-interpretation included digitization of all data sets, the construction of a GIS database, and extraction of relevant spatial maps. Interpretation of geophysical data, integration and analysis involved a correlation between the various data sources and, finally, the generation of the structural framework of the study area.

Implementation of these tasks required special software. As a result, ARC GIS, ERDAS IMAGINE 8.7, Surfer V8, GRAVCADW, and AutoCAD 2000 were used. Geo-spatial database was constructed.

Existing surface geological maps were utilized to produce a geological base map for the area under consideration to clarify its geologic setting in terms of major stratigraphic sequences and dominant surface structural elements. A qualitative and quantitative interpretative approach was carried out for a corrected Bouguer anomaly map in order to delineate the major structural framework and depth to the basement across the area. Study of the available borehole data provided much insight into the subsurface stratigraphic distribution and the structural style of the study area.

A set of fifteen 2D time-migrated seismic reflection profiles was used, on which five marker horizons were identified: Top of the Paleozoic, Top of the Triassic, Top of the Jurassic, Top of the Lower Cretaceous, and Top of the Cenomanian. Scarcity of deep boreholes that penetrated the Precambrian rocks and insufficient seismic coverage across the study area made identification of the top of the Precambrian difficult. Therefore, it was discarded from the interpretation to avoid ambiguity. In addition, seismicity of the area was taken into consideration. The results of interpretations for all available data sets and known studies were correlated to understand the dominant structural style and the stratigraphic distribution of the area.

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The resulting analysis revealed significant variations in the thickness and the regional dip of the rock sequences and significant structural style that dominate the area. The majority of the rocks cropping out are of sedimentary origin ranging from Jurassic to Quaternary ages. Basalt flows of Tertiary and Quaternary ages are abundant in the east, and southeast. A considerable thickening of the Mesozoic sedimentary cover toward the north, northeast, east, and southeast is noticeable. Regional dip is toward the north, northeast, east, and southeast.

The integration of all results shows that complex fault zones and series of fold belts prevail over the area. It is obvious that there are three major faulting systems of normal type that dominate the area; NW-SE, NE-SW, and appear as intersected with E-W and N-S faults. General throw of the NW-SE faults orients eastward, while for those of NE-SW trend, throw is southeastwards in the southeastern parts and northward in the northern parts of the area. E-W segments present northward throw. In addition, significant depressions and highs mark the structural style. Depths to the basement across the western parts of the area are shallower than those across the north, northeastern, east, and southeastern parts

The seismicity information of the study area show that the majority of events located in the study area were of magnitudes ranging between 1ML to 3.9ML.

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2.1. GEOLOGY

The use of the available surface geological data assists in the analysis of the stratigraphic and structural setting of the JNH area. This involved digitizing, edge matching, editing, and spatial adjustment processes of 10 geological maps of scale 1:50,000; Suwelih, Jarash, Al Mafraq, Umm Al Jimal, Irbid, Al Ramtha, Zarqa, Qasr el Hallabat, Umm el Qutein, and Al Hamada in order to create a comprehensive geological (GIS) database. The aforesaid maps, among others, are part of the National Geological Mapping Project for Jordan, which has been carried out by the Natural Resources Authority (NRA) of Jordan since 1985.

Further correlation with previous geological maps such as Beicip (1981, 1975) and Bender (1975) has been carried out to prepare a modified geological base map. In addition three geological cross sections (A-A', B-B', and C-C') were constructed.

2.1.1. GENERAL SURFACE STRATIGRAPHY AND LITHOLOGY

The majority of the rocks that are outcropping in the JNH area are of sedimentary origin ranging from Jurassic to Quaternary ages. Basalt flows of Tertiary and Quaternary ages are abundant to the east, and southeast parts. The upper Cretaceous and Tertiary sequences are overlain by alluvium and recent deposits across the north, northeast, and southeastern parts (Abdelhamid *et al*., 1993; Khalil, 1997; Sawariah *et al*., 1997 Tarawneh, 1996; Tarawneh *et al*., 2000; Qudaira, 2001; Suboh, 2003; Gharaibeh, 2003; and Al Hiyari, 2004). Figure 2-1 illustrates a Generalized Chronostratigraphic columnar section for the outcropping rock sequences in the JNH. The litho-stratigraphic subdivisions and nomenclature are related as follows: Tertiary and Cretaceous Formations are according to the Natural Resources Authority Petroleum nomenclature, while Jurassic and Triassic are according to Bandel and Khoury (1989) nomenclature.

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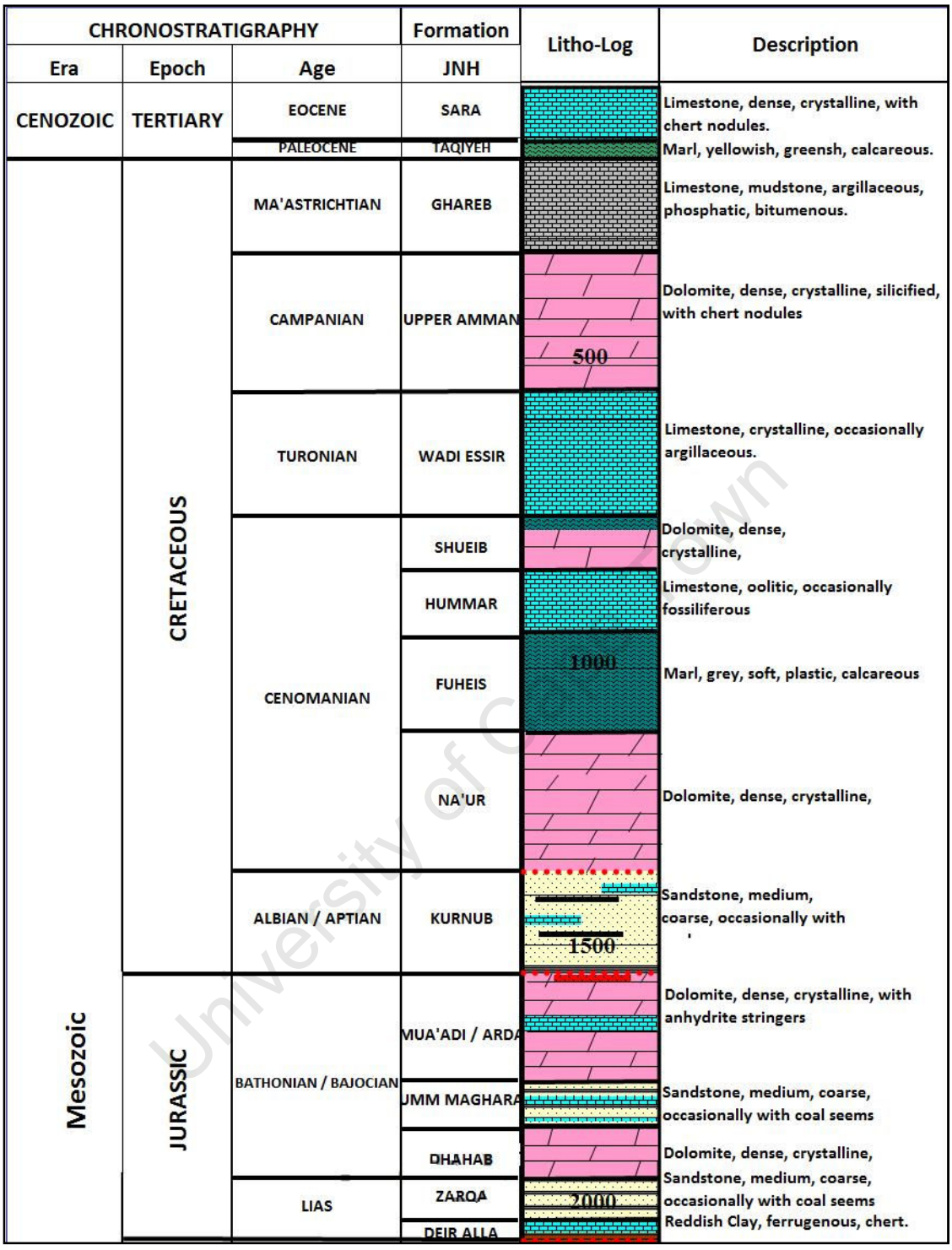

Figure 2-1 Generalized Chronostratigraphic columnar section for the JNH

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2.1.1.1. MESOZOIC ERA

THE JURASSIC PERIOD

The oldest outcropped rocks in the study area at outcrop belong to the Jurassic age (Figure 2-2). It is exposed along the Zarqa River with a total thickness of about 400m (Abdelhamid *et al*., 1991). It consists at the base of silty mudstones cut locally by sandstone, limestone, and dolomitic limestone, sandy and oolitic limestone intercalated with shale. The uppermost formation consists of thinly bedded fossiliferous micritic limestone and sand interbedded with greenish shale.

Most of the Jurassic succession in Jordan belongs to the Azab Group; it is exposed in the JNH a narrow belt extending from Wadi el Bassat in the south of Salt town in the Zarqa River. It is subdivided into six formations; Deir Alla, Zarqa, Dhahab, Umm Maghara, Maadi, and Arda (Abdelhamid *et al*., 1991).

The depositional environment of the Jurassic siliclastics was coasted with a continuously shifting shoreline. The Jurassic calcareous rocks are believed to have been deposited on a carbonate platform where intertidal to sub-tidal open marine regime prevailed.

THE CRETACEOUS PERIOD

Rock sequences of the lower Cretaceous belongs to the Kurnub (Alpian-Early Cenomanian) unconformably overlies the Jurassic sequence (Abdelhamid *et al*., 1991; Sawariah *et al*., 1997). This group of sequences comprises thicknesses of about 300-350 m (Batayneh *et al*., 1992; Abdelhamid et .al, 1993). In the vicinity of the Zarqa River, the base of this group overlies unconformably a Paleozoic horizon at top of the Jurassic sequence. It consists of Vari-colored sandstone interbedded with siltstone, shale, glauconite and clay stone (Abdelhamid *et al*, 1991; Abdelhamid, 1993).

The Kurnub Group facies indicates fluviatile deposition interrupted by short periods of marine regression.

Upper Cretaceous sequences belong to Ajlun Group which is up to about 500-600 m thick. It attests to a very well preserved and continuous marine transgression over the dominantly

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continental lower Cretaceous group. This resulted in the deposition of platform carbonates within lagoonal tidal and open marine environment. It consists of a sequence of alternating limestone and marl beds overlain by massive limestone, which forms an immense unit of nodular dolomitic limestone including chert nodules intercalated with limestone and marl (Khalil, 1997). The uppermost part of the Upper Cretaceous is characterized by a sequence of chalk, massive chalk; chert, marly limestone, and phosphate (Khalil, 1997).

Ajlun group of Cretaceous age is subdivided into five formations: Na'ur Limestone Formation; Lower Cenomanian, is 150-200m thick, The Fuheis Marl Limestone; Middle Cenomanian, Hummar Limestone Formation, Upper Cenomanian , Shueib Marl Formations; Cenomanian to Lower Turonian, and the Upper most part of Ajlun Group is Turonian in age; Wadi esSir Formation

Beds of Coniacian to Santonian-Eocene age represent the Belqa Group and cover most of the study area.

2.1.1.2. CENOZOIC ERA

THE TERTIARY SEDIMENTS

The Tertiary sediments consist of massive chalky limestone, chalky-marly limestone, chalk, fossiliferous sandy, glauconitic marls. The uppermost part of this sequence consists of gravels and conglomerates (Khalil, 1997).

Superficial deposits are differentiated into soil, calcrete, Pleistocene gravels, wadi sediments, mud flats, fluvial sediments, and conglomerate limestones (Khalil, 1997; Muneizil, 1993 and 2000; Abdelhamid, 1991). Pleistocene gravels and wadi sediments consist of poorly indurate sub-rounded to sub-angular clasts of limestone, chert, phosphate, and basalt (Smadi, 1997; Qudaira, 2001). Alluvium and mud flats are the most recent deposits, and conglomerate limestone. Conglomerate limestone belongs to the Sahm conglomerate limestone formation (Eyad, 1994). Towards the east and southeast in Azraq Area, alluvium and wadi sediments are floored the wadies while at the mouth of some wadies. Alluvial fans are developed (Khalil, 1993).

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2.1.1.3. VOLCANIC ROCKS

The majority of volcanic rocks the northeastern and east comprise a clastic continental basaltic succession which is part of the Harrat Ash-Sham Basaltic Super Group (Neogene-Quaternary age) that extends from Syria-Golan Heights and Jabel Ed Druze toward Saudi Arabia covering an area of 1200 Km² in Jordan (Tarawneh *et al*., 2000; Suboh, 2003). The basaltic flows erupted from different sources including fissure eruptive, feeder dykes and volcanic vents.

Boom and Swan in 1966 and Bender in 1968 recognized six eruptive phases; the oldest one in the area is of late Miocene age characterized by a hummocky, rough and blocky surface with porphyritic texture and micro vesicles that are filled with calcite (Gharaibeh, 2003). The youngest is of Pleistocene-Holocene age; Bishriyya Group (Tarawneh, 1996 and Gharaibeh, 2003). It is up to 20m thick, consisting of fine-grained basalt with aphanitic and clustered textures. Basaltic dykes are presented with NW-SE trend forming positive topographical features, linear ridges, and isolated hills (Gharaibeh, 2003).

Cover Basalts spread over the entire area of the Yarmouk River vicinity which is part of the Golan Heights to the utmost northwest corner. These basalts constitute the younger flows originated in southern Syria, and flowed through the Yarmouk gorge to the Rift Valley area (Basem, 2000)

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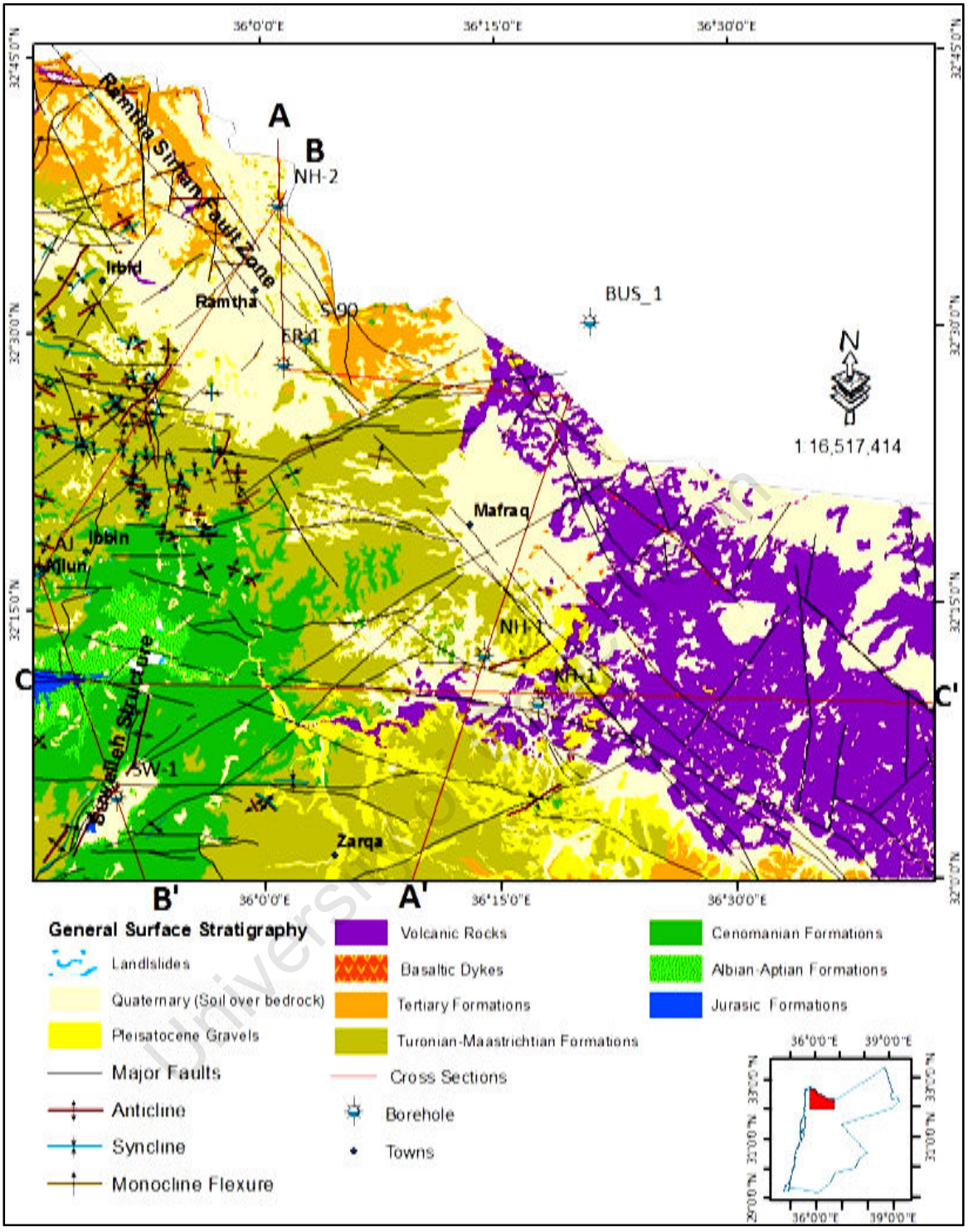
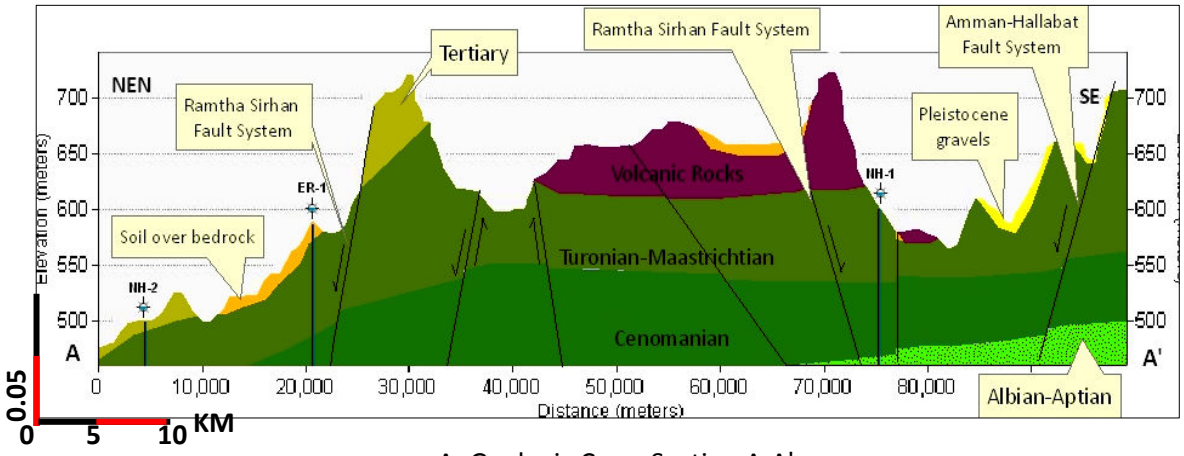
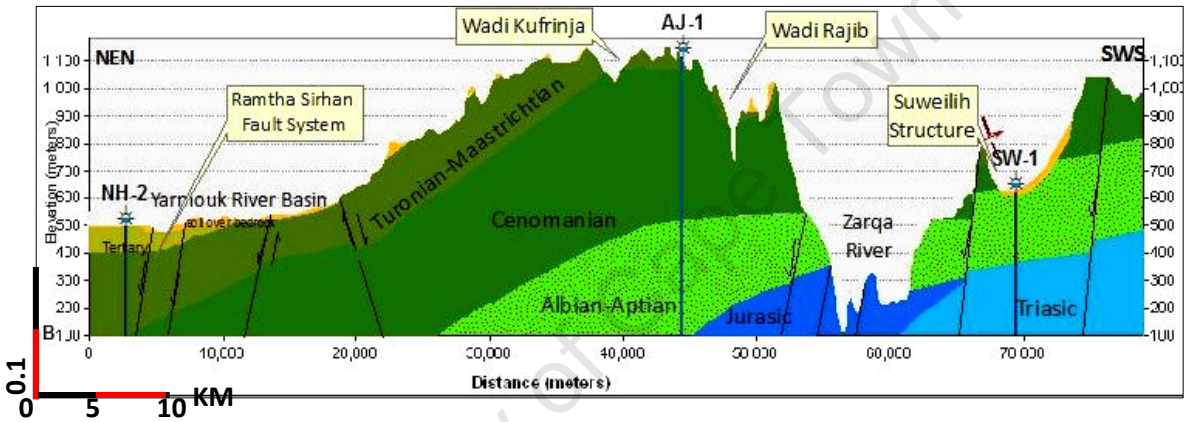


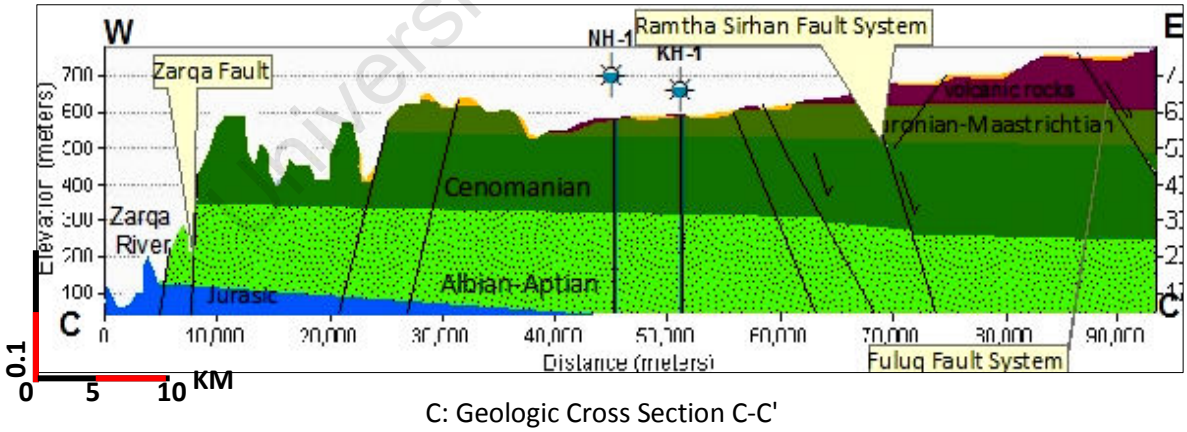
Figure 2-2 Geological base map of the JNH area with cross sections A-A', B-B' and C-C' modified from the 1:50,000 surface geological maps (Suwaylih, Jarash, Al Mafraq, Umm Al Jimal, Irbid, Al Ramtha, Zarqa, Qasr el Hallabat, Umm el Qutein, and Al Hamidiya) and Bender 1975



A: Geologic Cross Section A-A'



B: Geologic Cross Section B-B'



C: Geologic Cross Section C-C'

Figure 2-3: Geological cross sections A, B, and C; A-A', B-B', and C-C' (for legend see Figure 2-1)

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2.1.2. GENERAL SURFACE STRUCTURAL SETTING

The JNH study area is characterized by complex faulting zones which are mostly of N-S, E-W, NE-SW, and NW-SE trends. N-S, NNW, and NNE trends comprise a narrow zone adjacent to the Jordan Valley with a considerable down throw to the west forming step faulting systems (Figures 2-2)

ESE-WNW to E-W trend is restricted mainly to the central, southwestern, western and southern parts. The interpretation emphasized the presence of the Zarqa Fault system in the southern parts of the area. Beicip in 1981 stated that this is an E-W fault system of a lateral wrench type with northward down throw. It extends into the area for 60 km distance toward the east.

NW-SE trend dominates the area. It is characterized by a long extension accompanied by several secondary NE-SW faults that appear to be tension faults (Burdon, 1959 and Bender, 1975). The Ramtha Sirhan Fault system and the Fuluq Fault system are remarkable examples of the NW-SE trend. Ramtha Sirhan Fault system extends from Saudi Arabia into Jordan for more than 325 Km. it crosses most of the northern, northeastern and southeastern parts of the JNH. The Fuluq fault system is another NW-SE fault, which is formed of a zone of normal faults with a southwestward down throw and a possible strike slip movement (Tarawneh, 1996). Gharaibeh in 2003 described presence of basaltic dykes along the Fuluq Fault System and the Ramtha Sirhan Fault System to the southeast.

NE-SW structural elements are mainly of normal step faulting systems crossed by a series of tilted elements forming broad and narrow fold belts. Amman-Hallabat fold belt is a remarkable example for this trend in the JNH area.

Bender in 1975 described the JNH, as part of the up warping, tilting, and block faulting province in north Jordan. It is noticed that the majority of fold structures within the study area, are described as gentle, sub parallel, mostly narrow, and range in trend from ENE, NE to WNW which conform to the studies of Sawariah *et al*., 1997; Abdelhamid, 1993; and Khalil, 1997). In addition, several monoclines and flexures are mainly associated with major faults

The western parts of the area comprise a narrow zone of anticlines, synclines, and tilted blocks that are commonly delimited by flexures.

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A broad flat-topped anticline feature, known as the Ajlun Dome or the Anticlinorium, dominates the study area to the west and south west (Bender, 1968 and Trollinger, 1986). It extends ~80 Km in length (Trollinger, 1986). Ajlun Dome is considered to be the highest zone in the area; the Upper Cretaceous sediments over this feature reach a height of ~ 1247 m (Beicip, 1976). Jurassic and lower Cretaceous rocks are exposed in its core in the Wadi Zarqa River (Trollinger, 1986). The crest is localized near Ibbin town a few kilometers NE of Ajlun town, and ~45 Km NNW of Amman and strikes NNE for about 25 Km (Bender, 1975; Trollinger, 1986). It is highly faulted in its crest (Abdelhamid, 1993). Many local folds and faulted structures are superimposed on the Dome. Numerous faults associated with it exhibit various orientations such as E-W (Zarqa Fault) and NE (the Amman Fold Belt) among others. (Trollinger, 1986)

Suwaylih structure is a major anticline. It is located about 15 Km NW of Amman city (Filon, 1976 and Sawariah *et al*., 1993) and extends to the SW for about 15 Km. This structure rises gently from SE to NW and becomes ~4 Km wide before it dips steeply into the NW along a SW striking flexure accentuated by faults. It has a NE trending, strongly asymmetrical with a steep NW flank. Its western limb is steeply dipping to the west and locally overturned, but flattens out into the west in a short distance, whereas the eastern limb is gently dipping with angles 5º-15º to the east (Sawariah *et al*., 1997).

The northern extension of the NNNE-SSW deformation belt, which is called Wadi Shu'ayb structure, dominates Suwaylih structure. Wadi Shu'ayb structure consists of a series of en echelon folds, monoclonal flexures and faults (Mikbel and Zacher, 1981; Steen, 1987).

The General dip in the eastern parts of the area is to the east and northeast, while in the western parts, the dip gradually turns to the north, northwest, west, and southwest. The western margin of the study area is characterized by many flexures with high dip angles.

2.1.3. GENERAL SUBSURFACE STRATIGRAPHY

The analysis of the available borehole data provided much insight into the subsurface stratigraphic distribution across the study area. A stratigraphic and structural correlation was carried out between the wells NH-1, NH-2, ER-1A, SW-1, AJ-1, and BUS-1(Figure 2-3). KH-1 well was discarded from the correlation due to the uncertainty in the available information about it (Figure 2-4).

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BUS-1 well is an exploratory deep well drilled in 1995. It is located on the crest of Busra structure northwestern Busra Al Sham at about 17 Km (Ayed, 1996), and to the northeast of the study area. Rompetrol-Romania Company drilled NH-1 and NH-2 wells in 1987 to explore the hydrocarbon potential of the Triassic and the Jurassic accumulations (Rabi, 1987). NH-1 is located about 14 Km south of Al Mafraq town whereas NH-2 is at about 9 Km north of Ramtha town. ER-1A well is located at about 8 Km to the southeast of Ramtha town. Filon-Fuyo-Total group drilled this well in 1978 to explore the potential of the Triassic-Jurassic hydrocarbon accumulations (Nuweihed, 1982; GSI, 1985). NRA drilled the Ramtha well (S-90) in 1969 for groundwater and hydrocarbon exploration. It is located about 4 Km southeast of Ramtha town (Nuweihed, 1982; GSI, 1985). SW-1 well is located at about 23 Km southeast of Ajlun town. Phillips drilled this well in 1959 (Beicip, 1976; Rabi, 1987). Rompetrol-Romania Company drilled AJ-1 well in 1991 to explore the hydrocarbon potential of the Paleozoic and the Mesozoic sequence (Rabi, 1992).

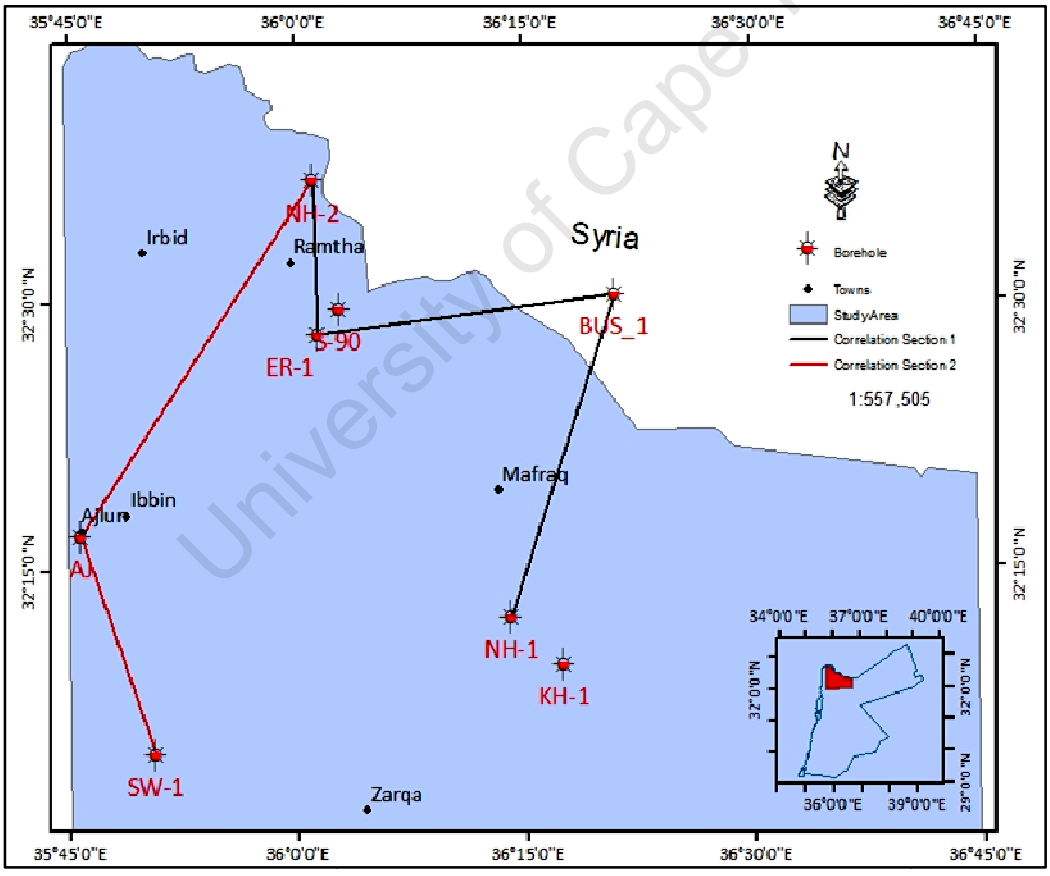

Figure 2-4: Location map of the stratigraphic and structural correlation cross sections between the key boreholes in the JNH area

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2.1.3.1. STRATIGRAPHIC CORRELATION

Two stratigraphic correlation cross sections were performed across the area of study; (1) Correlation cross section 1 between the NH-2, ER-1A, BUS-1, and NH-1 wells and (2) Correlation cross section 2 between the NH-2, AJ-1and SW-1 wells. Base Cretaceous Unconformity Surface (Albian-Aptian) was selected as the stratigraphic datum.

Stratigraphic correlation cross section 1 (Figure 2-5), clarifies the stratigraphic distribution across the study area and the Hauran Plateau (Southern Syria Desert) through a number of key boreholes; NH-2, ER-1, BUS-1, and NH-1 from the northeast toward the southeast regions.

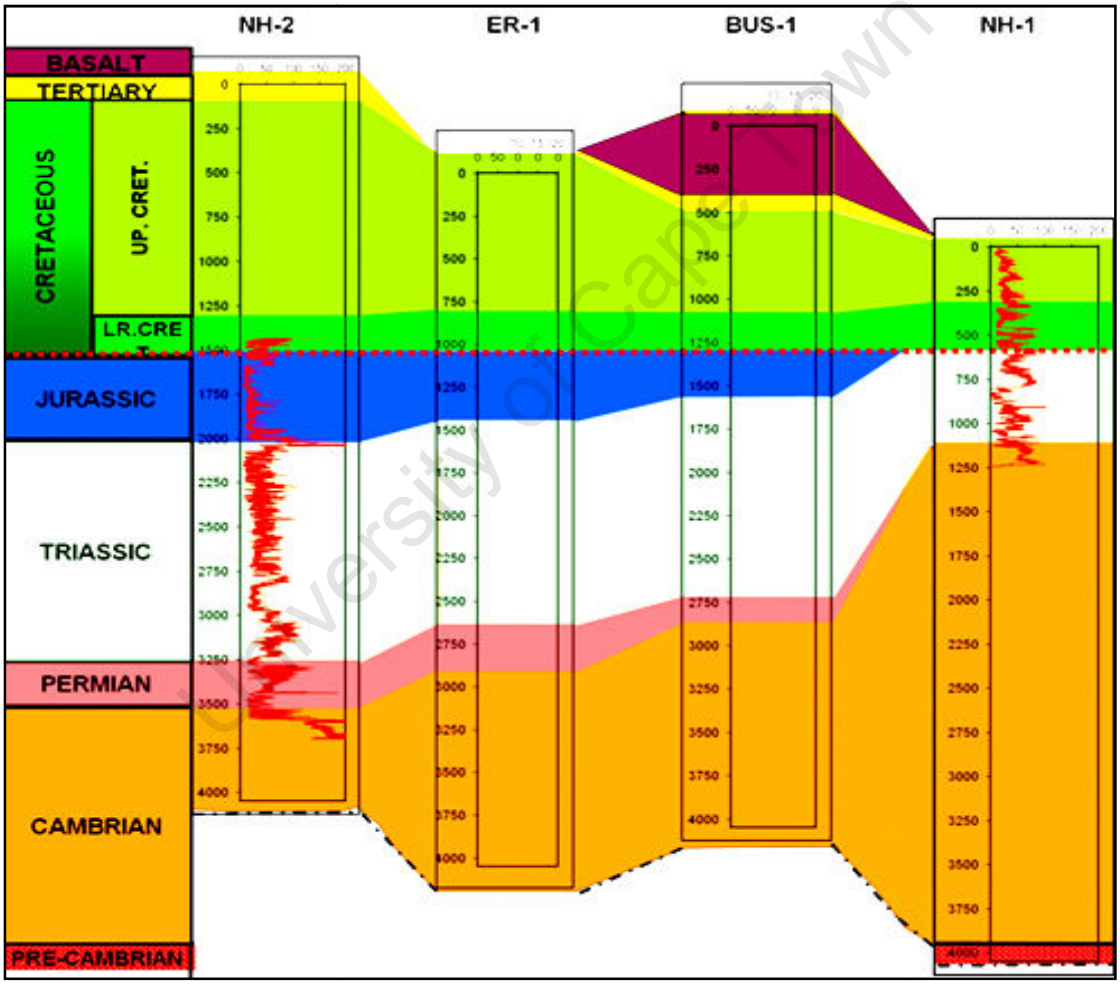

Figure 2-5: Stratigraphic correlation cross section 1 between NH-2, ER-1, BUS-1, and NH-1 boreholes. Vertical column represents the top of the stratigraphic unit in meteres and the gamma ray log

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Section in Figure 2-5 shows a significant thickening in the Paleozoic sequences (Cambrian) toward the southeast and an absence of the Jurassic and Permian sediments in this direction. Lower Cretaceous sediments show uniform thickness along the section from northeast toward southeast, however, a slight thinning in the northeast and slight thickening in the southeast are presented. Thinning in the Triassic, the Jurassic and the Upper Cretaceous sequences is noticeable in this direction in comparison to those toward the northeast. Tertiary sediments comprise the northeast parts as evidenced in the NH-2 log data. Basalt is only recognized in the BUS-1 borehole with a considerable thickness. Stratigraphic correlation cross section 2 (Figure 2-6) clarifies the stratigraphic distribution variation from the northeast toward the west and the southwest through NH-2, AJ-1, and SW-1 key wells.

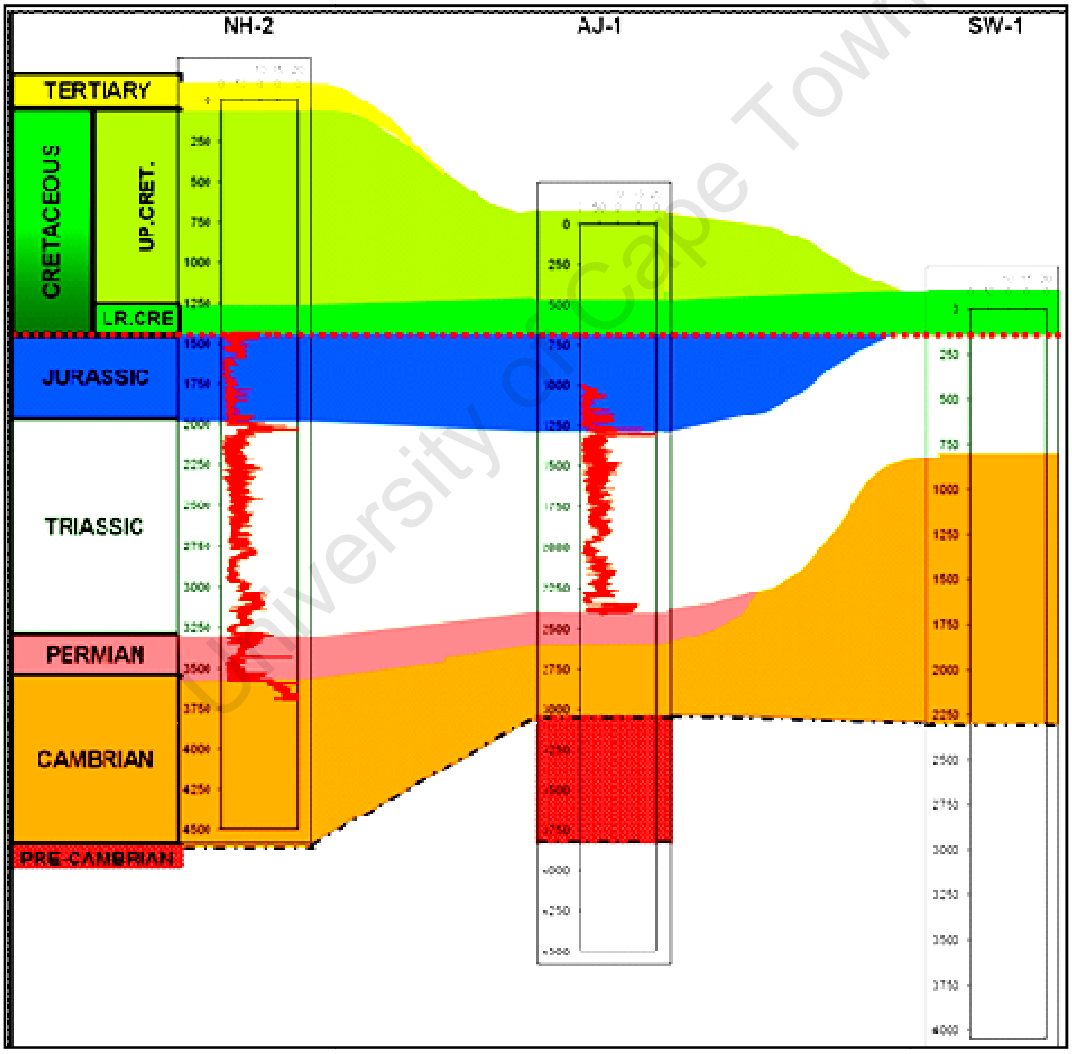

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Figure 2-6: Stratigraphic cross section 2 between NH-2, AJ-1, and SW-1 boreholes. Vertical column represents the top of the stratigraphic unit and gamma ray log

This section (Figure 2-5) exhibits the considerable thickness of the Cambrian sequences in the SW-1 well (southwest) and the absence of the Permian, Jurassic, Upper Cretaceous, and Tertiary. However, Lower Cretaceous sediments show a gradual increase in thickness compared to those in the northeast and in the west.

2.1.3.2. STRUCTURAL CORRELATION

Two structural correlation sections were performed between the aforesaid key wells. The correlation provided much clarification about the structural style of the area (Figures 2-7 and 2-8). The sections show that the lower Mesozoic sediments (Triassic-Jurassic) are overlain by the Lower-Upper Cretaceous and lower Tertiary sediments. Unconformity of the surface marks the boundary between the Paleozoic (Permian-Cambrian) – Mesozoic (Triassic) sequences.

Correlation with cross section 1 (Figure 2-7) exhibits a considerable increase in the thickness of the Mesozoic and the Cenozoic sequences toward the northeast with a major dip toward the north and north east. On the other hand, thinning of these sequences is remarkable toward the south east where the Jurassic sediments disappeared (pinched out).

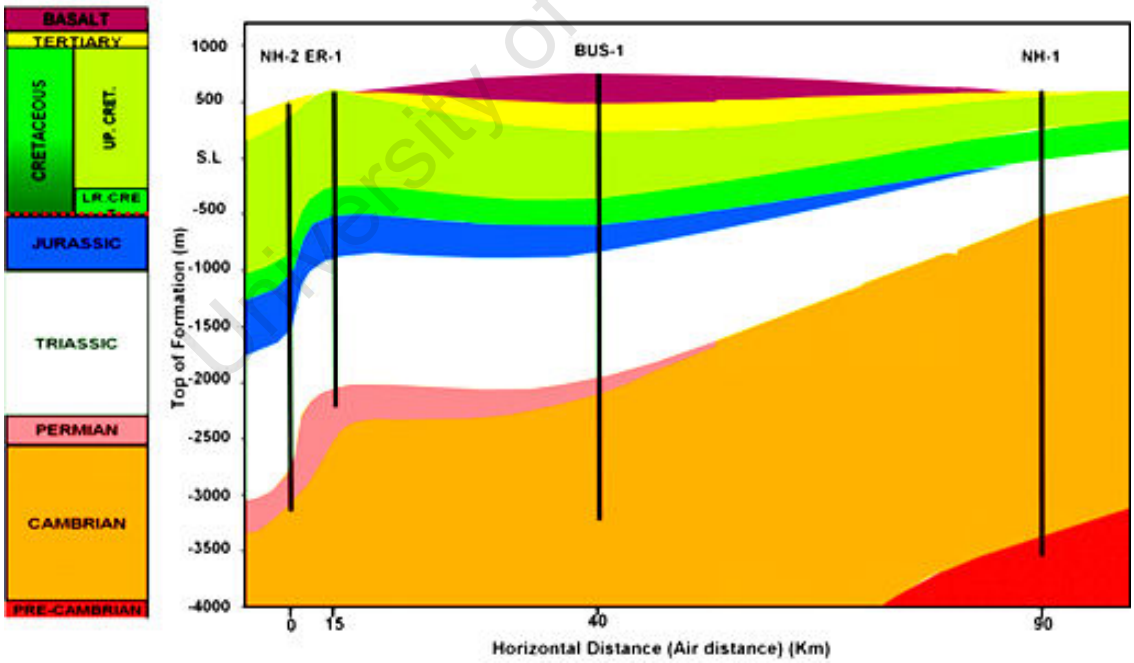

Figure 2-7: Structural correlation cross section 1 between NH-2, ER-1, BUS-1, and NH-1 boreholes. Vertical column represents top of the stratigraphic unit in meters while the versus represents distance in Km

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A major fault system with northeast downthrown marks the area within the vicinity of NH-2 and ER-1 wells (Figure 2-7) which emphasized the effect of the Ramtha Sirhan Fault System as a major NW-SE trend caused by tensional stresses. NH-1 and AJ-1 wells are the only wells that penetrated the Precambrian at depths of-3328.2m and-2015 m respectively (Figures 2-7 and 2-8). This suggests that the basement is down stepping toward the southeastern regions toward the Fuluq Fault System where tensional effects are remarkable.

NH-2 well (Figure 2-8) displays stratigraphic sequences at deeper depths than those in the wells to the south east (within the vicinity of NH-1) and south west (within the vicinity of AJ-1) with a noticeable increase in the thickness of both the Paleozoic (Cambrian-Permian) and the Mesozoic sequences. BUS-1 well (north east) exhibits similar stratigraphic sequences at shallower depths (Table 2-1) but deeper than those observed in NH-1 in the south east. This indicates the existence of a large subsidence structure striking NW-SE, and plunging toward the NNE.

Thick Triassic-Jurassic and Lower-Upper Cretaceous sequences are overlying the lower Permian with increase in elevation and thickness toward the west where the Precambrian rocks become shallow. This strongly indicates the effect of a combination of tension and compression which are mainly subjected to the Dead Sea Transform Fault. This resulted in significant uplift within the Vicinity of Ajlun where Ajlun Dome is lies. Middle-Upper Cretaceous sequences pinch out toward the west and southwest, where the Lower Cretaceous sequences (Albian-Aptian) overly the Triassic sequences with an unconformity surface. Lower Cretaceous rocks are observed at depth 630 m with 150m thickness in SW-1 well in this direction.

SW-1 and NH-1 wells demonstrate considerable thickness of the Cambrian sequence in the southwest and toward the southeast while the Permian and Jurassic are missing in this direction. Suwelih structure is significant within the vicinity of SW-1.

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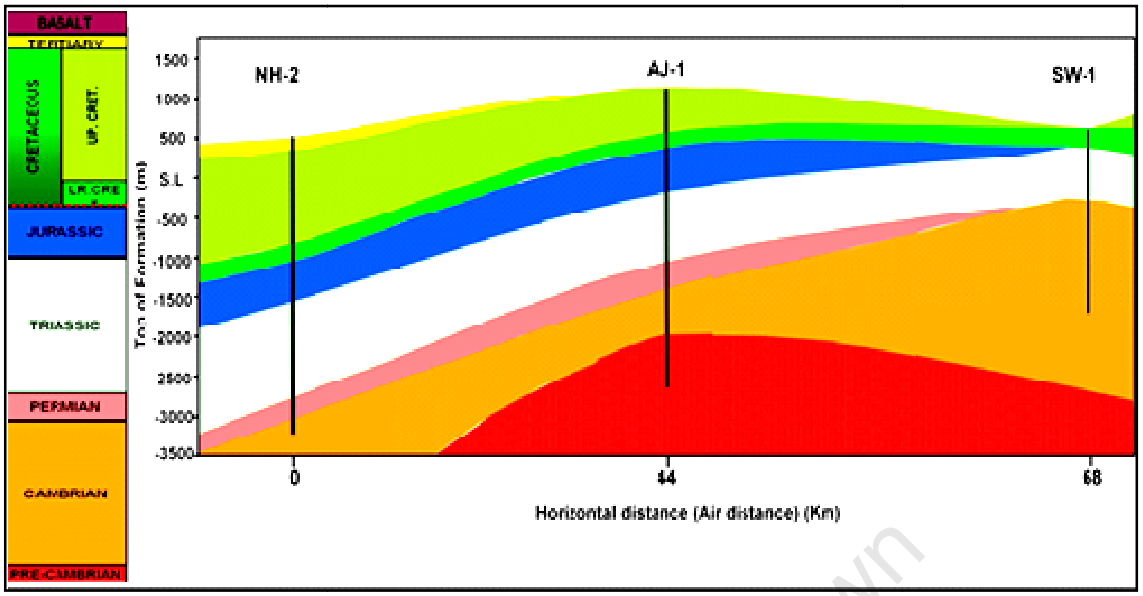

Figure 2-8: Structural cross section 2 between NH-2, AJ-1, and SW-1 boreholes. Vertical column represents top of the stratigraphic unit in meters while the versus represents distance in Km

Age	BUS-1	NH-2	S-90	ER-1	AJ-1	SW-1	NH-1
Tertiary	498	507	Missing	Missing	Missing	Missing	603
Up. Cret.	263	364	578	598	1140	Missing	552-8
Lr. Cret.	-353	-836	-420	-265	573	630	262-8
Jurassic	-581	-1043	-690	-510	391	Missing	Missing
Triassic	-833	-1556	-1103	-899	-184	389	-10.2
Permian	-1952	-2769	N.P.	-2044	-1207	Missing	Missing
Cambrian	-2103	-3021	N.P.	N.P.	-1433	-245	-517.2
Pre-Cambrian	N.P.	N.P.	N.P.	N.P.	-2015	N.P.	-3328.2
Total Depth(m)	-3163	-3208	-1613	-2151	-2649	-1695	-3408

Table 2-1 Mean Sea Level (msl) depth variations (meters) of the stratigraphic sequences in the study area as measured from the BUS-1, NH-2, S-90, ER-1, AJ-1, and SW-1 wells' logs

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2.2. GEOMORPHOLOGIC INTERPRETATION

Digital Elevation Model (DEM) was extracted from eight topographic maps of scale 1:50,000 with contour interval 20m (Figure 2-9). This was carried out in order to identify the main terrain units of the study area. The flow direction of the main drainage network was also delineated based on the interpretation of the topographic maps. The visual interpretation of the elevation map conveyed to that there are five distinctive terrain classes (Figure 2-9)

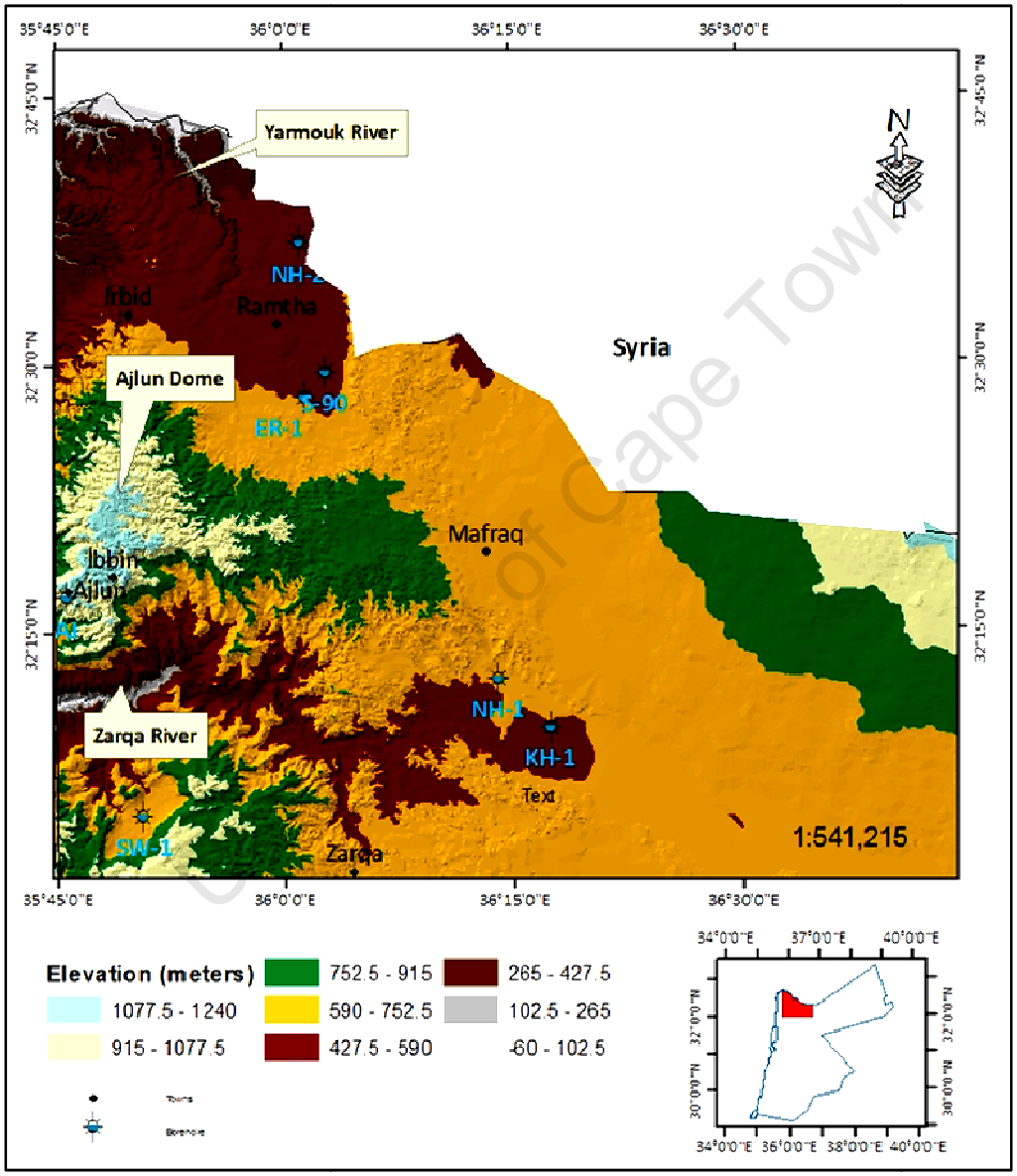

Figure 2-9: Digital Elevation Model of the study area as processed from the topgraphic maps of contour interval 20m

Ajlun area comprises the highest point in the study area. The areas along the eastern margin toward Jordan valley, present steep slope to the west, while to the east it steeps gently.

Figure 2-10 displays the major geomorphological classification. Yarmouk and Zarqa Rivers exhibit the lowest elevated areas. Sirhan Basin, from the extension southeast toward the northwest, comprises a Plateau region with moderate relief. Ajlun area and south of Zarqa River comprises the highest terrain areas.

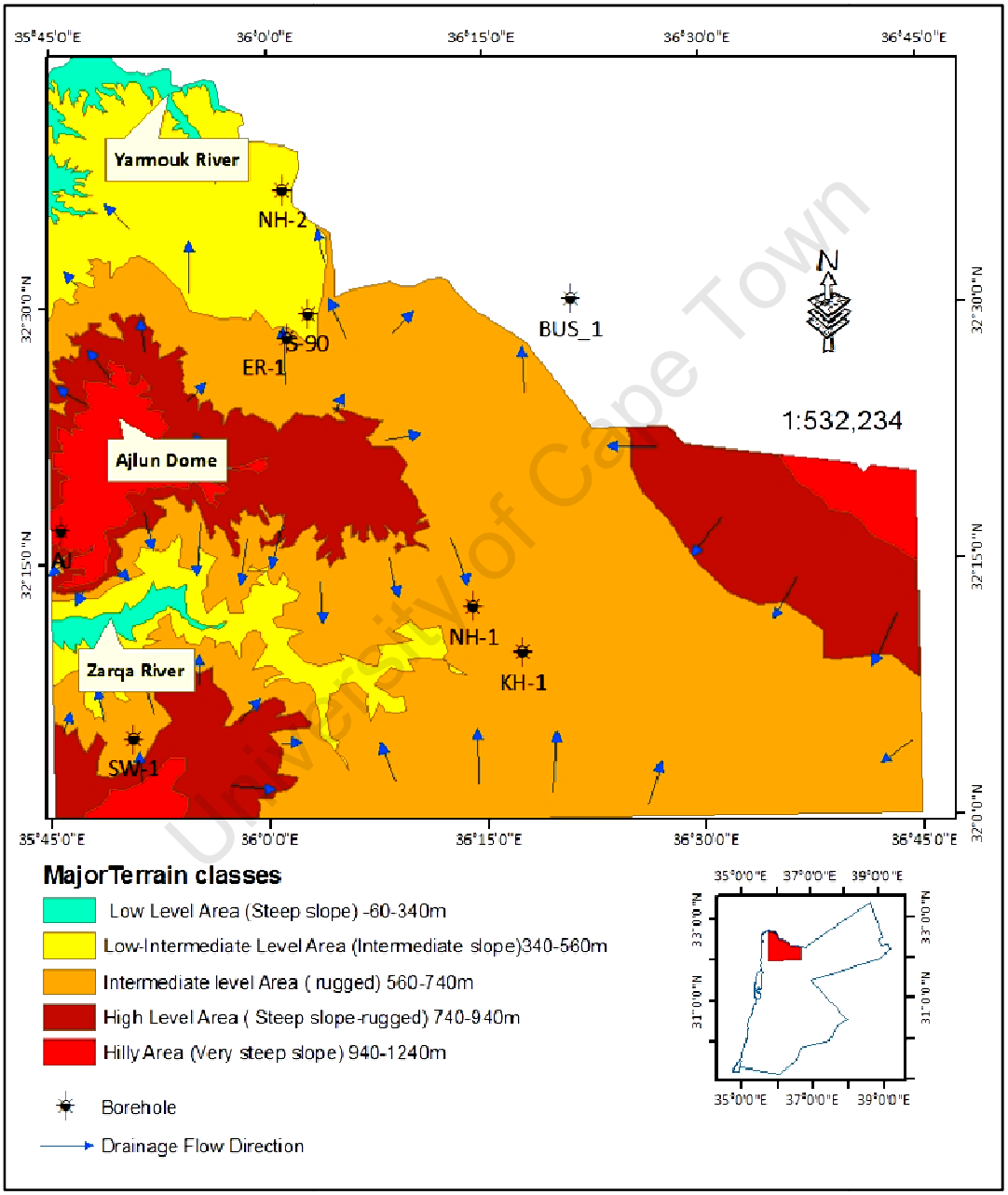

Figure 2-10 Major Terrain classes

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2.3. GRAVITY AND MAGNETIC

A Bouguer anomaly map corrected by the Geophysical Division at the Natural Resources Authority was utilized. The Bouguer anomaly indicates valuable information about depth of gravity sources, basement trends, nature of intrusive bodies, and thickness of sedimentary cover (Qureshi, 1971). In addition, it enables delineation of the major deep faults, highs, and lows (Qureshi, 1971). Thus, qualitative and quantitative interpretation techniques were carried out to delineate the subsurface elements with location and trend, as well as to explore the basement's depth, relief, and structure.

The interpretation involved analysis of five gravity profiles. Bouguer anomalies appear as combinations of sharp (short wavelength) and broad (long wavelength) anomalies along these profiles. Sharp anomalies could be of shallow origin while broad anomalies could be of a regional nature (Batayneh *et al*., 1992; and Abu Hamideh, 2000). In addition, shape of the gravity contours, gradient changes and pattern of anomalies were also taken into consideration since they usually infer the presence of major fault trends, (Batayneh *et al*., 1992). Negative Bouguer anomaly values (low) may indicate a lower density anomaly while positive values (high) may point out higher density. According to Qureshy, 1971, decrease in Bouguer anomaly indicates thick sedimentary cover or thick crust.

Qualitative interpretation techniques involved analysis of these profiles by examination of major anomalies and their characteristics such as location, trend, amplitude, and gradient changes (Batayneh *et al*., 1992). While quantitative interpretation involved the use of 2D gravity modeling approach using modeling and basin inversion techniques (Singh *et al*., 2004; Abu Hamideh, 2000). Modeling and basin inversion were derived by polynomial fitting of the observed gravity readings with the calculated using the GRAVCADW program to explore the depth to the Pre-Cambrian basement across the study area.

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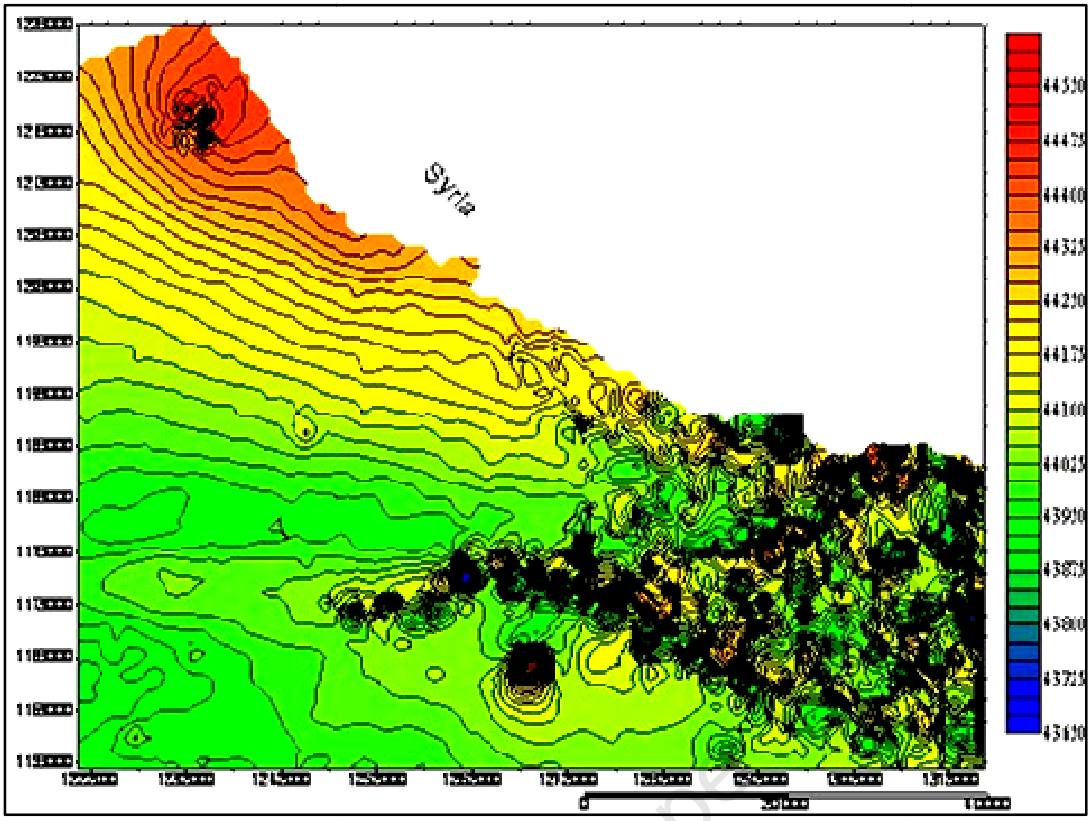

Figure 2-11: Aeromagnetic total intensity map of the JNH area

Aeromagnetic data (Figure 2-11) presents a high degree of noise across the area, mainly the eastern and southeastern margins, where Basalt outcrops, unlike the gravity. Therefore, aeromagnetic data were discarded from interpretation to avoid ambiguity.

2.3.1. GRAVITY INTERPRETATION

The Bouguer anomaly map was prepared with a contour interval of two mgal to recognize short and long wavelengths. The resulting map is characterized by gravity ranges from +3 l to – 60 mgal. Gravity variations along five selected profiles were analyzed, (Figure 2-12).

A preliminary visual interpretation showed remarkable variations in the Bouguer values, range from positive values in the west within the vicinity of Ajlun Dome to low negative value to the east and southeast. Changes in the Bouguer values indicate the existence of four major fault trends: NW-SE, NE-SW, N-S, and E-W dominating the area.

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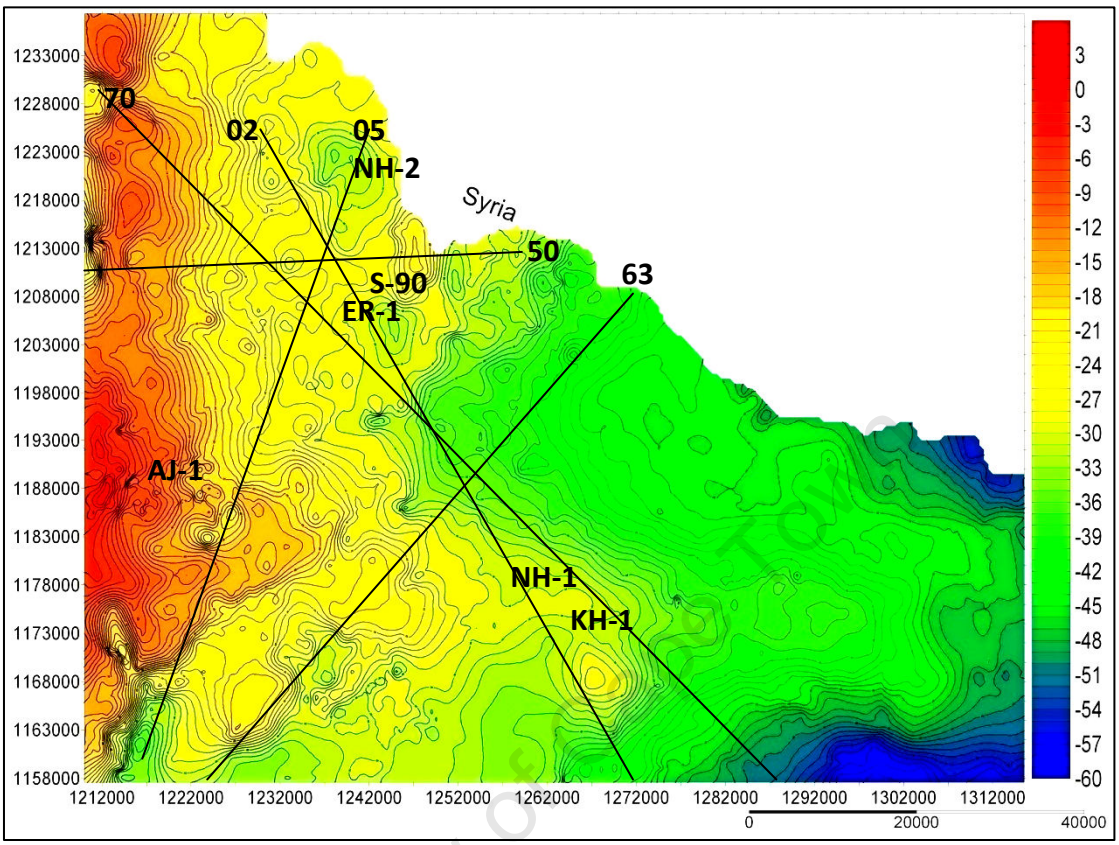

Figure 2-12: Bouguer gravity anomaly map of the JNH area showing location of the Bouguer profiles

NW-SE GRAVITY PROFILES GROUP (FIGURE 2-13)

This group of profiles crosses the study area along NW-SE direction, along the same path of the seismic profiles; N-02 and N-70, having total lengths of 88 and 109 Km respectively. These profiles display a noticeable decrease in the Bouguer anomaly across toward the southeast which indicates a General decrease in the density, and consequently suggests an increase in the thickness of the overlying sedimentary cover (Pilkington, 2000). Bouguer is between ~-10 mgal in the northwest and ~-60 in the southeast. Sharp and broad anomalies comprise this group of profiles.

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Profile 02 and 70 (Figure 2-12); Quantitative interpretation presents remarkable variations in depth to basement along these profiles. To the east and south east, basement is deeper than to the northwest.

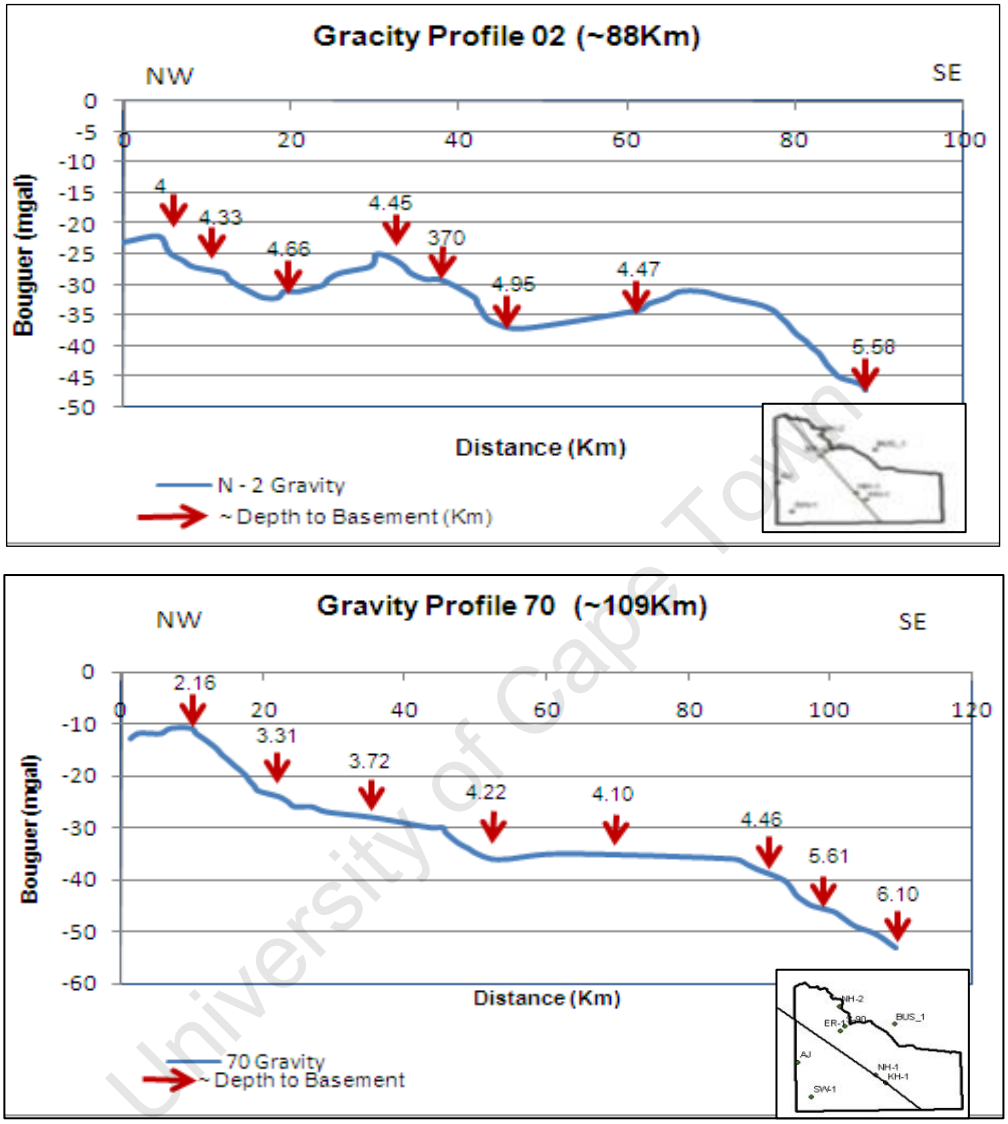

Figure 2-13: Gravity (Bouguer) profiles; 02 and 70

SW-NE PROFILES GROUP (FIGURE 2-14)

This profile extends along the seismic profile N-63 for a distance of about 57Km. Gravity values vary from-26 mgal in the southwest to-45 mgal northeast. Broad anomalies characterize this profile cut by long extension NW-SE and E-W discontinuities. Basement becomes deeper toward the east and northeast where it reaches ~-4.72 Km.

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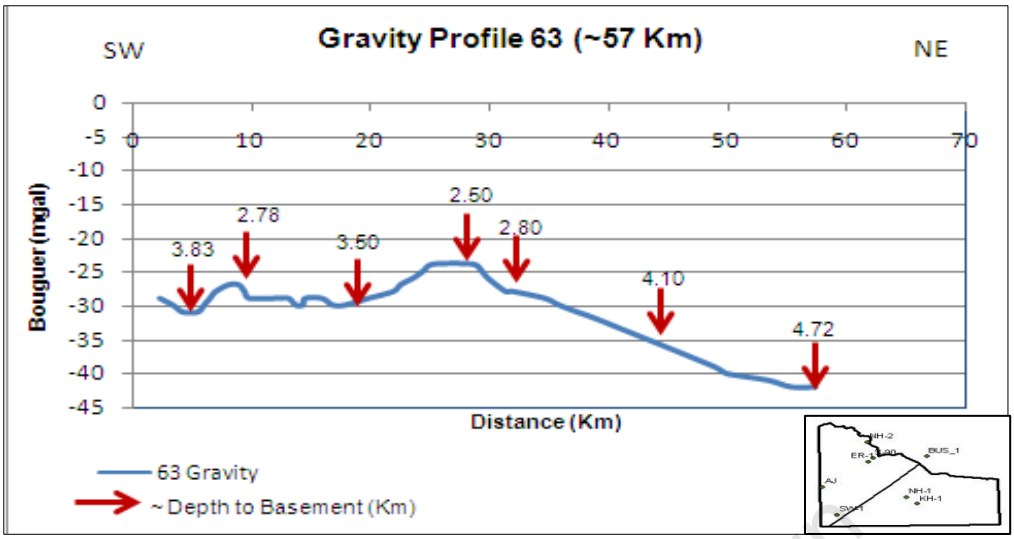

Figure 2-14: Gravity (Bouguer) profile 63

SSW-NNE PROFILE (FIGURE 2-15)

This profile extends along the N-05 seismic profile with a 56 Km length. It displays typical compression element between ~22 Km-~30 Km distance relative to Ajlun Dome. Depth to basement reaches ~-2-87 Km, while on the flanks it declines to ~-4.32 Km. Major normal faults of NW-SE trend cross this profile.

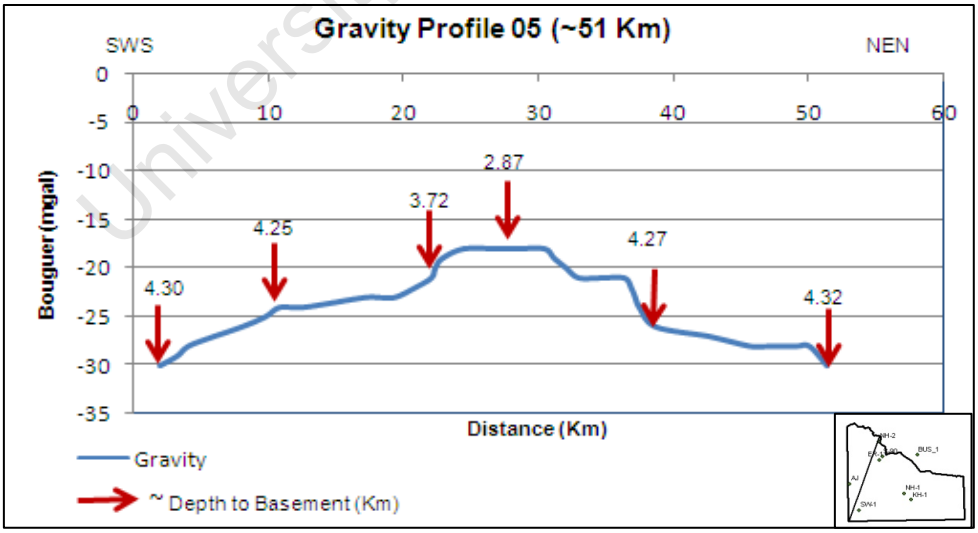

Figure 2-15: Gravity (Bouguer) profile 05

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E-W PROFILE (FIGURE 2-16)

This profile extends along the seismic profile N-50. It displays a gentle decrease of Bouguer values toward the east where the basement becomes deeper and thickness of the sedimentary cover increases. Toward the west, the depth to basement reaches ~-2.98 Km and declines to ~-4.13 Km to the east.

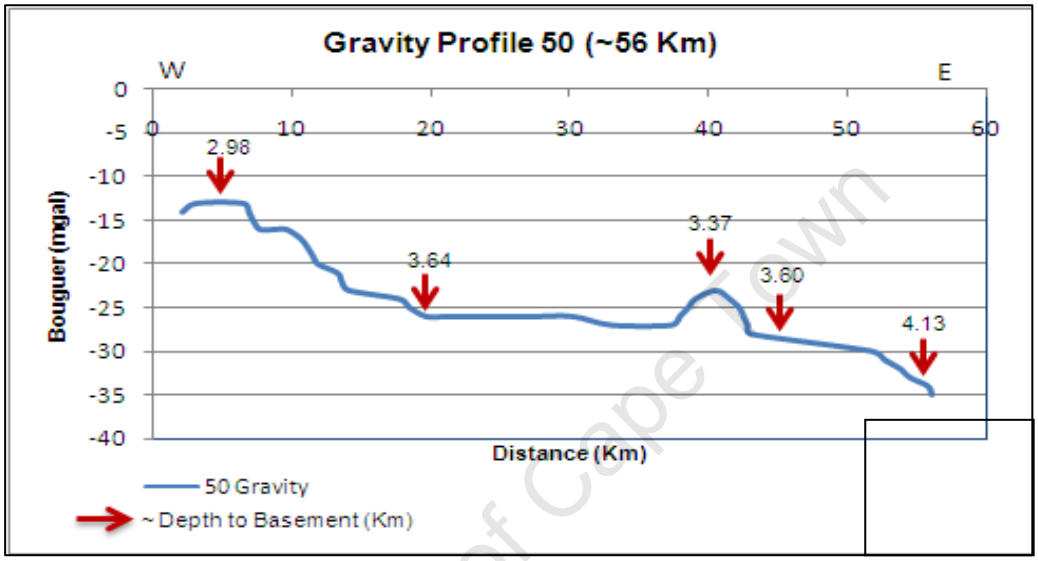

Figure 2-16: Gravity (Bouguer) profile 50

2.3.2. GRAVITY ANALYSIS

An analysis of the qualitative and quantitative interpretation was carried out in order to delineate the major structural framework in the study area. The resultant interpreted elements were correlated to seismic and previous surface geological studies, which proved to be highly consistent. Calculated depths to the basement were correlated to the NH-1 and AJ-1 wells as well as previous studies.

Figure 2-16 illustrates a subsurface structural framework map. It exhibits a complex structural style of the area as delineated from the Bouguer anomaly map. This style is characterized by the presence of multi faulting zones with various orientations. Two major trends: NW-SE and NE-SW of normal type are dominating the area and appear as intersected with E-W and N-S faults. Secondary normal faults are intersecting these major trends forming horsts and grabens which appear as lows and highs on the map. One of the major

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NW-SE trends crossing the areas from the southeast toward the northwest was correlated to the Ramtha Sirhan Fault System. Two major E-W trends are intersecting this major trend to the east of NH-1 and KH-1 wells and in the south and southeastern parts of the area. This major element (E-W in the southern parts) is correlated to the Zarqa Fault System. N-S trends are minor and appear in the southern parts as intersecting the Zarqa Fault System. The gravity profiles displayed series of successive folding elements (low and high magnitude) with major NE-SW orientation (Figure 2-17).

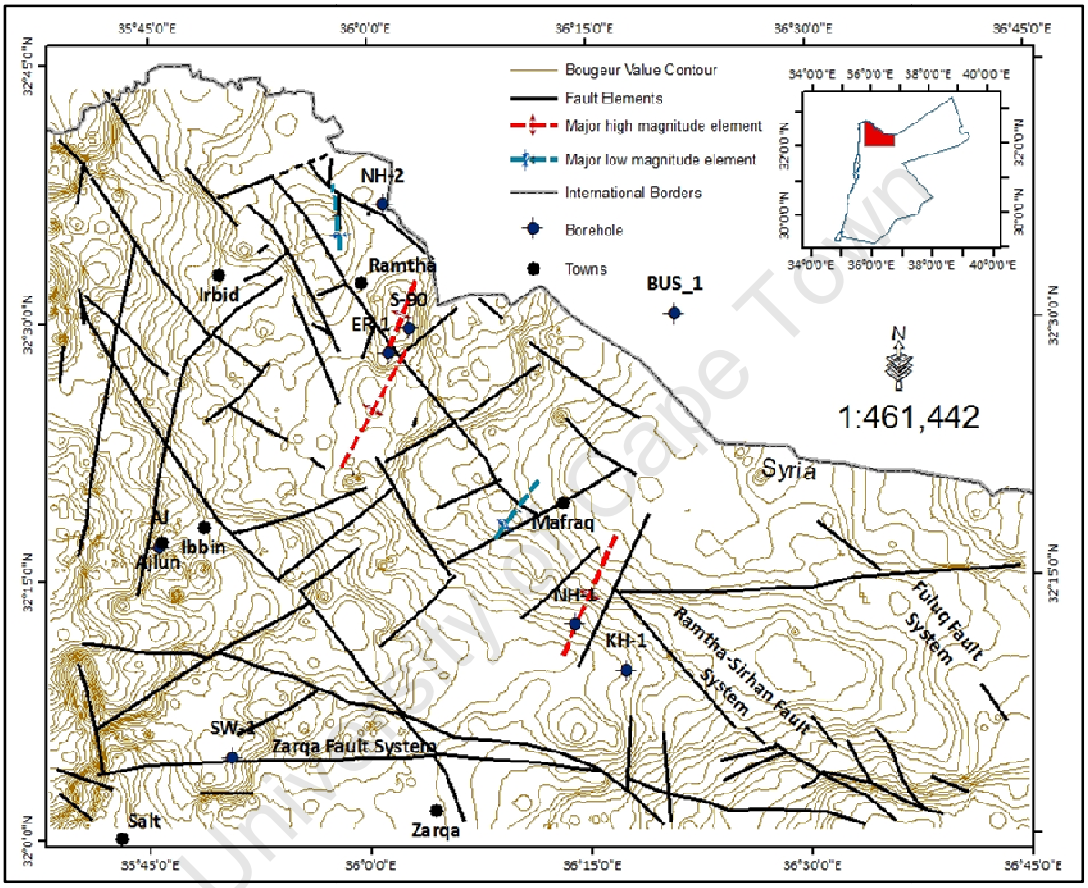

Figure 2-17: Structural framework map as a result of gravity data interpretation and correlation with surface geology

A structural contour map for the top of the basement across the study area was produced based on the results that were obtained from the quantitative interpretation of the gravity data (Figure 2-18).

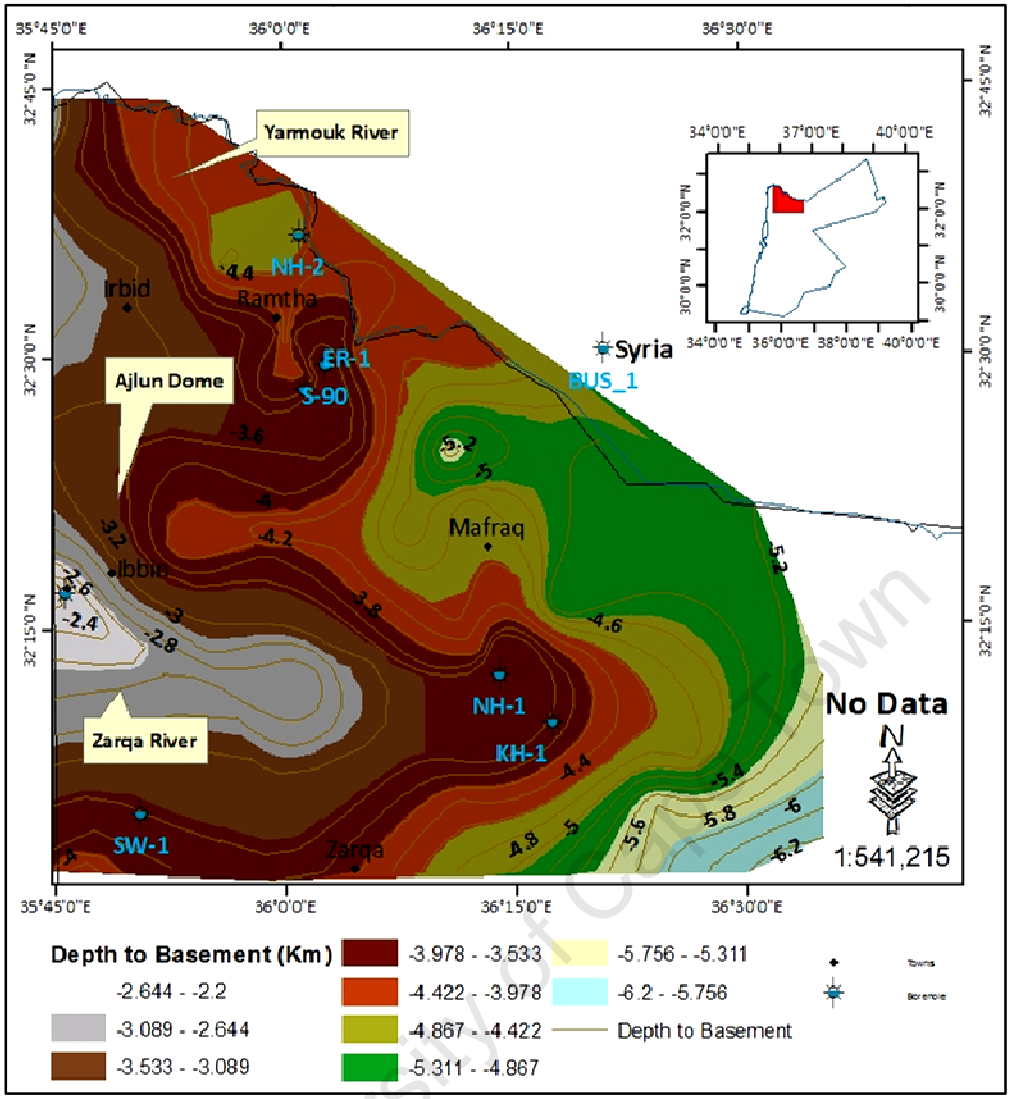

Figure 2-18: Depth to basement contour map as calculated from Bouguer profiles. Depth unit is in kilometers

This map displays a SE-NW trend of depth to the basement; it comprises shallower depth across the northwestern and western margins than east and southeast parts, where depths range from ~-2-16 to about-2-6 Km along western margins. Northward toward the Syrian borders, the basement deepens gradually. Depths across these parts reach ~-4.35 Km. Toward the east and southeast it continues deepening for about-6.38 Km.

Compilation of the calculated depths using the quantitative modeling techniques with the NH-1 and AJ-1 wells information matched the results.

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2.4. 2D SEISMIC REFLECTION PROFILES INTERPRETATION

The interpretation of the 2D seismic reflection data relied on an interrelated loop interpretation scheme for fifteen 2-D seismic profiles (350 km) over the study area (Figure 2-19). The data of these profiles was preprocessed by GSI with some of the data reprocessed by CGG. The data is 48 fold CDP stack data which were shot using a split spread configuration. The vibrosis sweep was 12 seconds duration. The processing of this data included detailed static corrections and velocity and/or coherent filtering.

Initial step in the interpretation was to tie the seismic data to the NH-1 and NH-2 wells. The time depth relationship was determined from NH-1 and NH-2 WST/VSP logs. Horizon depths were taken from information supplied by the Natural Resources Authority (NRA) and these were plotted on the WST depth versus time summary graph. Two way travel times for the main horizons were then taken from the chart. Depths were calculated using RMS velocity.

The following describes briefly the first stage of interpretation which is included:

1-Identification and picking of five (5) marker horizons

2-Tying the marker horizons on intersection

3-Picking of two-way-travel (TWT) time values from the interpreted seismic profiles to produce time structure maps

4-GenEration of the depth contour maps using RMS velocity calculations

5-Interpretation of the faults and posting them on the base map

6-Inserting fault throws and displacement orientation

7-Correlation with the surface and the gravity interpretation results

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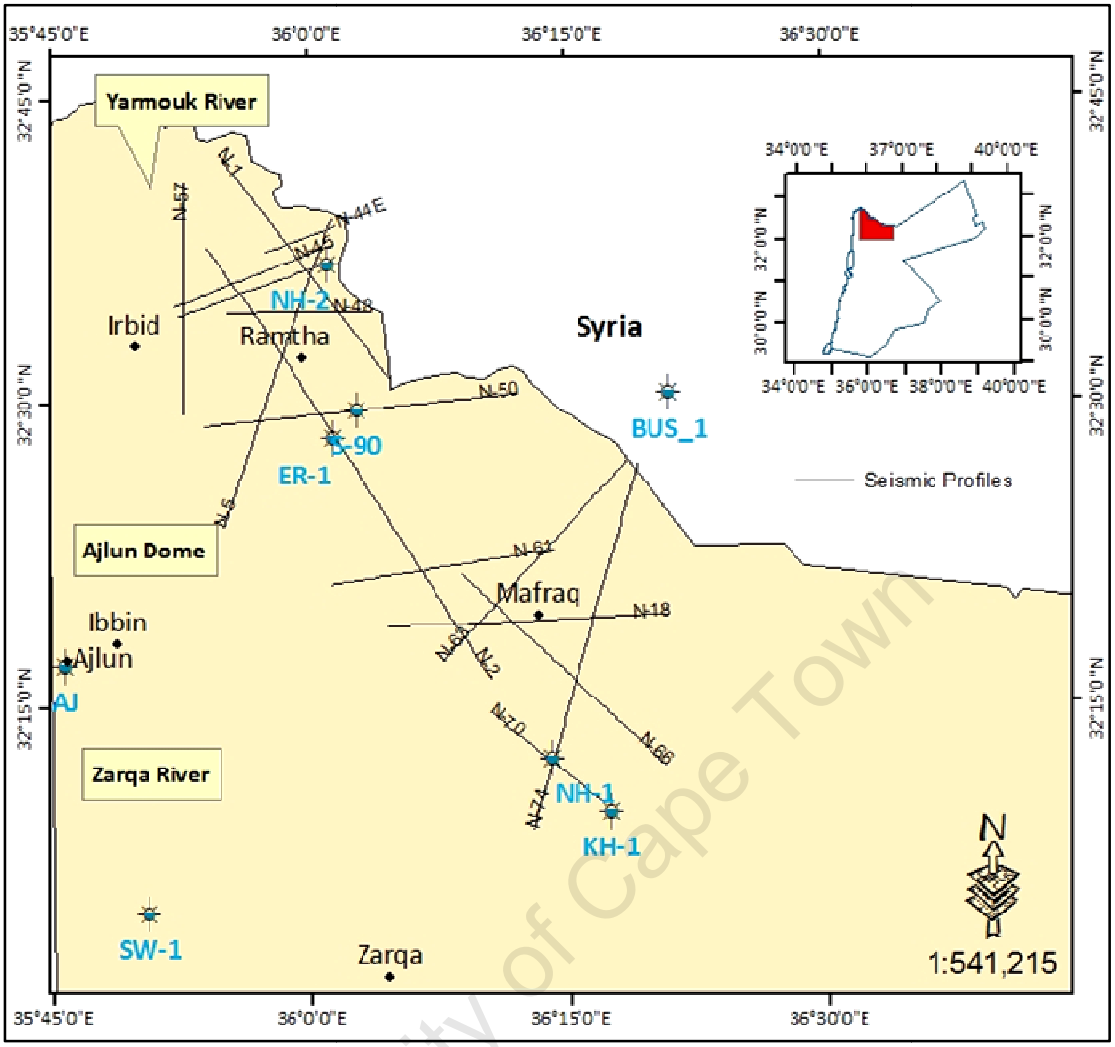

Figure 2-19: Location map of the seismic profiles

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2.4.1. IDENTIFICATION OF THE SEISMIC HORIZONS

Initial interpretation identified five seismic horizons: Horizon1 to Horizon 5. Stratigraphically, the horizons were tied to the VSP logs of NH-1 and NH-2 and identified as:

- Horizon 1(H1) is near the top of the Cenomanian age rock formations which belongs to the Upper Cretaceous sequences.
- Horizon 2 (H2) is near the top of the Lower-Cretaceous sequences which belongs to the Albian-Aptian age rock formations (Lower Cretaceous).
- Horizon 3 (H3) is near the top of the Jurassic.
- Horizon 4 (H4) is near the top of the Triassic.

- Horizon 5 (H5) is near the top of the Unconformity surface between the Mesozoic sequences (base of Triassic) and the underlying Paleozoic sequences of Cambrian – Permian age.

Scarcity of deep boreholes that penetrated the Precambrian rocks and insufficient seismic survey coverage over the study area made identification of the top of the Precambrian difficult. Therefore, it was discarded from the interpretation to avoid ambiguity.

2.4.2. DELINEATION OF THE MAIN STRUCTURAL ELEMENTS

In spite of the variable quality of the seismic profiles as well as the complex fault pattern which made tying faults from one line to another difficult, the interpretation exhibited a maze of intersecting faults and folds of varying characteristics and orientations. Most of the interpreted faults are near vertical normal fault patterns characterized by some strike slip offsets and crossed by secondary faults forming step faulting blocks with combination of horsts and grabens. All horizons appear on the seismic profiles as continuous markers gently dipping toward the north, north east north, and north east.

PROFILES N-01, N-02, N-66, AND N-70

This group of profiles extends NW –SE (Figures 2-19-2-22). They illustrate a maze of high angle step normal faults striking E-S, NE-SW, and NNE-SSW with westward and eastward throws. Most of these faults affect all horizons and penetrate up to the surface. Some antithetic and synthetic secondary faults are also deforming the seismic horizons.

Profile N-01 (Figure 2-20) displays, clearly, a dominant structural style of folding and faulting. A step faulting system of major NE-SW trend is significant with dense faulting phenomena toward the northwest while to the southeast it decreases. This indicates the strong effect of the Dead Sea Transform. A broad low magnitude element appears toward the southeast. The traced faults appear deep. The sedimentary cover along this profile comprises thick Mesozoic sections toward the North West with gentle dipping toward the north, northeast, and northwest. Bouguer values along this profile range between-26 mgal in the northwest to-34 mgal in the southeast.

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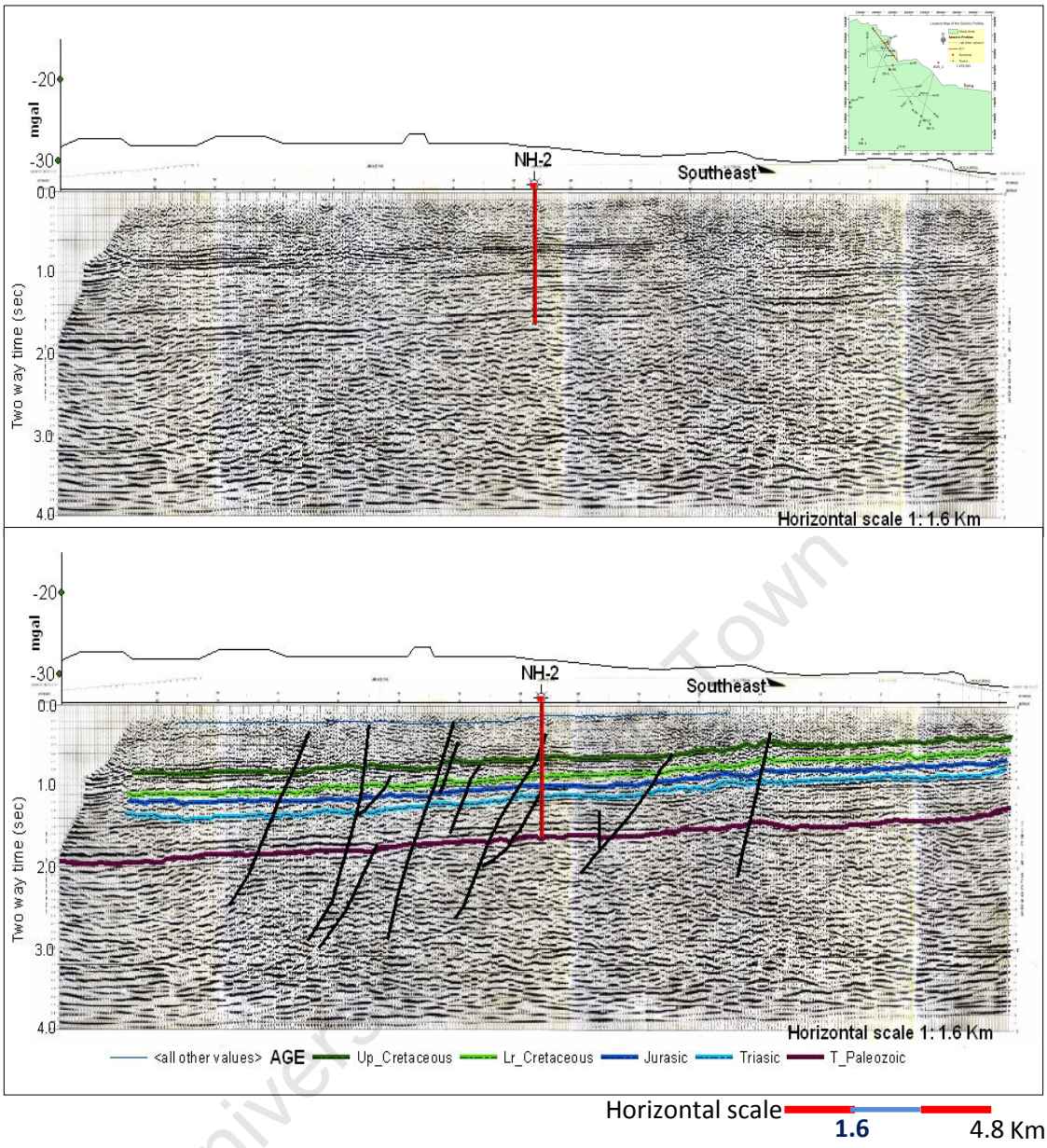


Figure 2-20: Major structural elements along N-01 seismic profile

Profile N-02 exhibits a zone of major and minor faults with two major trends; NNW-SSE and NNE-SSW. The effect of this fault zone is marked by formation of a large horst block element, striking NE-SW, within the vicinity of ER-1 and S-90 wells. This horst is bordered by two small scale depressions (Figure 2-21). This structural style indicates episodes of compression and tension stresses over the area. Thickening in the overlying Mesozoic sedimentary cover is remarkable northward. On the contrary, the Jurassic sequences disappear while Triassic sequences appear thick toward the south and south east, which

indicate existence of a Paleozoic –Mesozoic unconformity. Bouguer values range from-30 mgal in the NW to-26 mgal within the vicinity of the S-90 and ER-1 wells, while it reaches to

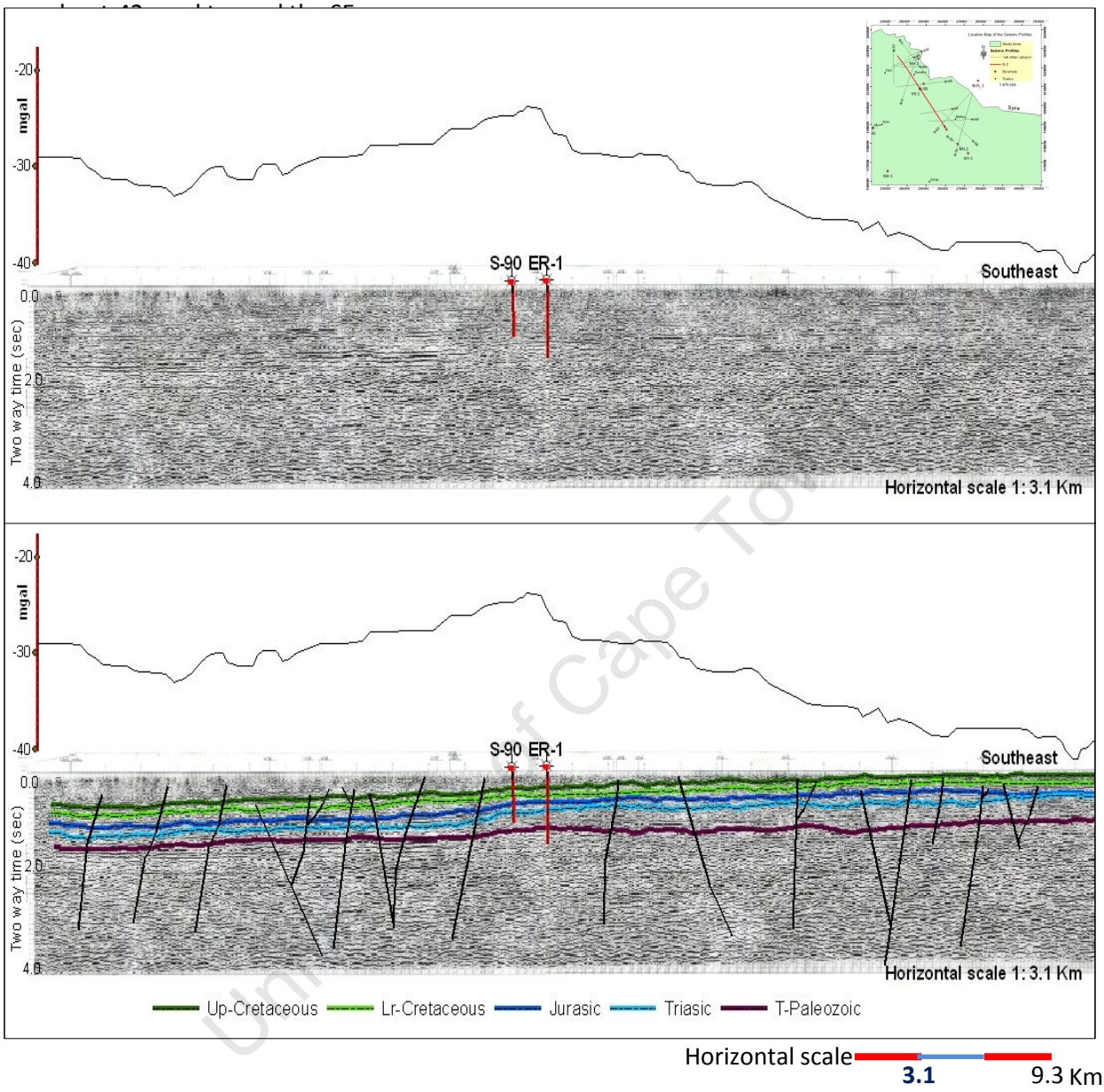


Figure 2-21: Major structural elements along N-02 seismic profile

There was no available original copy for profile N-70; therefore further evaluation for the pre-existing interpretation was carried out.

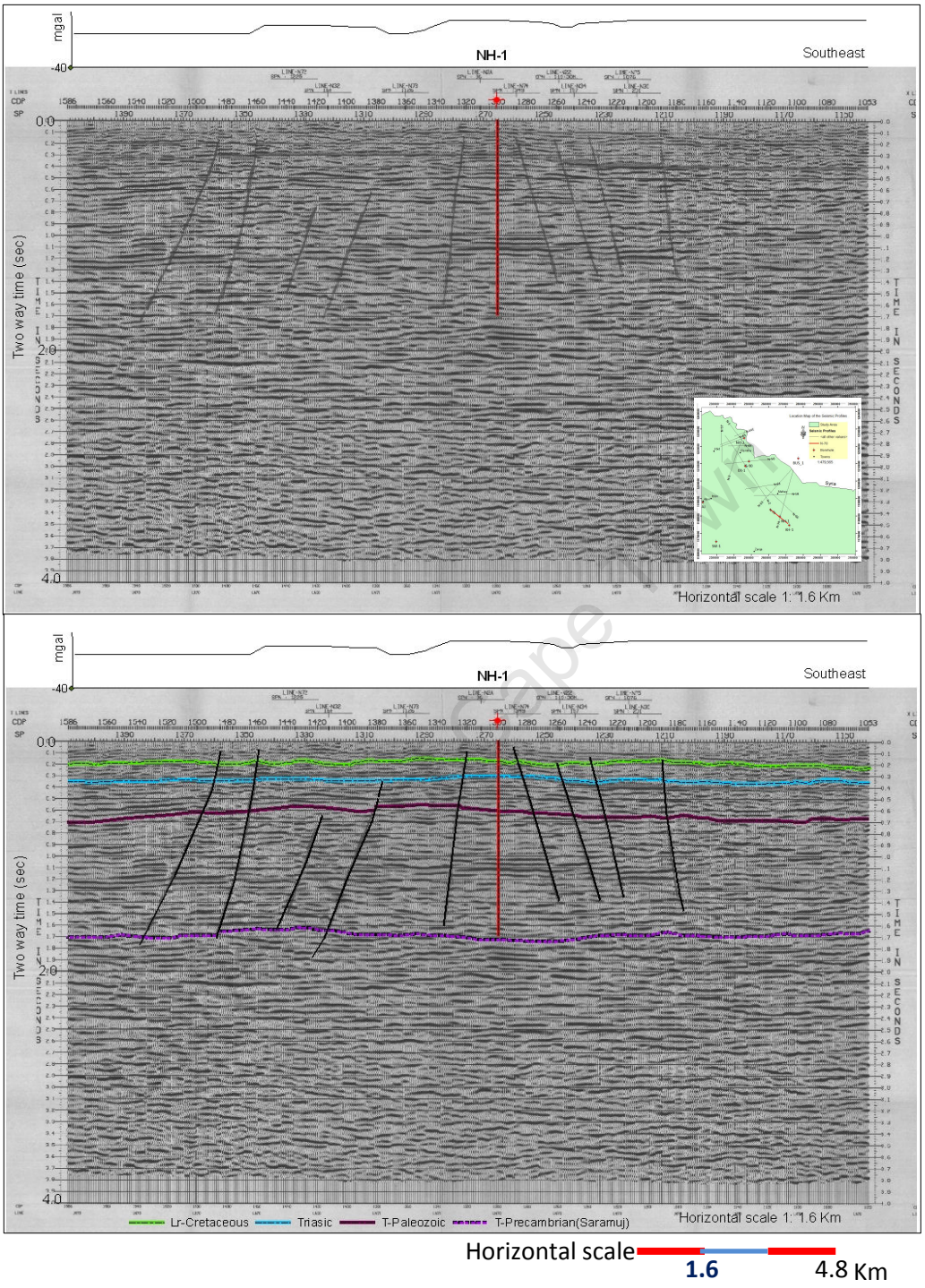


Figure 2-22: Major structural elements along N-70 seismic profile

Profile N-70 (Figure 2-22) outlines a high magnitude horst block element that is characterized by a remarkable step block-faulting complex. Two high angles~ 70 º-80 º faults sets throwing westwards and eastwards bound this complex. Along this profile a lower Cretaceous –Triassic unconformity surface is recognizable. Bouguer values range between-32 mgal to-34 mgal.

(Figure 2-23) seismic profile N-66 traces a horst block element with two high angle normal faults border it. The Lower Cretaceous –Triassic unconformity traced toward the southeast .Bouguer values range between-38 mgal in the NW to-42 mgal in the SE.

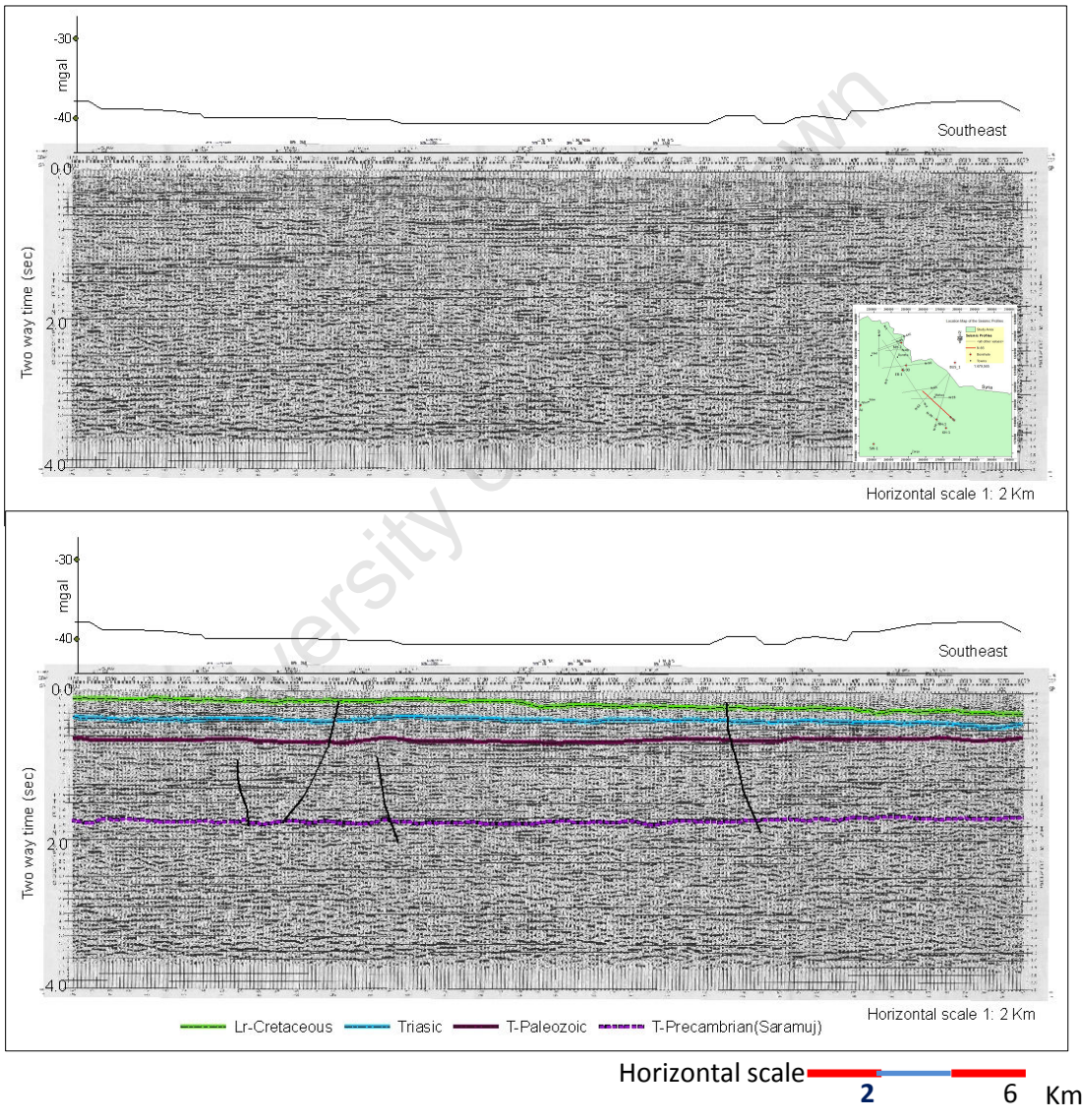
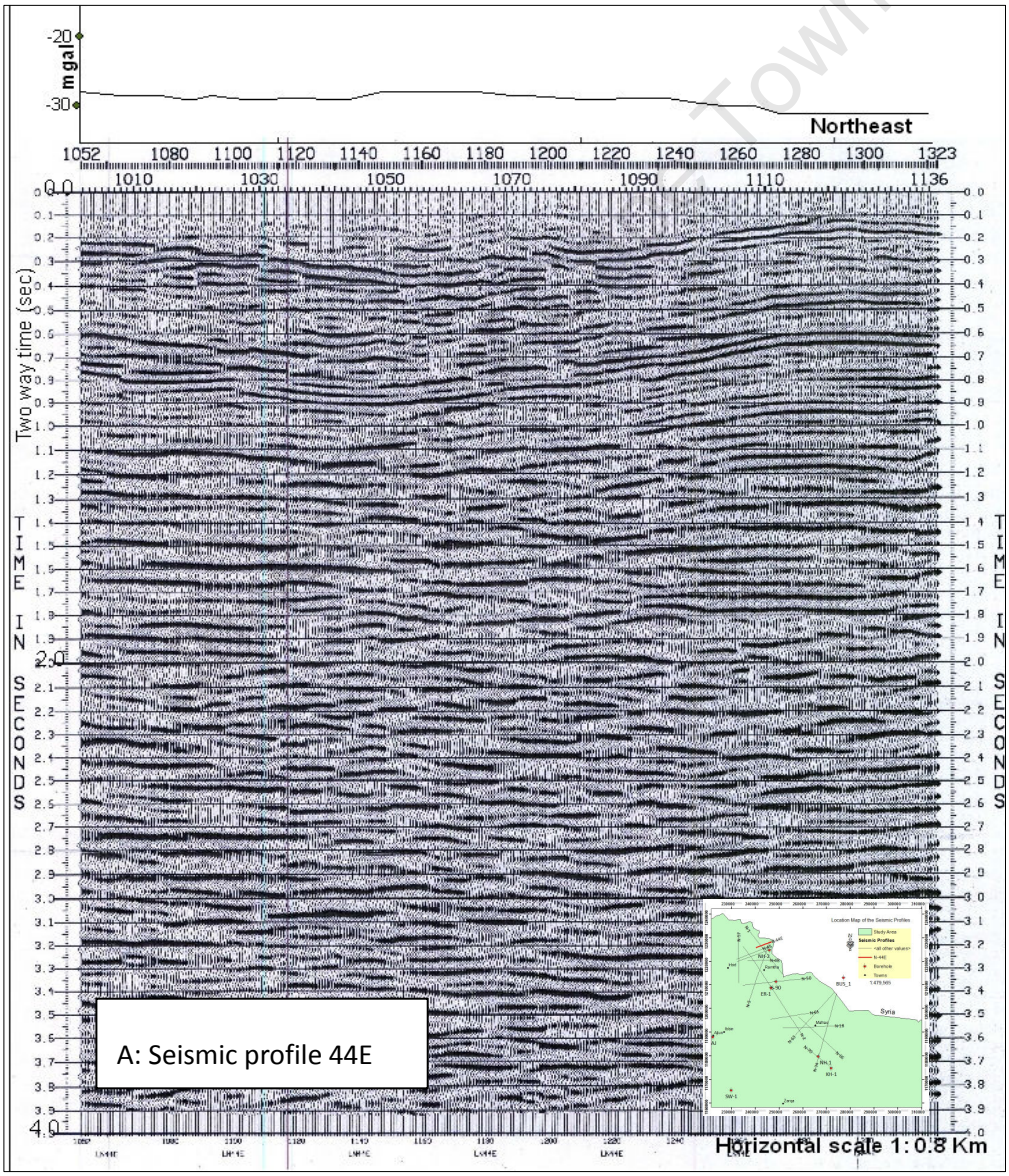


Figure 2-23: Major structural elements along N-66 seismic profile

PROFILES N-44E, N-45, AND N-46

These profiles extend from the southwest toward the northeast. They illustrate a complex faulting system with major NW-SE trend. Combination of high angle fault pattern traversed by a number of antithetic and synthetic faults forming a low magnitude structure (depression), characterizes these profiles. Bouguer values vary from about-28 mgal in the SSW to about-32 mgal over the low magnitude structure and reach about-26 mgal in the NNE. Mesozoic are gently dipping toward the north and north east.

Profile N-44E (Figure 2-24 A & B) displays fault pattern which contributes to formation of significant extensional structural element with N-S major trend axis. This element may be considered as a major plunging syncline.



Horizontal scale 0.8 2.4 Km

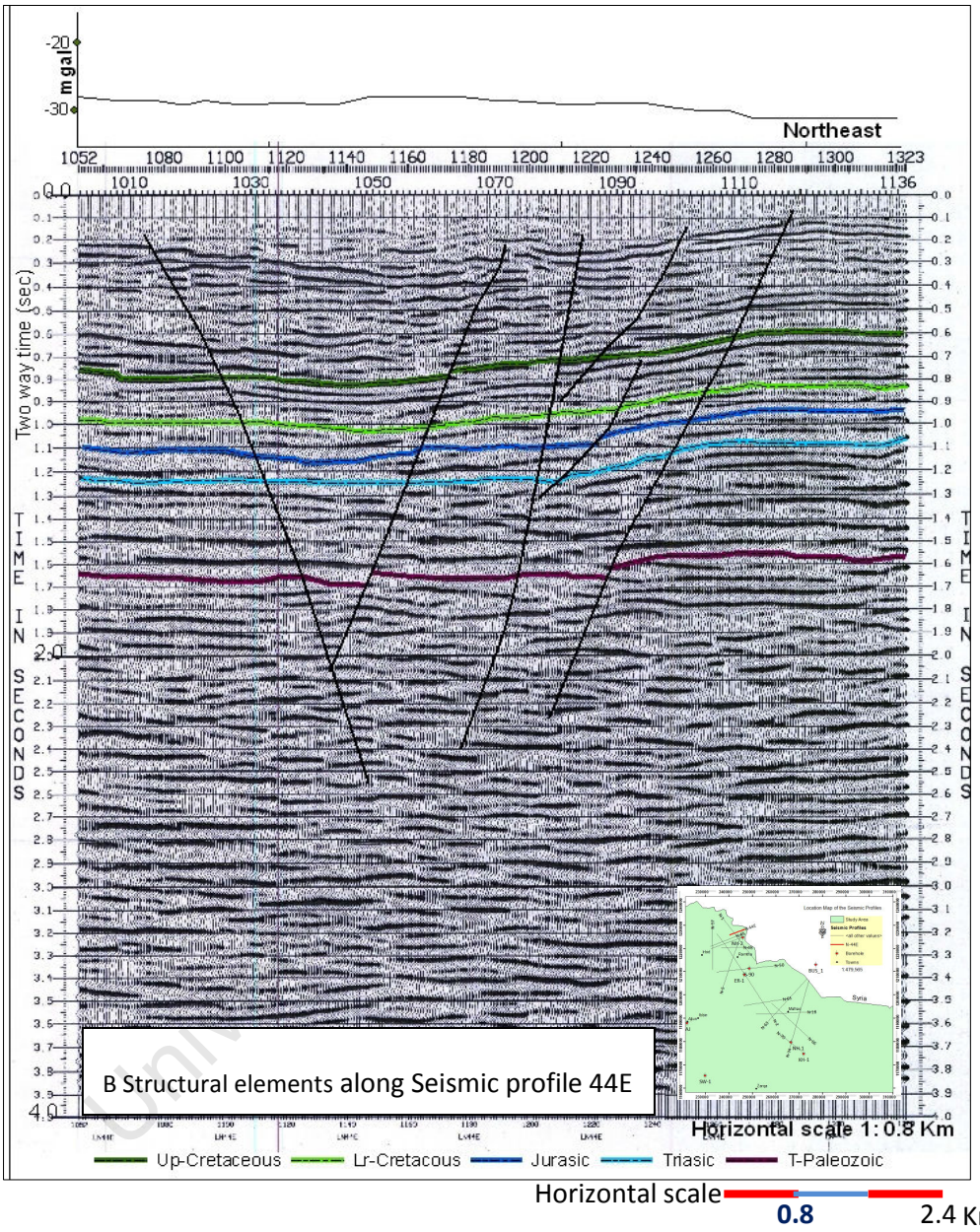


Figure 2-24 A and B: Major structural elements along N-44E seismic profile

Profile N-45 presents number of high-angle normal faults throwing to the southwest and south east. Mesozoic and Paleozoic sequences appear highly tilted with dip toward the north and north east (Figure 2-25).

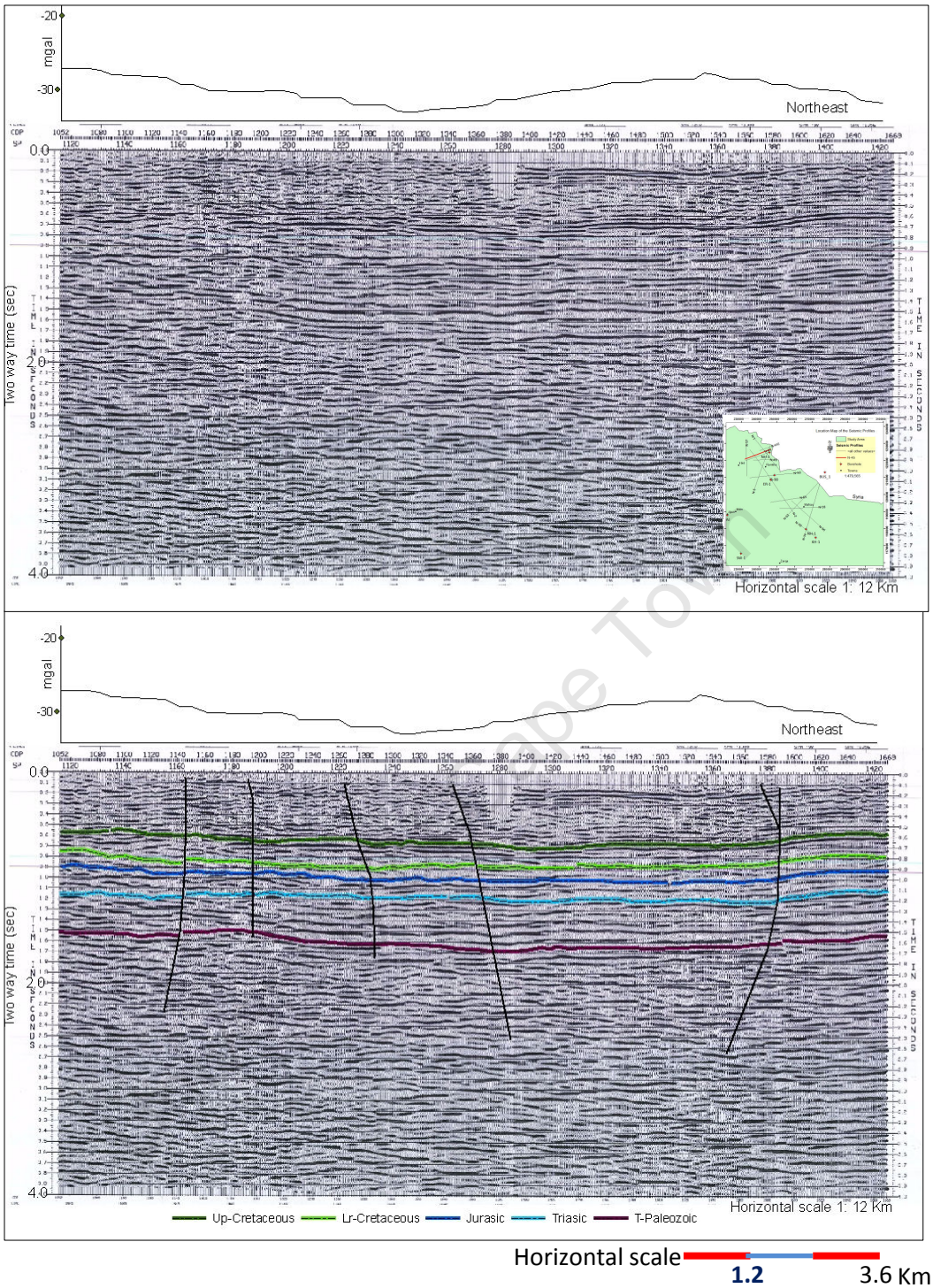


Figure 2-25: Major structural elements along N-45 seismic profile

Profile N-46 displays a set of deep seated high angle normal fault forming a low Magnitude structure with a remarkable thickening in the overlying sediments. Compilation with surface geology and gravity inferred that these faults are related to the Ramtha-Sirhan Fault System, (Figure 2-26).

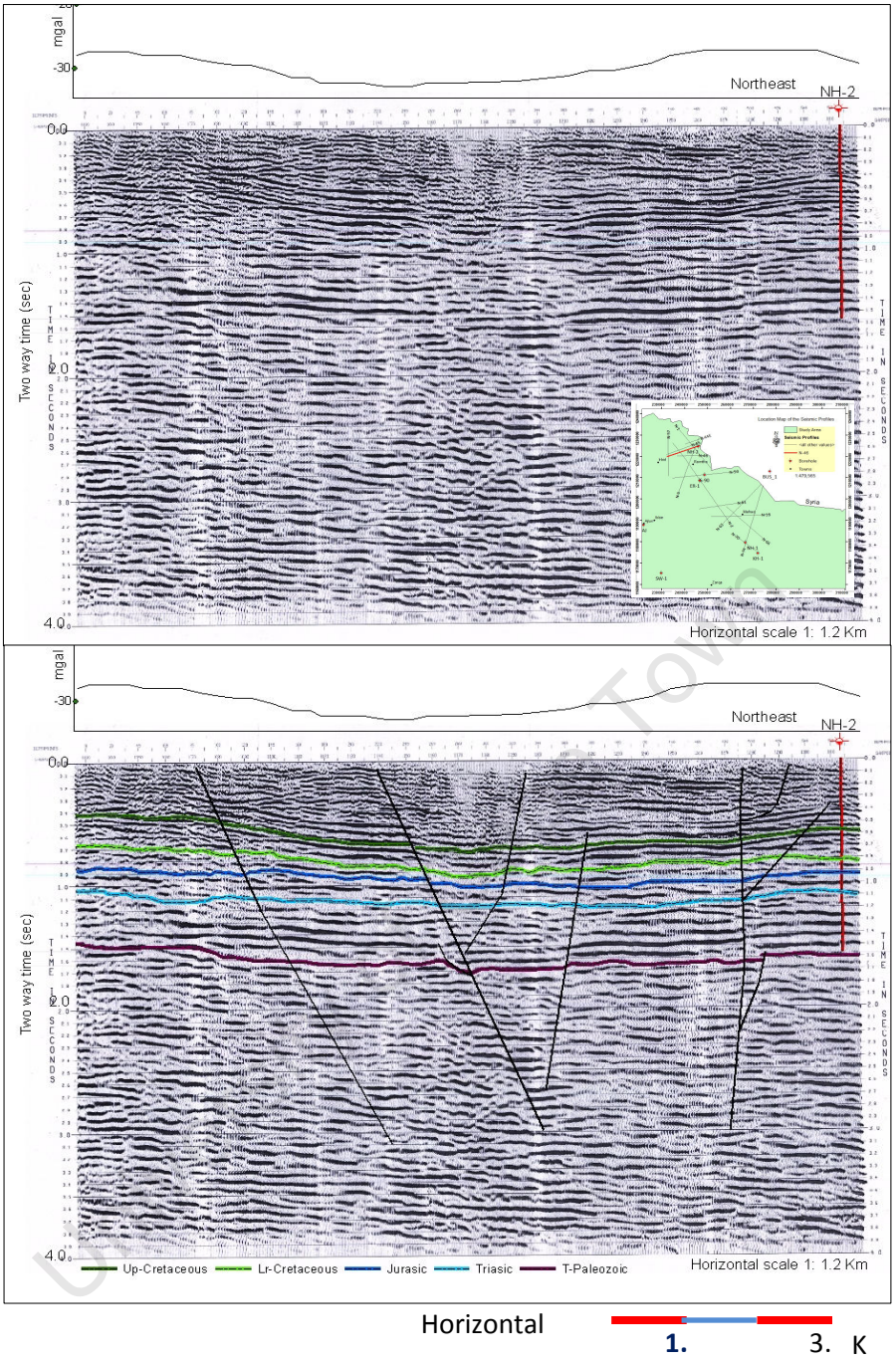


Figure 2-26: Major structural elements along N-46 seismic profile

PROFILES N-48, N-50, N-18, & N-61

These profiles extend from the west toward the east. They are characterized by series of normal step faults with secondary antithetic and synthetic small faults forming a low magnitude feature that is related to the extensional features delineated on the previous

Profiles (N-44E, N-46, and N-45); the horizons appear dipping toward the east and northeast. Profile N-48 reveals three major faults of NW-SE and NE-SW trends forming a major low magnitude structure where tilting is obvious. Compilation with the surface geology inferred that this set of faults is belonging to the Ramtha-Sirhan Fault System (Figure 2-27).

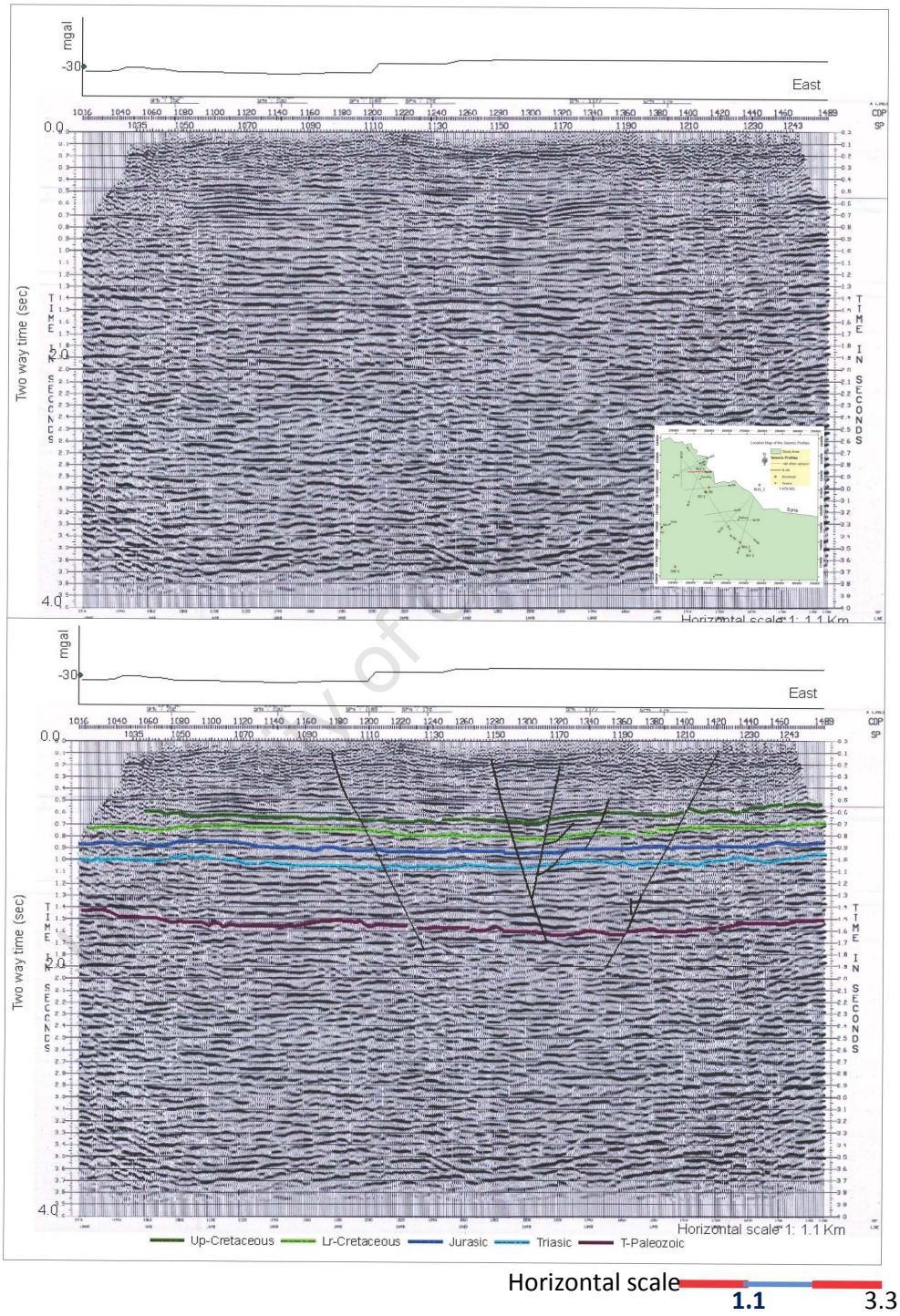


Figure 2-27: Major structural elements along N-48 seismic profile

Profile N-50 shows a number of high angle normal faults with northeastwards throw and southwestwards. The overlying sedimentary cover shows high tilting with gentle thinning westward and southwestward toward the vicinity Ajlun Dome. The lower cretaceous horizon appears close to the surface toward the west. Significant vertical deep faults appear crossing all horizons up to the high sedimentary accumulation on both sides.

Bouguer values vary from about-26 mgal to about-42 mgal (Figure 2-28).

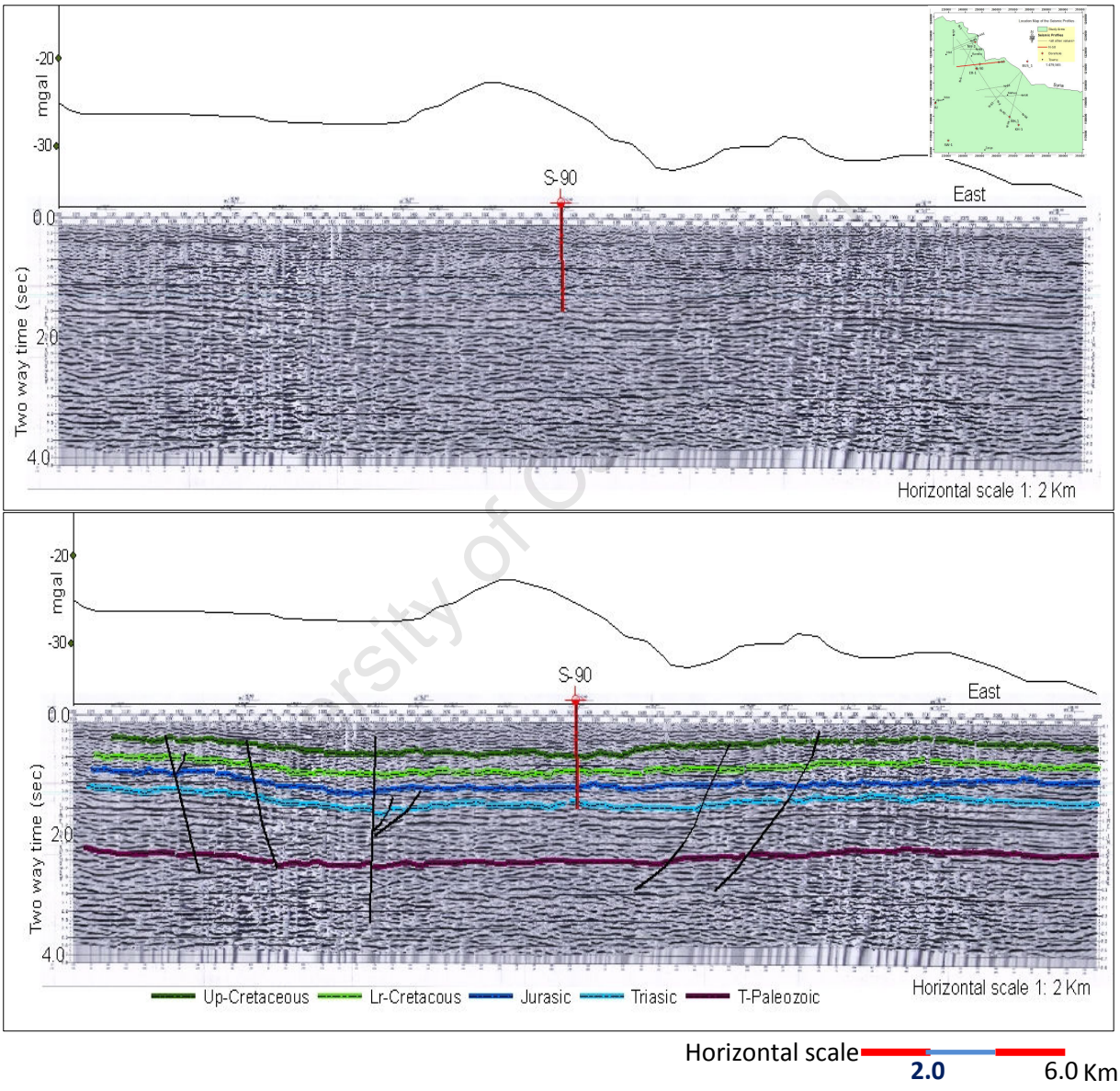


Figure 2-28: Major structural elements along N-50 seismic profile

Profile N-61 presents a series of normal step fault systems with major trend NW-SE. The rock sequences show gentle dipping toward the east. The Triassic and the Paleozoic

sequences are characterized by a remarkable thickness. The unconformity surface of (Lower Cretaceous-Triassic) is significant along this profile (Figure 2-29).

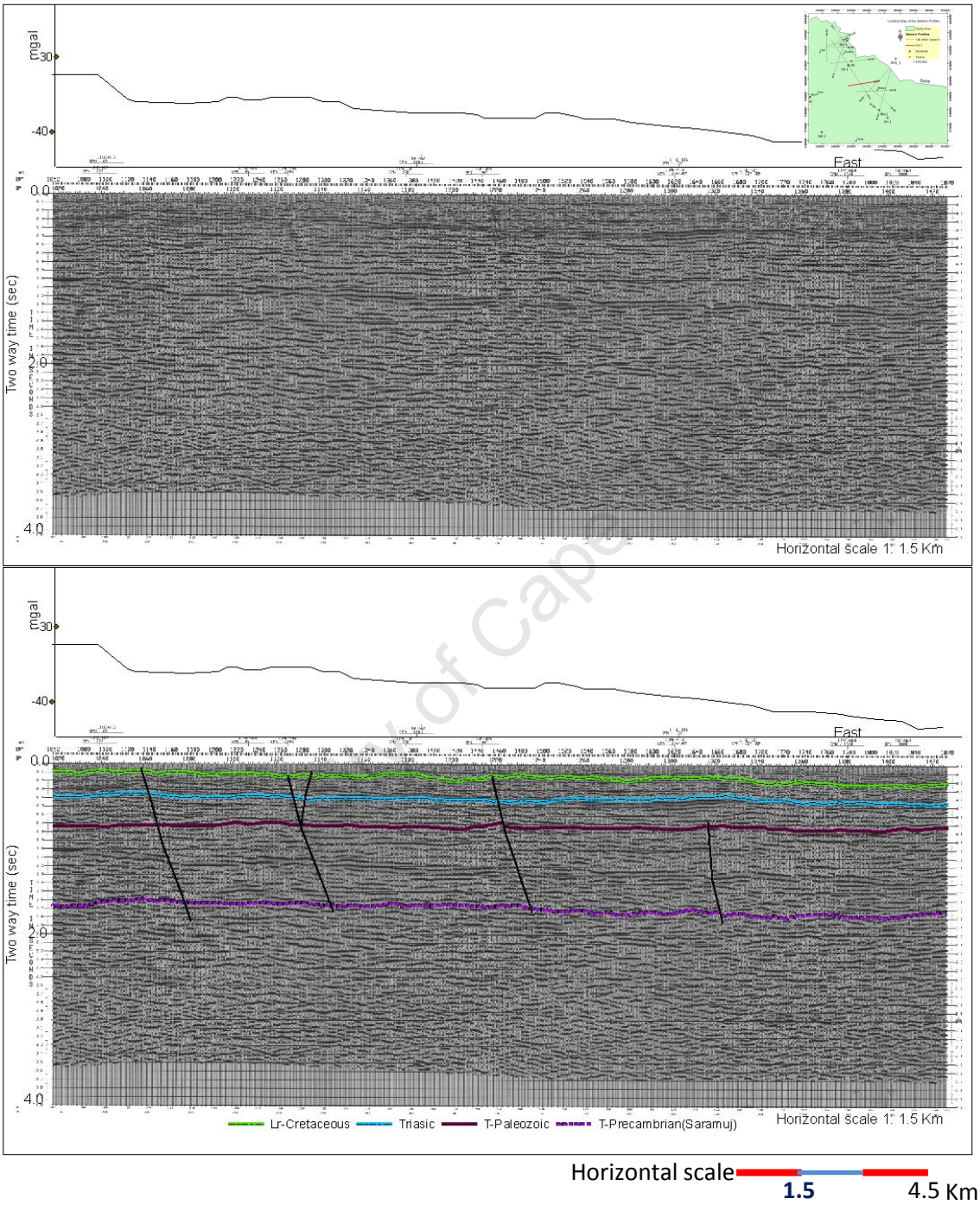


Figure 2-29: Major structural elements along N-61 seismic profile

This profile (N-18) presents a significant high magnitude element. Along the western margin of this high element, a complex structural style is exposed where Jurassic and Upper

Cretaceous sediments pinched out. This indicates the effect of simultaneous episodes of compression, tension, and rifting stresses. All traced horizons along this profile show gentle down stepping toward the east and northeast where Bouguer values reach-40 mgal –45 mgal (Figure 2-30). This broad high magnitude element comprises existence of regional

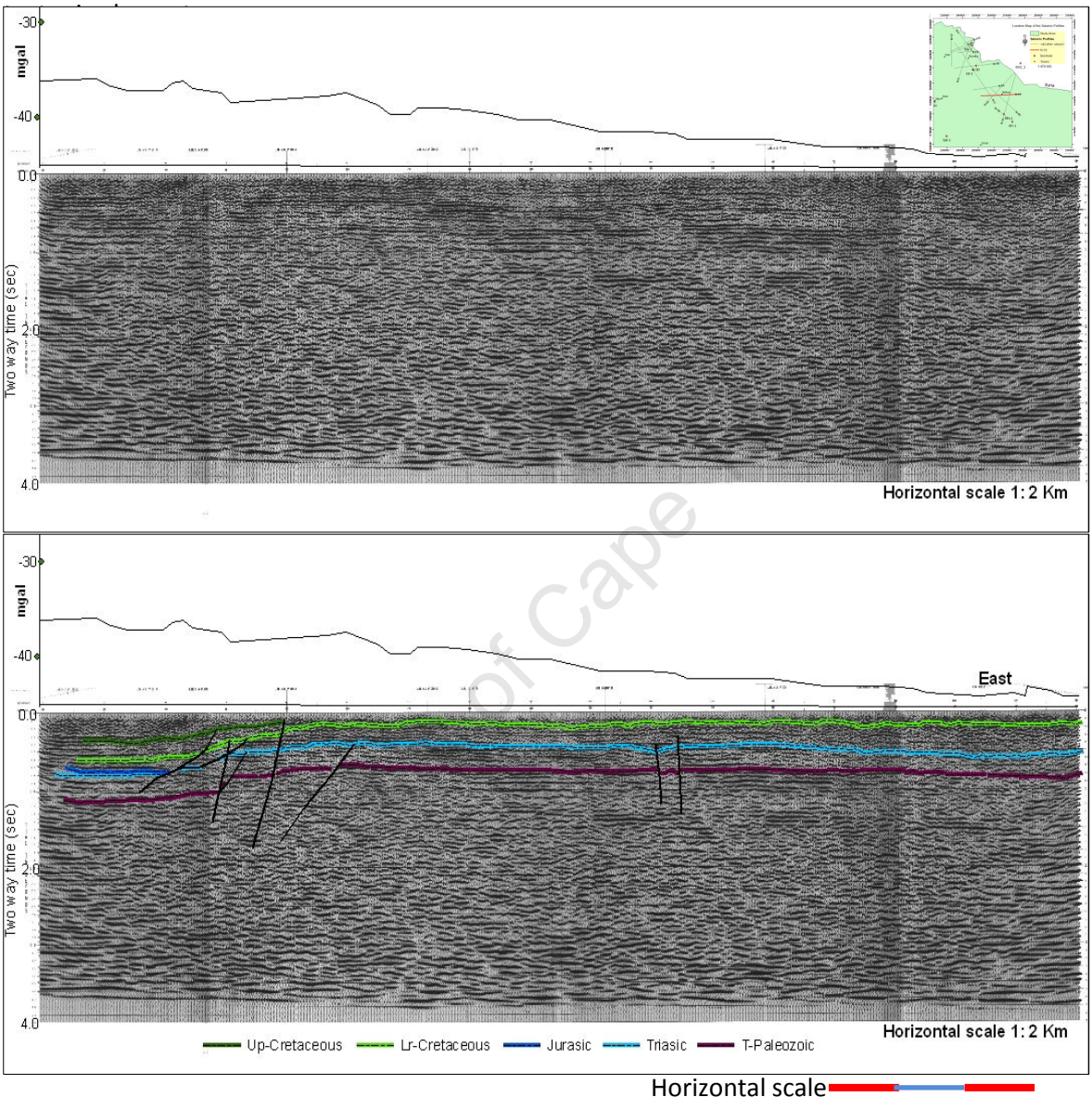


Figure 2-30: Major structural elements along N-18 seismic profile

PROFILES: N-05, N-63, AND N-74

This group of profiles extends from the southwest toward the northeast. It represents a complex structural style composed of step faulting system with multiple horsts and grabens

The regional dip appears northeastward with General down stepping eastward and southeastward. Antithetic and synthetic faults increase toward the southwest forming minor horsts and grabens. Bouguer values recorded explicit variations from about-28 mgal in the north east to about-42 mgal in the east and south east. To the west and south west, the values are between-20 mgal--18 mgal.

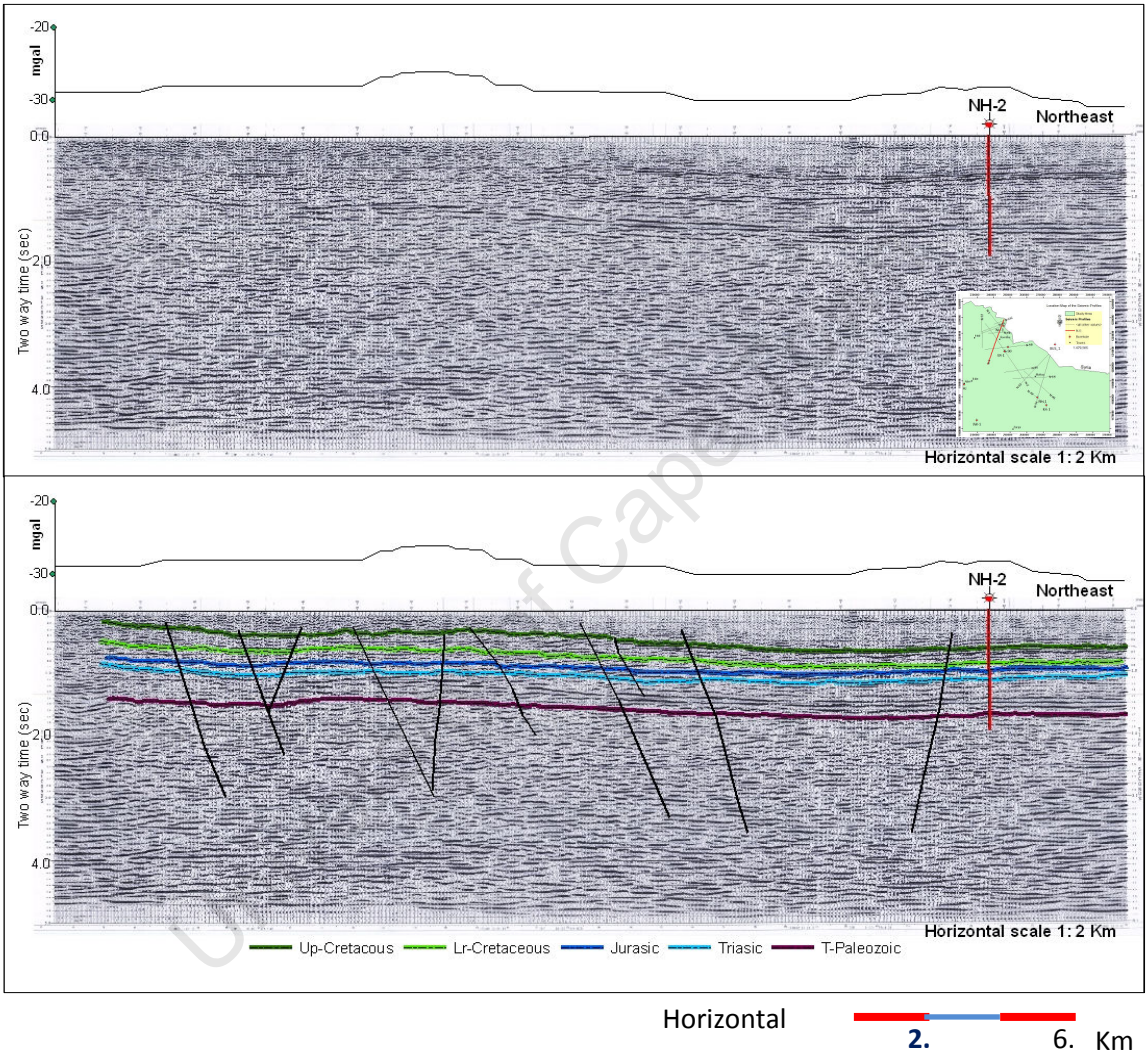


Figure 2-31: Major structural elements along N-05 seismic profile

Profile N-05 (Figure 2-31) displays step normal fault systems with trending NNW-SSE and NW-SE. The utmost southwest section of this profile traces a remarkable thinning of the Cretaceous sedimentary cover. Increase of regional tilting toward the southwest close to Ajlun Dome was significant

Profile N-63 displays a series of sub-vertical normal faults. The sedimentary cover is gently dipping to the north east. The Upper Cretaceous (Cenomanian) and the Jurassic sequences were not traced along this profile, while the Triassic and the underlying Paleozoic sequences present high thickness. Bouguer value reach to about-45 mgal toward the north east (Figure 2-32)

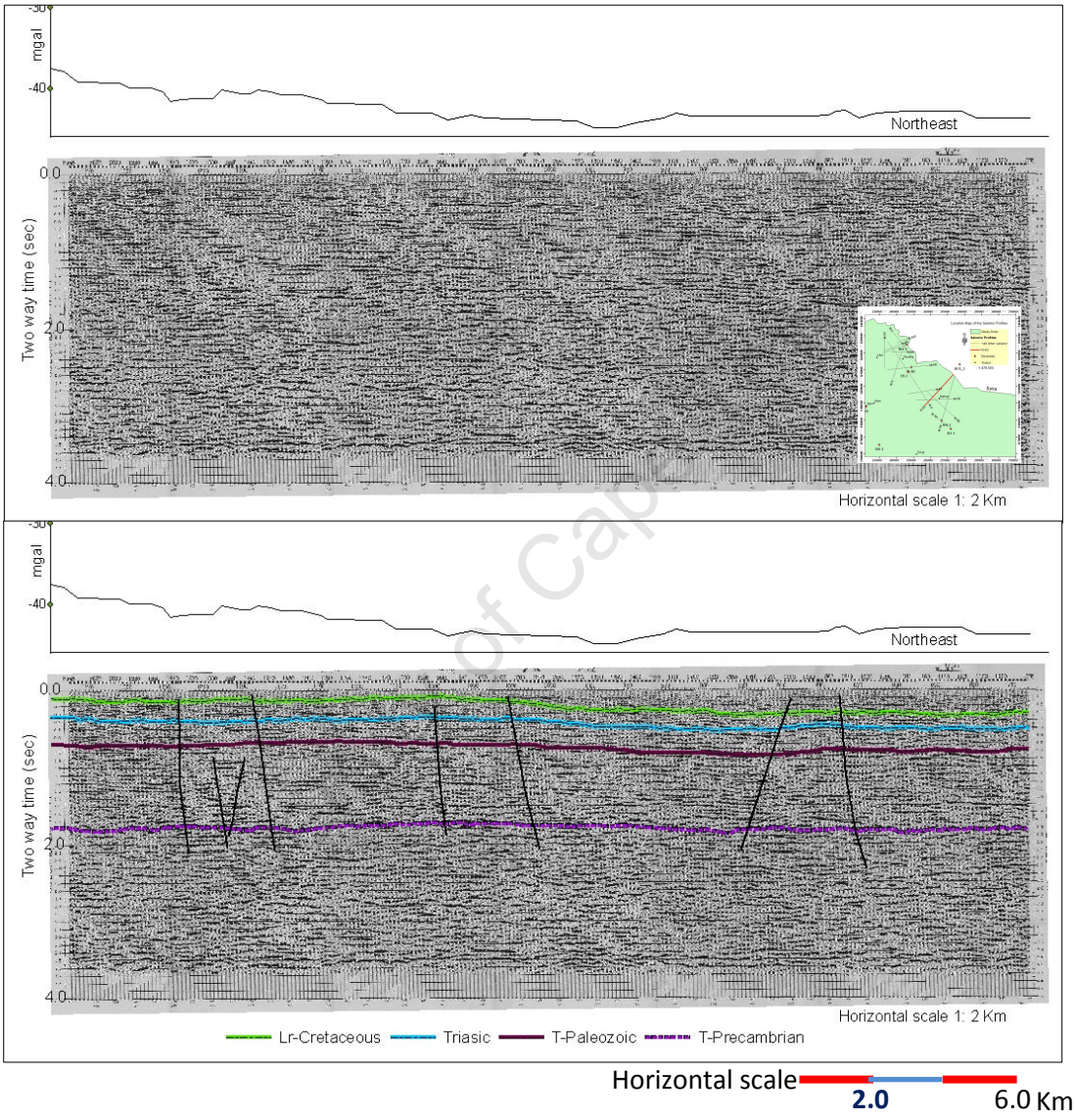


Figure 2-32: Major structural elements along N-63 seismic profile

Profile N-74 displays a number of high angle faults throwing northeastwards and southwestwards. Some of these faults inclined deeper into the older sequences. This profile presents thinning in the overlying sediments toward the southwest, and thickening toward

the northeast, this suggests down stepping toward the northeast. Bouguer values dropped from about-30 mgal in the south west to about-50 mgal toward the north east, (Figure 2-33).

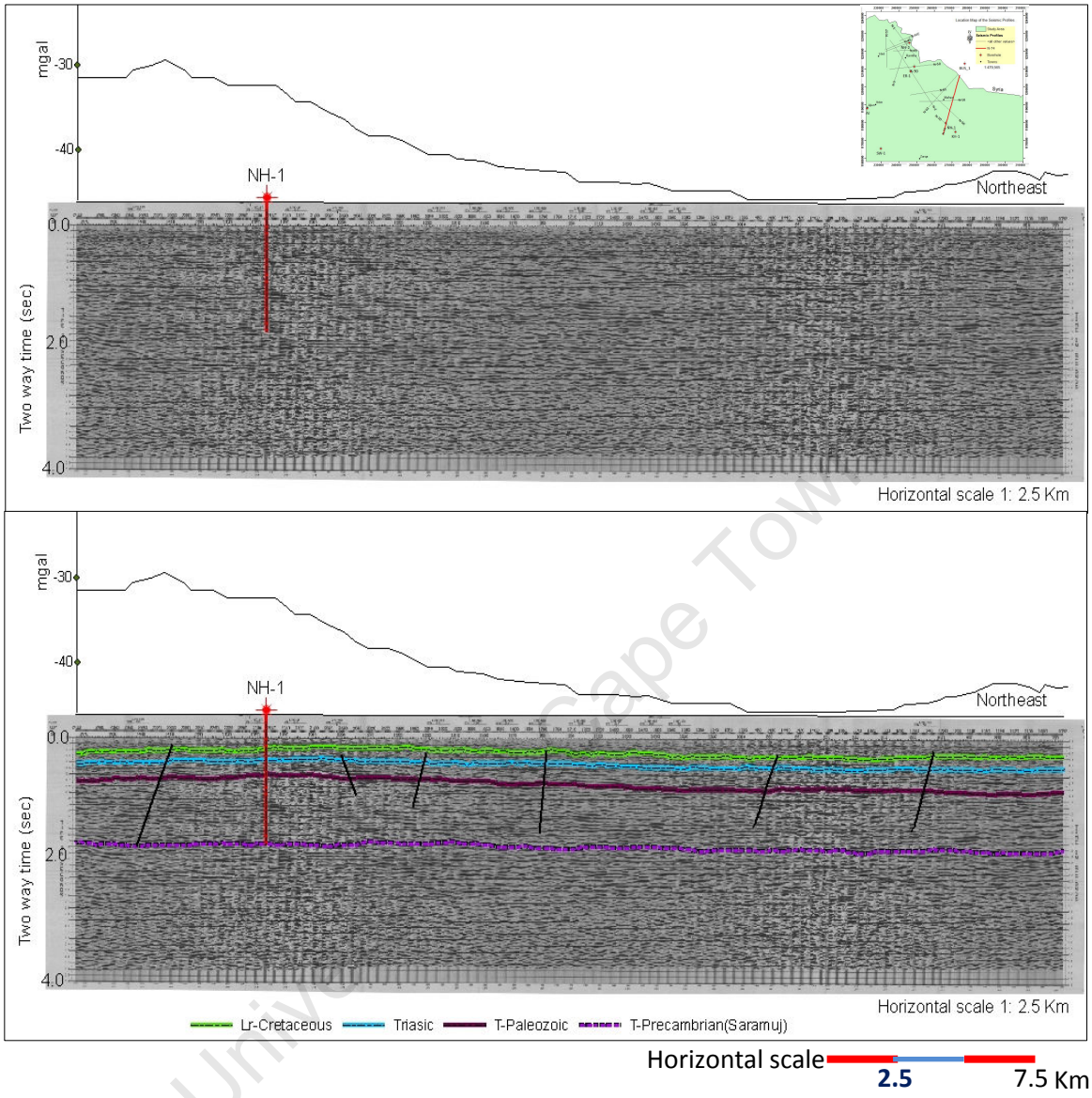


Figure 2-2-33: Major structural elements along N-74 seismic profile

S-N PROFILE N-57

Profile N-57 extends from the south to the north along the northern margin of the study area. It displays series of deep high angle faults strike E-W with northward throw. The regional dip along this profile appears gentle toward the north. The two fault sets in the northern section of this profile indicate a slight decrease in the dip of fault surfaces at deeper sequences. This may suggest that this fault set is near listric fault structures that are

probably detached the basement. Bouguer values range between about-30 mgal to about-25 mgal to-20 mgal (Figure 2-34).

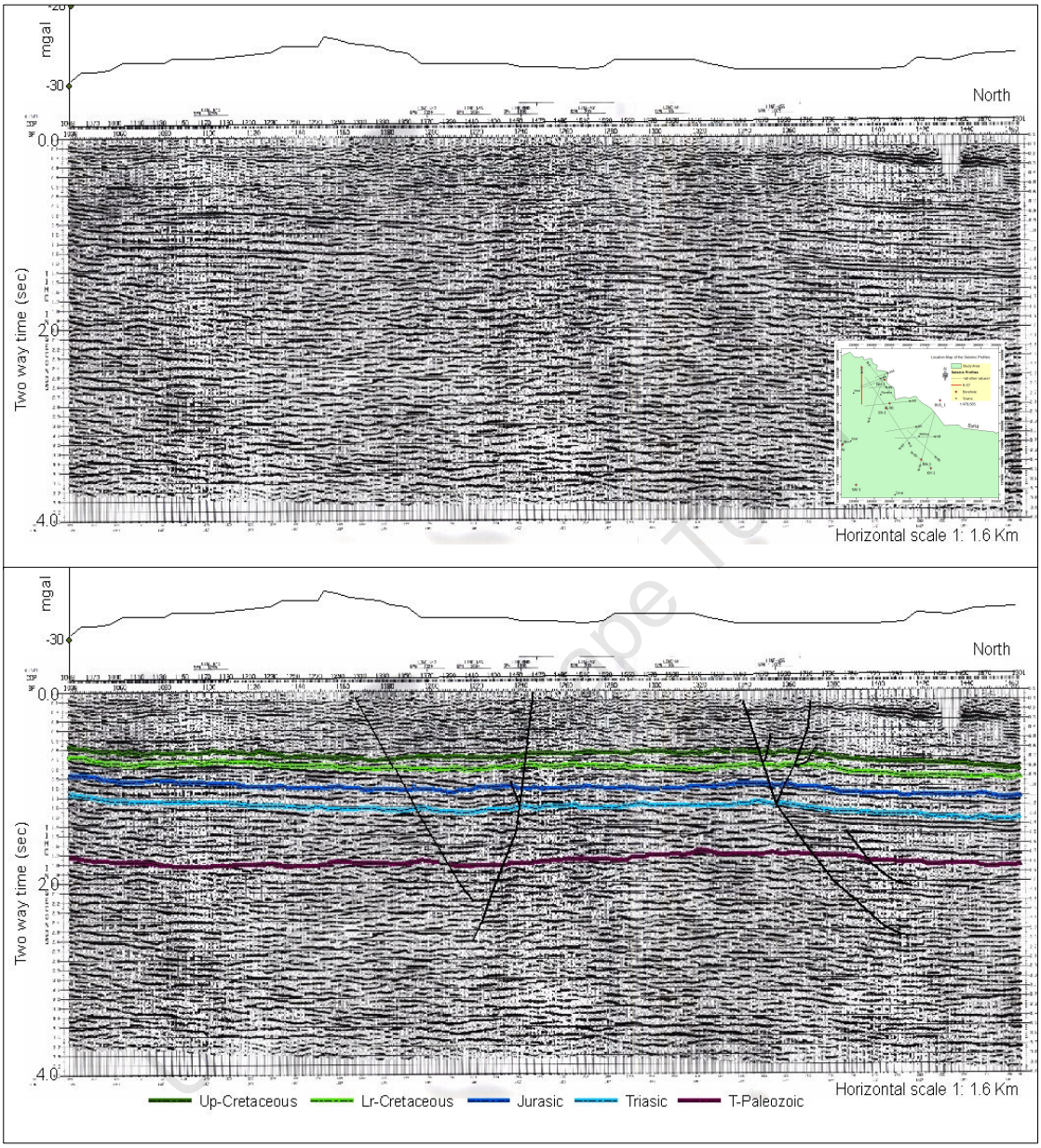


Figure 2-34: Major structural elements along N-57 seismic profile

2.4.3. STRUCTURAL MAPS OF THE IDENTIFIED SEISMIC HORIZONS

2.4.3.1. SEISMIC HORIZON 1 (H1)-TOP OF THE UPPER CRETACEOUS (THE CENOMANIAN) HORIZON

The structural contour map of Horizon 1 (H1, Fig. 2-35) illustrates that this horizon (the Cenomanian) is cut by a maze of intersecting faults with major trends of NW-SE, NE-SW, and NNE-SSW; however E-W trend is minor.

One of the major NW-SE trends crosses the area from the west of Mafraq town toward the North West passing between the S-90 and ER-1 wells.

The area lies within the vicinity of the northern portion of this fault is characterized by the presence of tilted elements crossed a by step faulting complex which forms a significant low magnitude element (depression). This depression was traced along the profiles N-44E, N-45, N-46, N-48, N-05, and N-50. The mean sea level depth contour map as calculated from the seismic profiles shows a General gradual decrease in depth from the North West toward the south east.

In the north and north east, the Cenomanian sequences show gentle dipping toward the north, east and north east. Rapid variation in depth is remarkable alongside the major fault trends.

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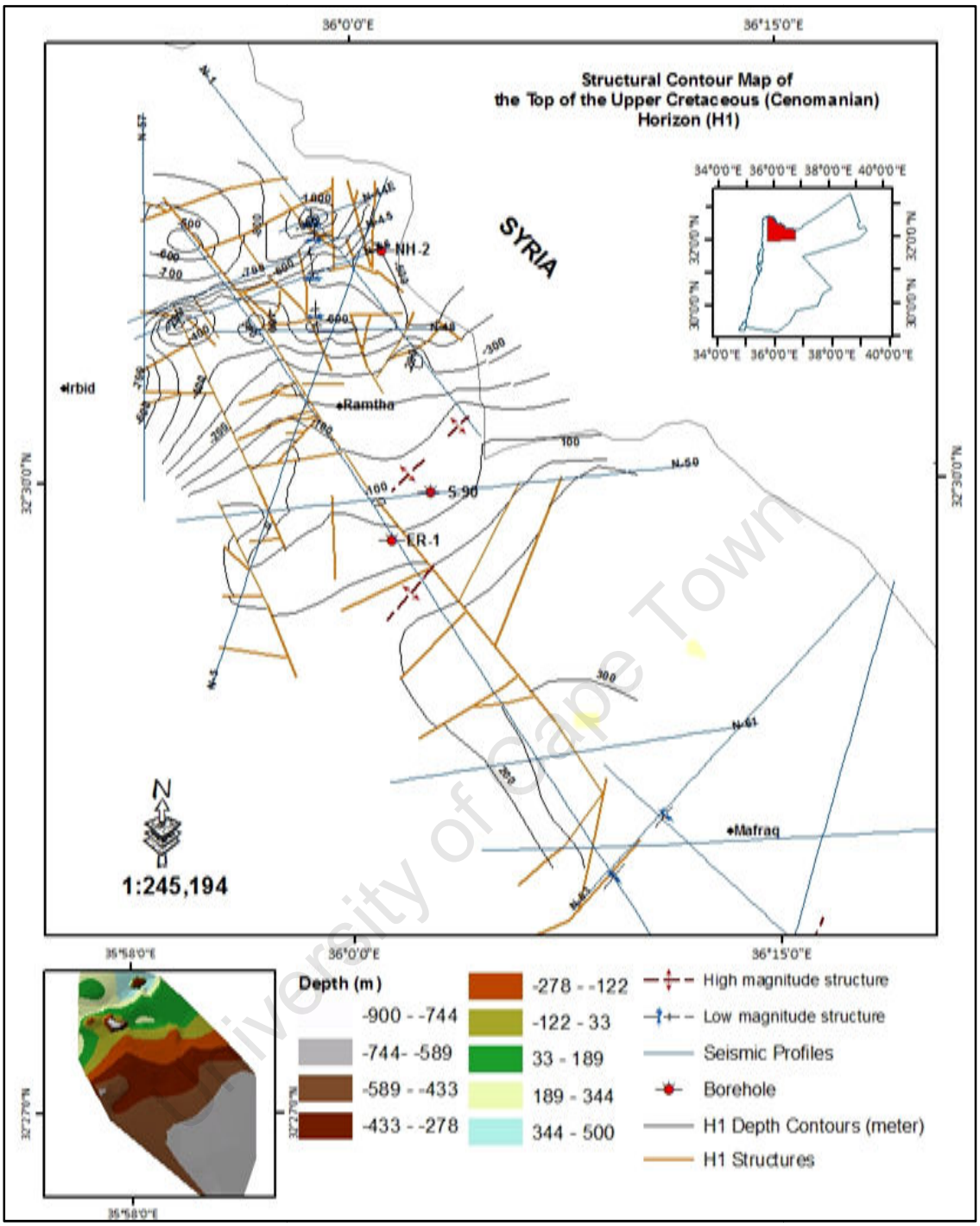

Figure 2-35: Structural contour map of the top of Horizon 1 (Top of Cenomanian)

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2.4.3.2. SEISMIC HORIZON 2 (H2)-TOP OF THE LOWER CRETACEOUS (THE ALBIAN-APTIAN) HORIZON

The structural contour map of Horizon 2 (H2, Fig. 2-36), which manifested the top of the Lower Cretaceous sequences, illustrates the presence of a highly complex fault system with major trends of NW-SE, NNE-SSW and NE-SW.

A major NW-SE trend fault crosses and passes the wells S-90 and ER-1. Along this trend, series of successive folding elements were identified with NE-SW and NNE-SSW orientation.

The northern portion of this trend illustrates similar folding structural elements to those of the overlying H1. Another NW-SE major trend along the borders with Syria and parallel to the previously mentioned trend was identified.

The depth contour map shows gradual declination in depth toward the south east around the Mafraq town.

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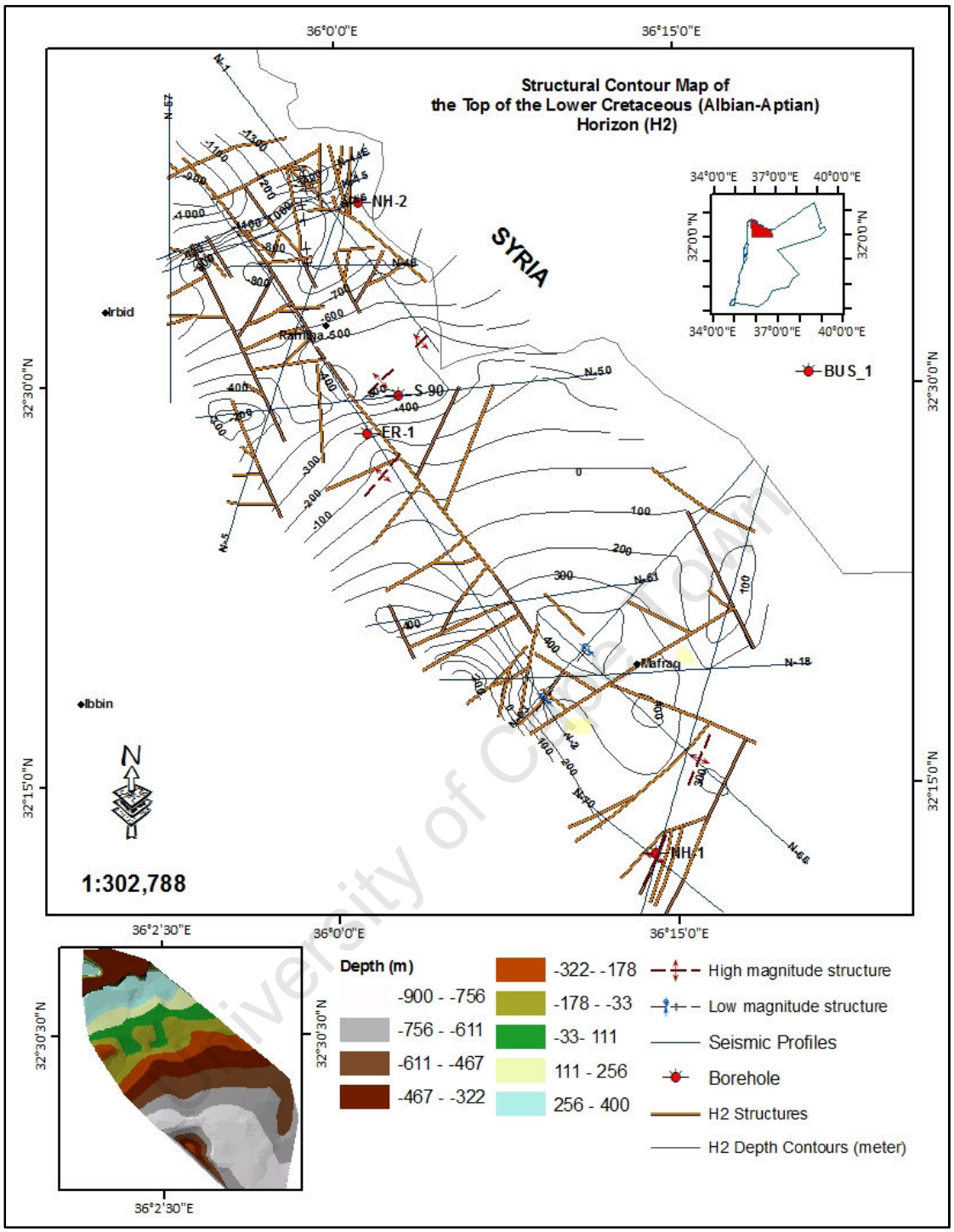

Figure 2-36: Structural contour map of the top of Horizon 2 (Top of Lower Cretaceous)

2.4.3.3. SEISMIC HORIZON 3 (H3)-TOP OF THE JURASSIC HORIZON

The Jurassic sequences illustrate remarkable tilting structural elements along the major NW-SE fault trend (Figure 2-37). A major NE-SW structural high element is evidenced within the vicinity of S-90 and ER-1 wells and close to the Ajlun Dome Structure.

The top of this horizon was identified at deeper depths in the northeastern parts than that in the southeastern parts around Mafraq town north of NH-1 well where it reaches to about 300m above sea level. A major low magnitude element was evidenced in this part.

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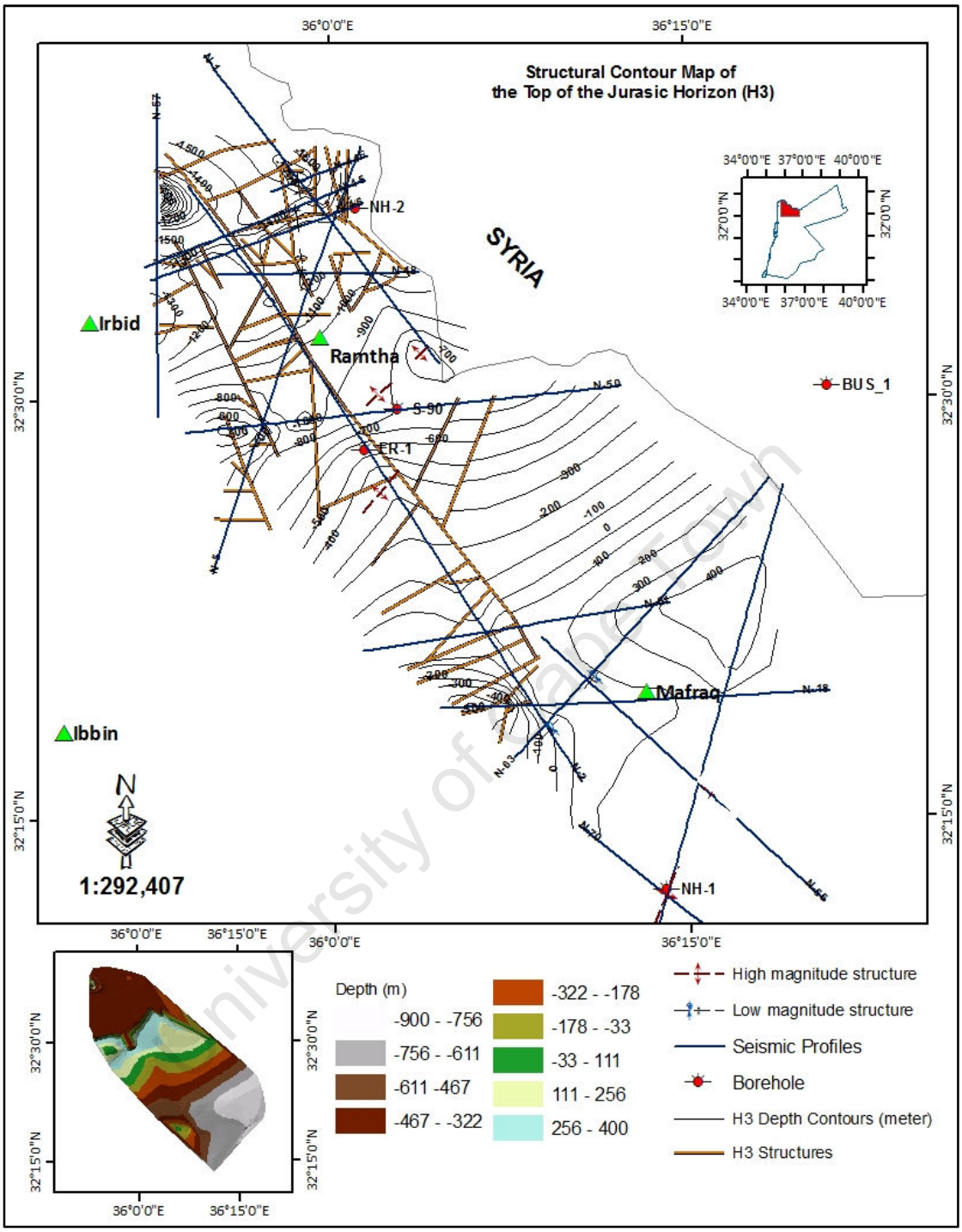

Figure 2-37: Structural contour map of the top of Horizon 3 (Top of Jurasic)

2.4.3.4. SEISMIC HORIZON 4 (H4)-TOP OF THE TRIASIC HORIZON

The Triassic is significantly structured by a series of NNE-SSW trending listric faults. These faults are downthrown most often to the northwest. However, a significant antithetic faulting, downthrown to the southeast, also occurs. Regionally, the Triassic is dipping to the northwest. There is some anticlinal features were mapped. In the area around the NH-2 well, the top of Triassic shows a horst block with closures along the margin of the bounding faults. NH-2 is drilled into a closure of this type. However, absence of seismic data into Syria prevent confirming closure to the northeast.

The age of listric faulting is probably tertiary. The seismically defined intervals do not show significant thickening on the downthrown side of the listric faults to suggest movement during deposition of the Mesozoic.

Depths show gradual declination toward the north, North West, and northeast.

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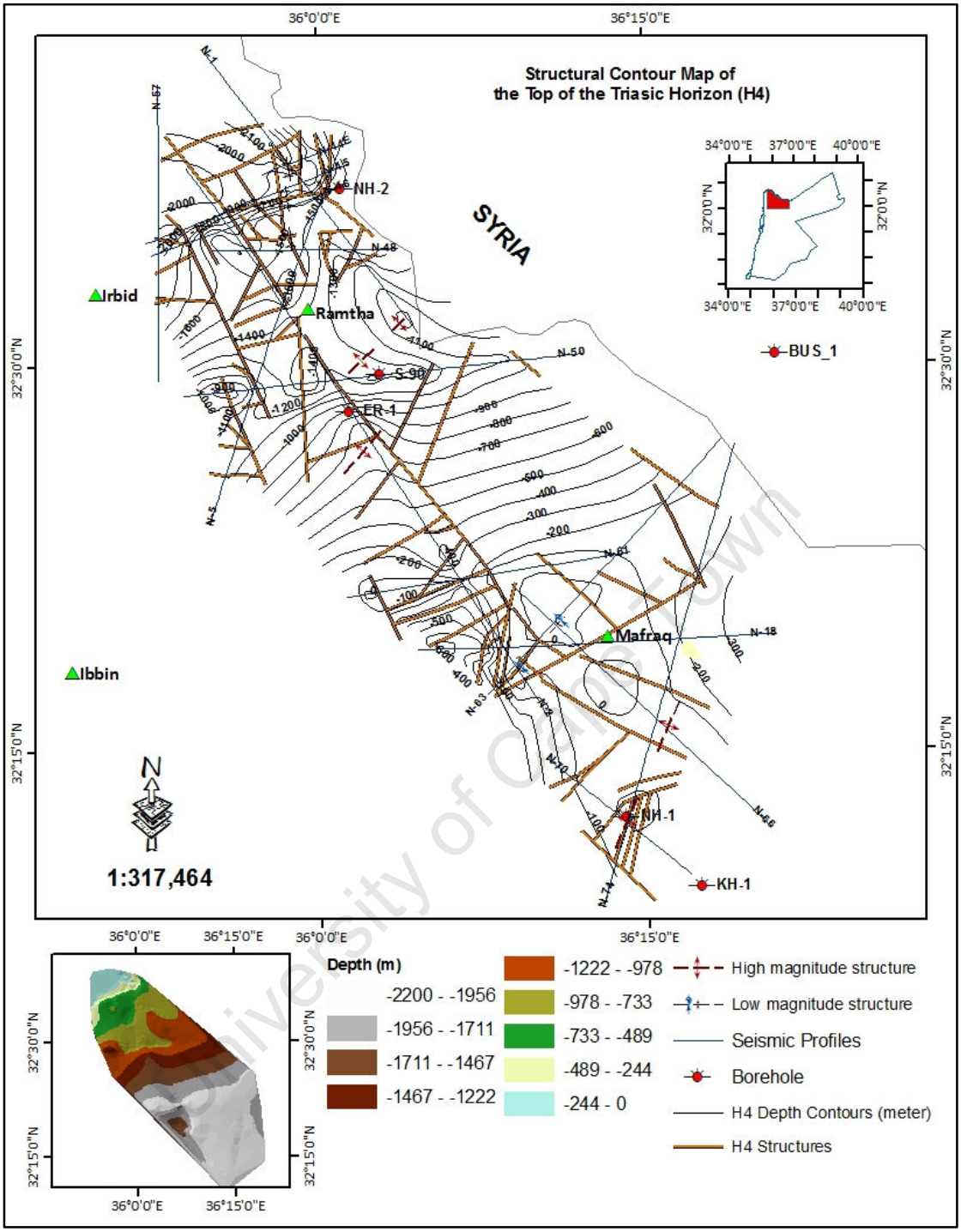

Figure 2-38: Structural contour map of the top of Horizon 4 (Top of Triasic)

2.4.3.5. SEISMIC HORIZON 5 (H5)-TOP OF THE PALEOZOIC HORIZON

The top of the Paleozoic horizon, which was identified at the NH-2 well, was mapped over western portion of the study area. The Paleozoic's are present to the east but the data quality is unusable.

The structure in the Paleozoic is primarily fault blocks with minor anticlinal development. An inspection of the top of the Paleozoic time structure map shows two significant fault trends. The first fault trend strikes NE-SW and consists of faults downthrown to the northwest. The second fault trend strikes N-S. The faults on this trend are downthrown both east and west. This N-S system forms a series of narrow horst block .This trend could continue to the east. Wells S-90 and ER-1A were drilled into this trend. It is difficult to determine due to deteriorating record quality if these well were in the highest portion of the horst block. In the case of the S-90 well, the well appears to be on a culmination on a horst block. In the case of the ER-1A well, the well may be off the highest portions of a long N-S horst block. The NH-2 well appears to be drilled in a favorable location at the intersection of the tow significant fault trends. However, as with the top Triassic structure, the limit of data into Syria does not allow for good definition of this structure at the NH-2 well.

Age of the faulting of the top Paleozoic is difficult to determine from the seismic data. Inspection of the seismic correlated intervals does not give any specific insight into the age of faulting. The time of block faulting could be any age as the faults are attenuated in the Triassic anhydrites.

In the southern portion of the concession area, there does appear to be some leads in the Paleozoic. These structures are poorly defined because of poor to very poor data quality.

The top of this horizon declines gradually toward the east and southeast and become shallower toward the west and North West. Figure 2-39

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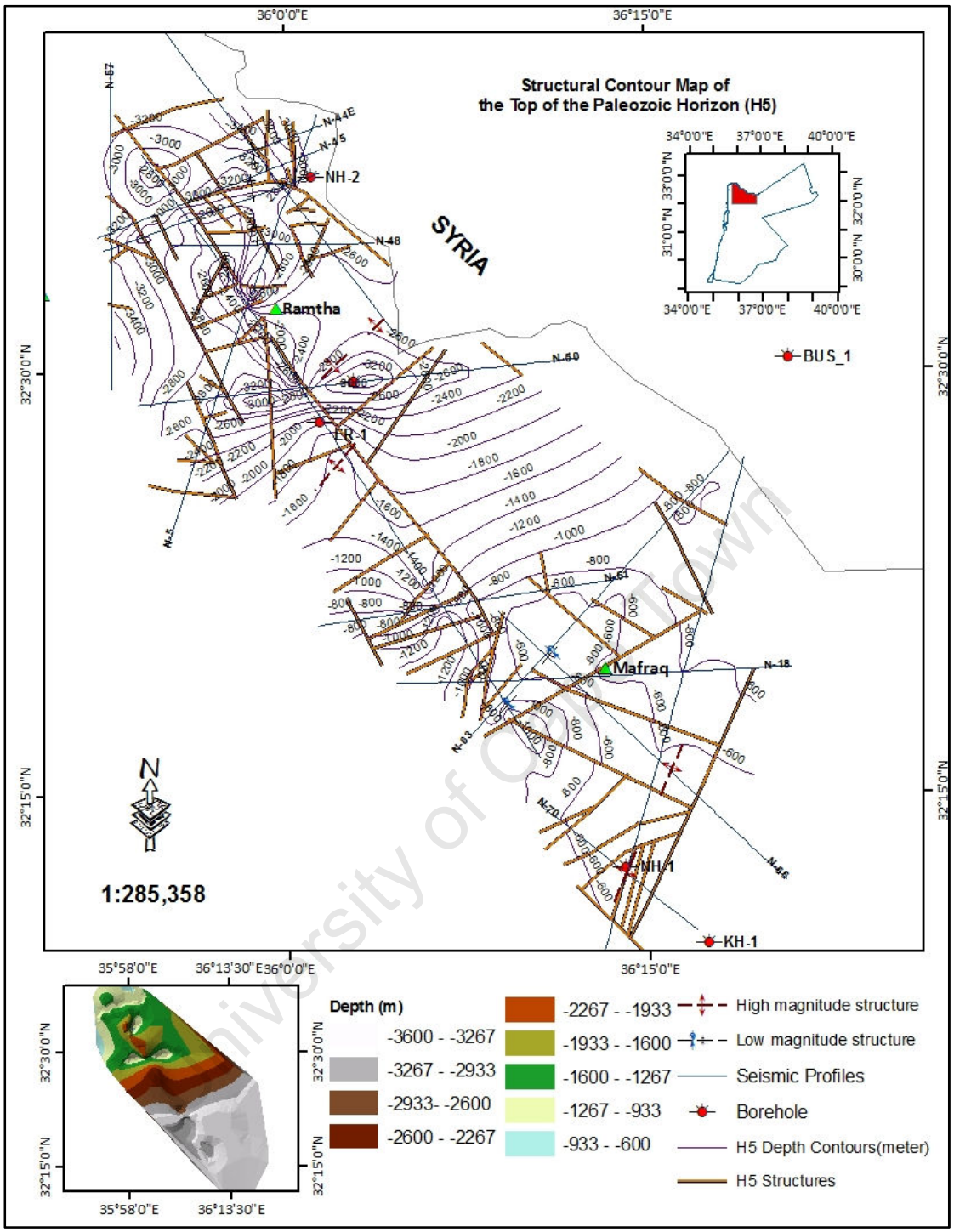

Figure 2-39: Structural contour map of the top of Horizon 5 (Top of Paleozoic)

2.4.4. STRUCTURAL ANALYSIS

2.4.4.1. MAJOR TREND AND GENERAL DIP

Insufficient seismic coverage in the central and western regions of the study area made it difficult to tie fault segments from one profile to another. However, classification of those segments based on their cross-cutting relationship to the stratigraphic horizons, eased analysis.

The structural maps outlined a maze of intersecting faults with General dip toward the northeast. Faults that cross-cut all horizons and either penetrate up to the surface or near the surface dominate the area with two major trends NW-SE and NE-SW. One of the major NW-SE fault trends crosses the area from southeast to the northwest between the S-90 and ER-1 wells to the west of Ramtha town. Correlation with the surface data implied its relation to the Ramtha-Sirhan Fault System.

Gravity interpretation implied another major NW-SE fault, extending into the area from southeast to the northwest along the borders with Syria in parallel to the previously mentioned major NW-SE fault. Correlation with surface geology indicated that this major element may be related to an extension of the Fuluq Fault System.

NE-SW trend appears intersecting the major NW-SE fault at angles varying from ~N07º to the southeast, ~N25º to the northeast, and ~N45º to the north. The area on intersection between these two major trends displays highly complex faulting systems with General dip eastwards.

Poor coverage of seismic data has lead to poor outlining of the N-S trend; however, line N-44E north of the area presents one segment of this trend.

2.4.4.2. THROW AND DISPLACEMENT ORIENTATION

As a result of correlation of the interpreted fault segments with the surface geology and the gravity interpretation, three major faulting systems are dominating the area; NW-SE, NE-SW, and E-W. N-S trend appears minor. General throw of the NW-SE faults orients eastward, while for those of NE-SW trend, throw is southeastwards in the southeastern parts and northward in the northern parts of the area. E-W segments present northward throw.

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2.4.4.3. THICKNESS VARIATIONS

Analysis of the depth contour maps shows a remarkable thickening in the Mesozoic sedimentary cover toward the north, northeast, east, and southeast and significant thinning toward the west and southwest where Cretaceous horizons almost reach the surface .This may suggest regional uplifting in this direction close to the Ajlun Dome at the southwestern edge of line N-05. Analysis of the marker horizons and their depth contour maps exposed the presence of successive folding structures with NE-SW and NNE-SSW orientation, and cut by complex faulting systems mainly of the NW-SE and NE-SW trends. Among these, a high relief closure orienting NE-SW was identified to the southeast on the intersection of profiles N-70, N-74, and N-66. Two deep seated-faults border it on both sides. Profiles N-46,-46, and-44E present another distinctive low relief horst block structure orients northeastward. High angle deep-seated listric normal faults trending NW-SE and NNE-SSW are bounding it.

Figure 2-40 displays depths of the top of the horizons as delineated along seismic profile N-01 which extends to the southeast for about 25 km. It displays an increase in thickness of the Mesozoic sequences toward the northwest with gentle dipping in this direction. Triassic and Paleozoic sequences show remarkable thickening toward the southeast.

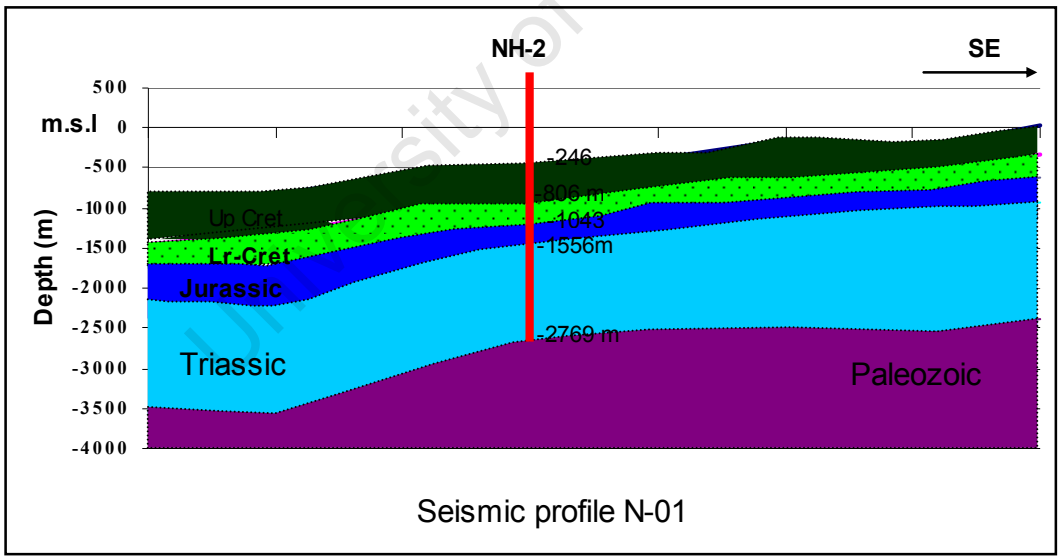

Figure 2-40: Depth (m) variations along seismic profile N-01 (length is about 25 km)

Along profile N-02 (Figure 2-41) the depth decreases toward the southeast with an increase in thickness of the Paleozoic and Triassic sequences. Lower Cretaceous rocks are thinning toward the southeast. Jurassic sequences are missing toward the southeast.

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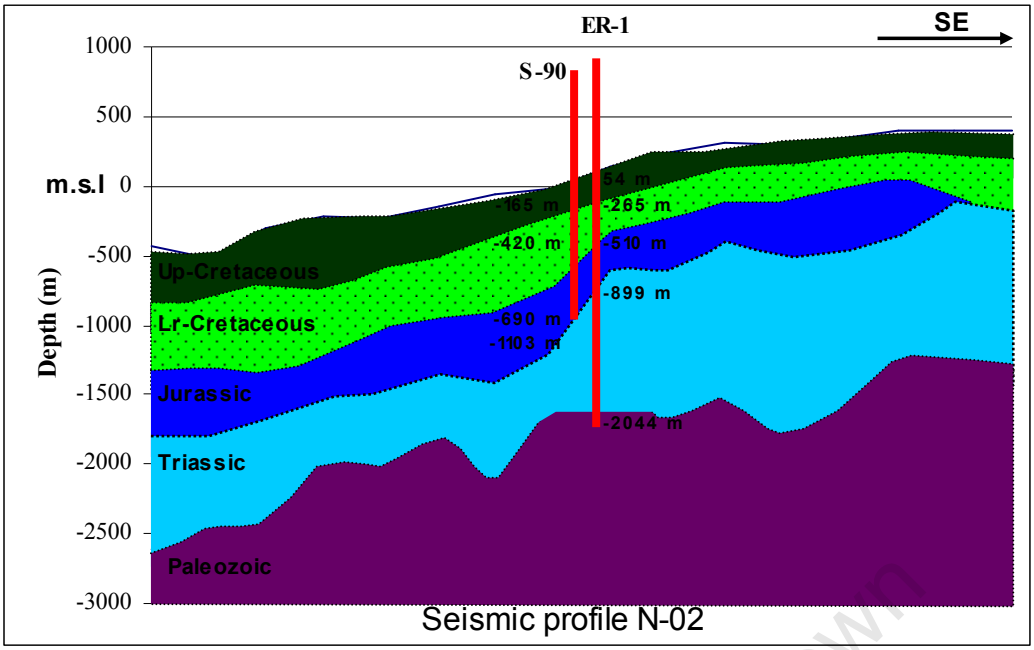

Figure 2-41 Depth (m) variations along seismic profile N-02 (length is about 47 km)

Figure 2-42 displays significant thickness of Paleozoic sequences that is noticeable towards the southeast where Jurassic and Upper Cretaceous sequences are missing which indicates episodes of tilting and erosion took place across the area

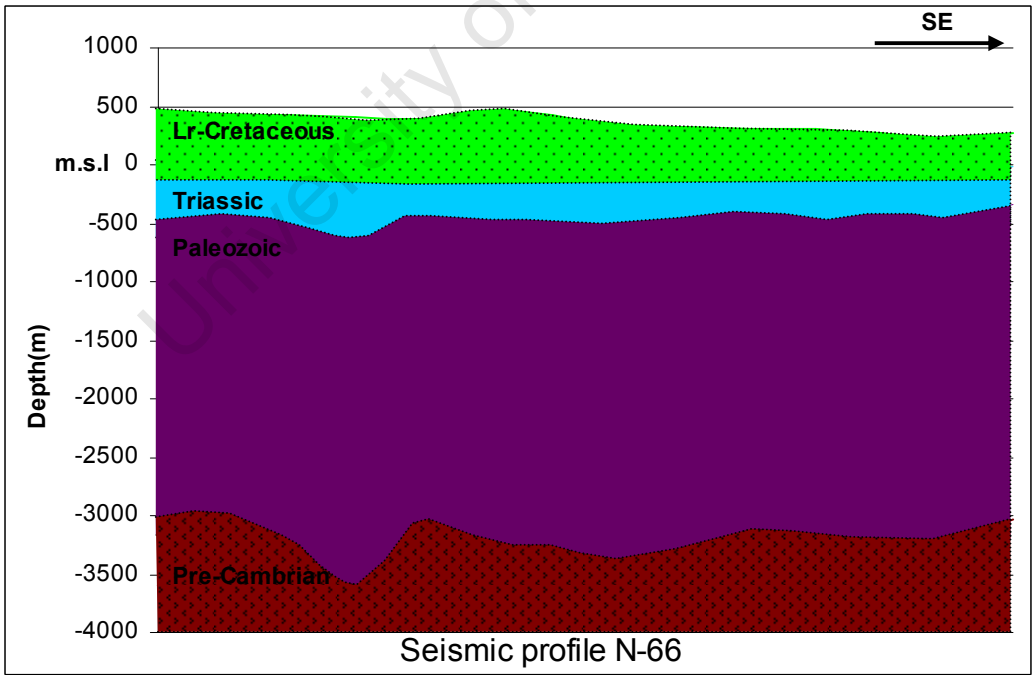

Figure 2-42 Depth (m) variations along seismic profile N-66 (length is about 25 km)

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Figure 2-43 illustrates depth variations along profile N-70 which extends toward the southeast to about 14 km. It emphasizes the same depth characteristics illustrated by N-66.

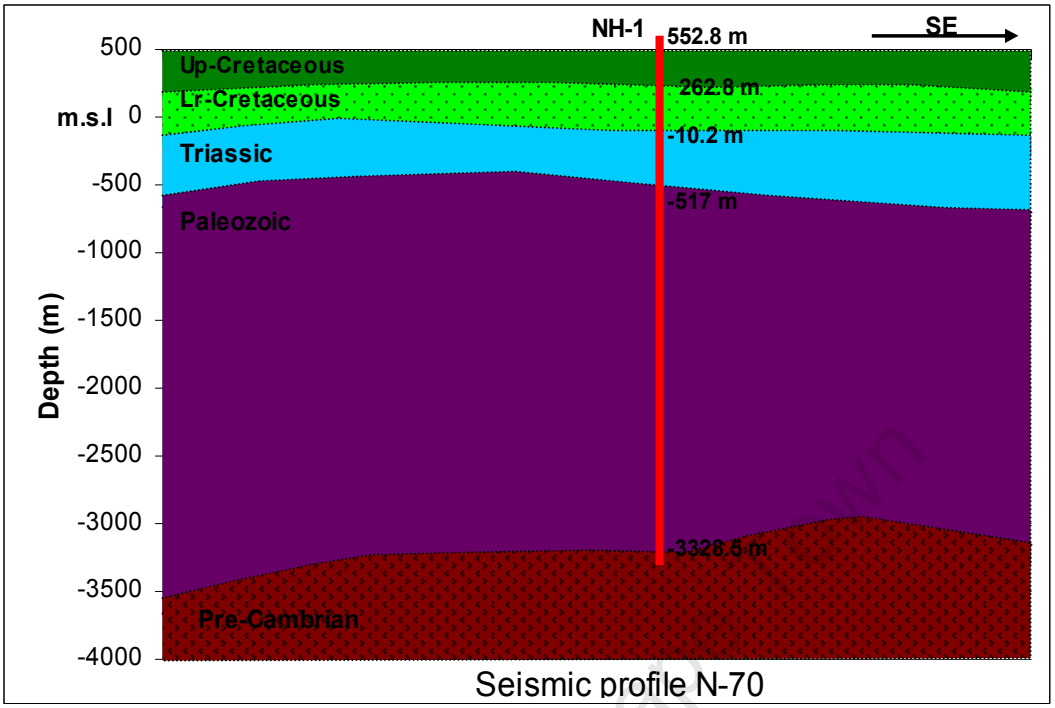

Figure 2-43: Depth (m) variations along seismic profile N-70 (length is about 14 km)

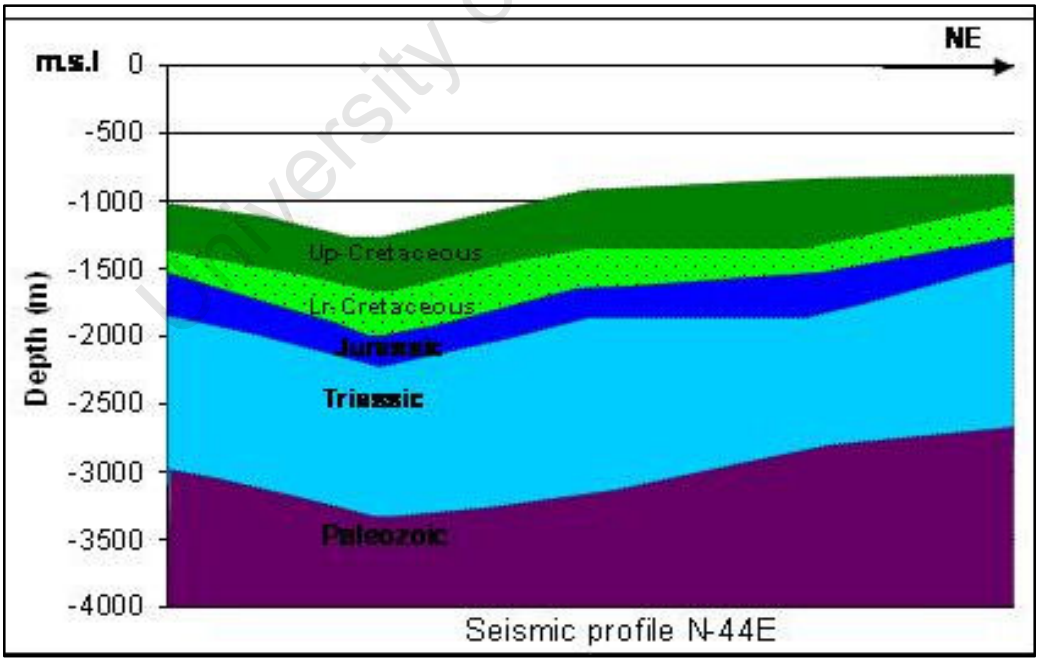

Figure 2-44 Depth (m) variations along seismic profile N-44E (length is about 14 km)

Figure 2-44 illustrates depth variations along profile N-44E, which extends toward the northeast. In this direction, Tilting is remarkable where a main synclinal element is recognizable. All stratigraphic horizons present stable thickness. Tilting characterizes this profile, which indicates compression stress effects in this direction (Figures 2-45, 2-46, and 2-47)

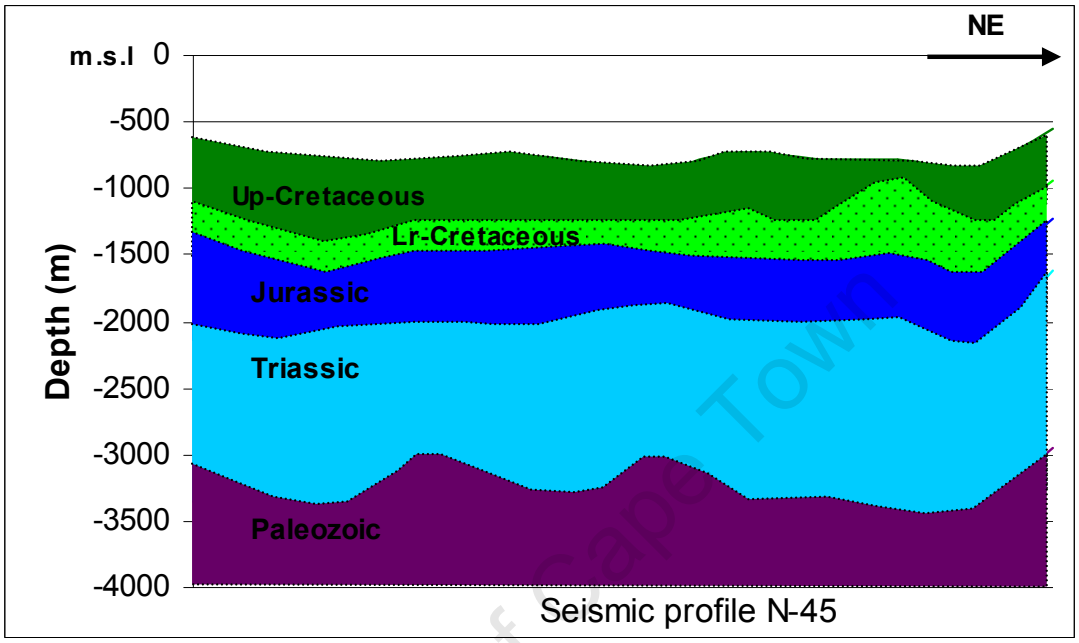

Figure 2-45: Depth (m) variations along seismic profile N-45 (length is about 16 km)

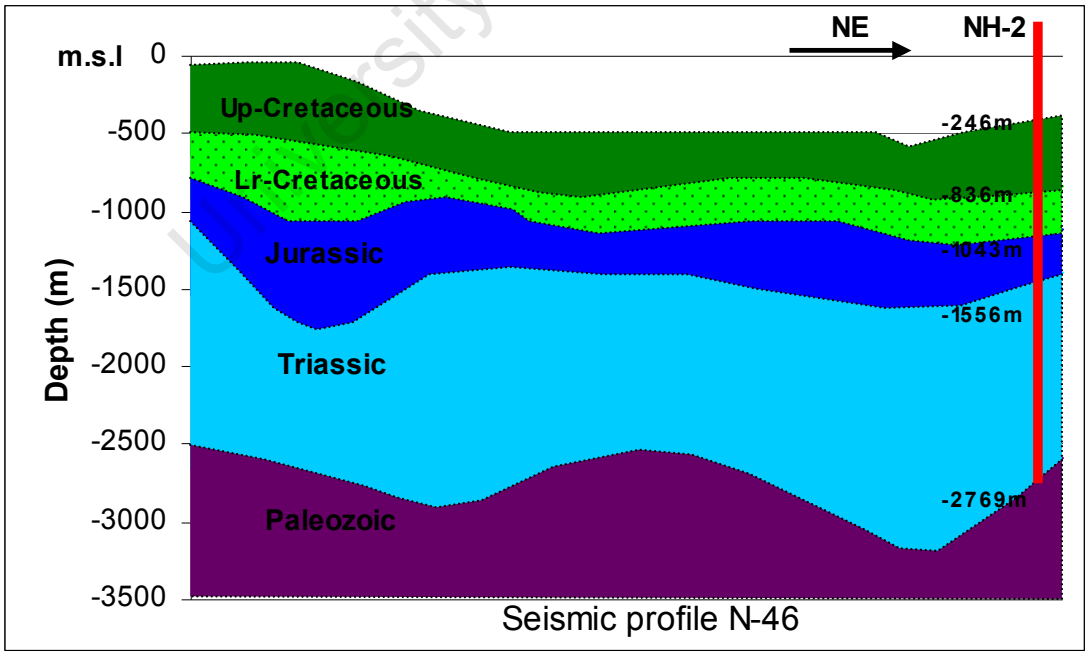

Figure 2-46: Depth (m) variations along seismic profile N-46 (length is about 15 km)

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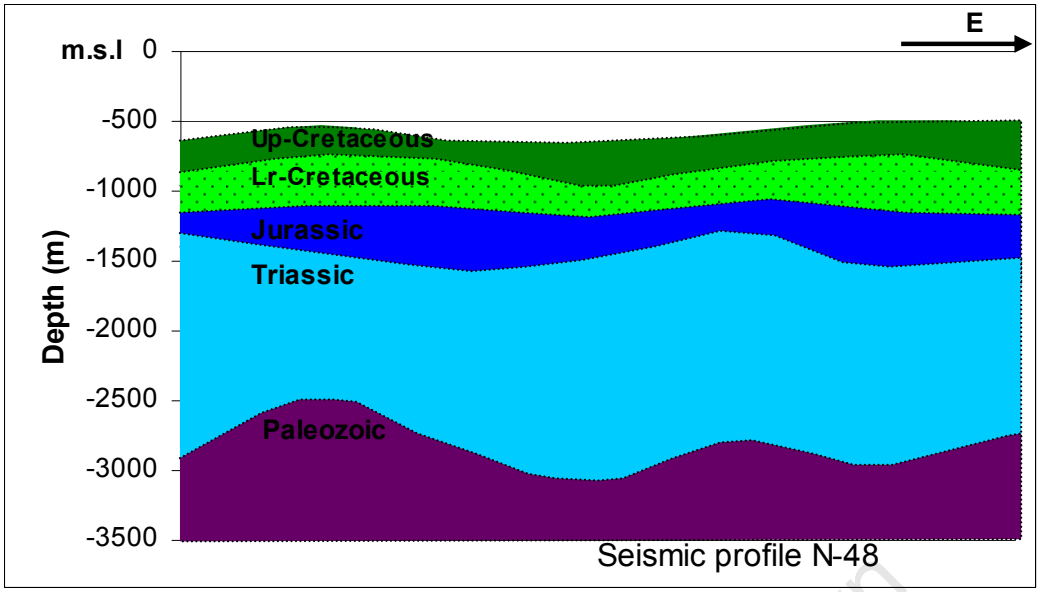

Figure 2-47: Depth (m) variations along seismic profile N-48 (length is about 14 km)

Figure 2-48 illustrates remarkable Triassic thickness within the vicinity of S-90 well.

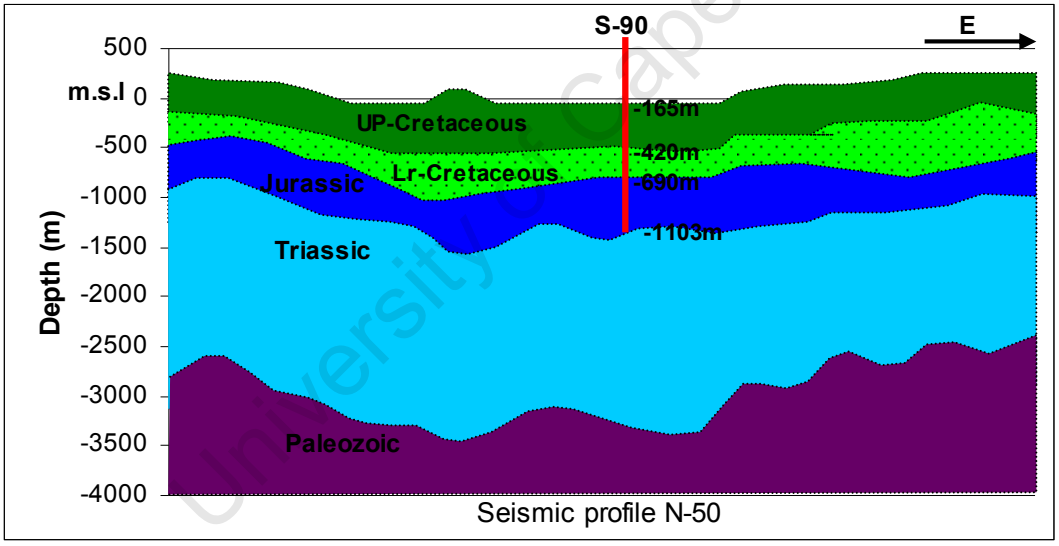

Figure 2-48: Depth (m) variations along seismic profile N-50 (length is about 29 km)

Profiles N-61, N-18, N-74, and N-63 illustrate uniform thickening of the Paleozoic and Mesozoic sequences toward the east and southeast. Yet, Jurassic and Upper Cretaceous sequences are missing toward the east which emphasizes episodes of compression, tension, and erosion. (Figures 2-49, 2-50, 2-51, and 2-52)

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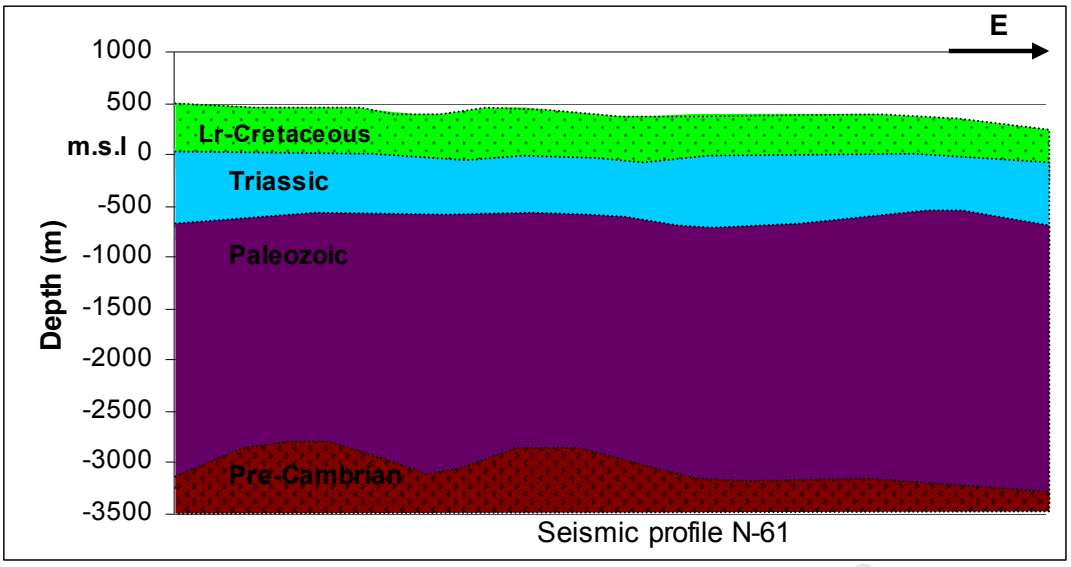

Figure 2-49 Depth (m) variations along seismic profile N-61 (length is about 20 km)

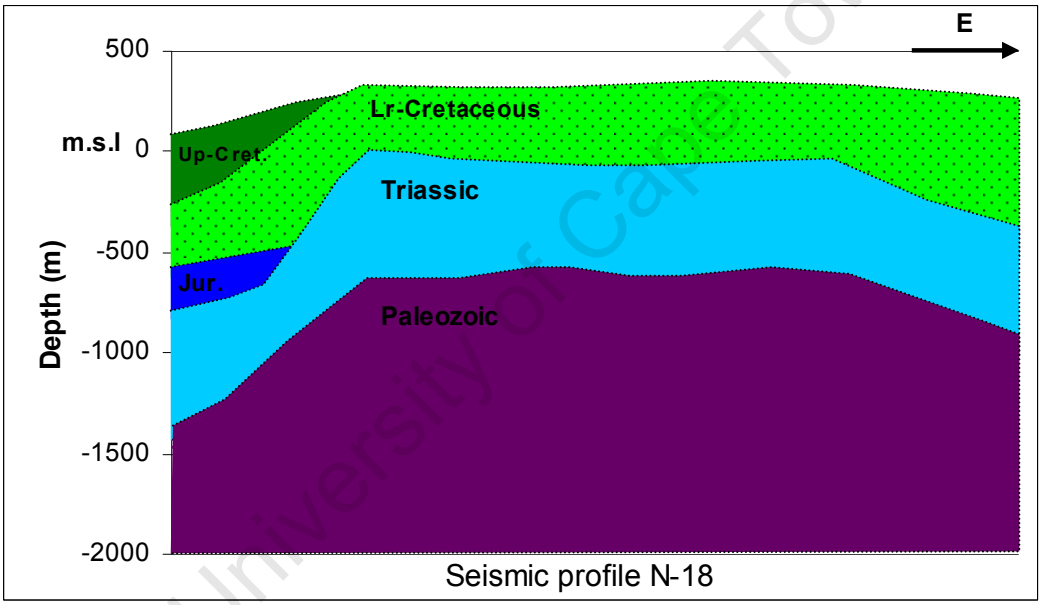

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Figure 2-50: Depth (m) variations along seismic profile N-18 (length is about 26 km)

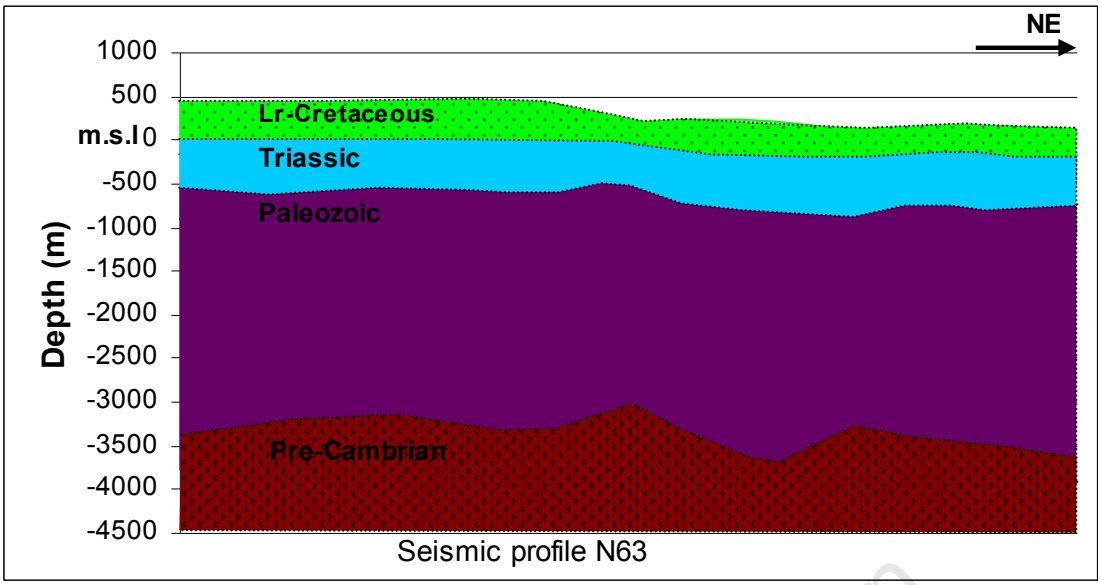

Figure 2-51: Depth (m) variations along seismic profile N-63 (length is about 25 km)

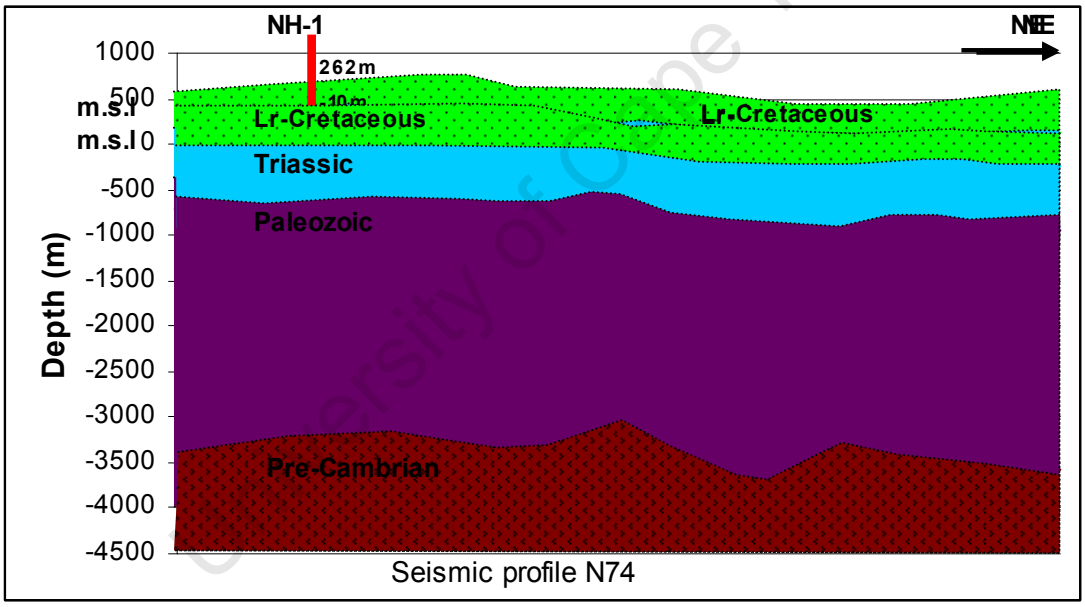

Figure 2-52: Depth (m) variations along seismic profile N-74 (length is about 34 km)

Figure 2-53 illustrates the depth variation in the direction southwest-northeast. Triassic sequences show slight thickening towards the northeast, while Jurassic and lower Cretaceous show slight thinning in this direction. On the contrary, Upper Cretaceous appears almost uniform. A major structural low element to the west of NH-2 well is remarkable.

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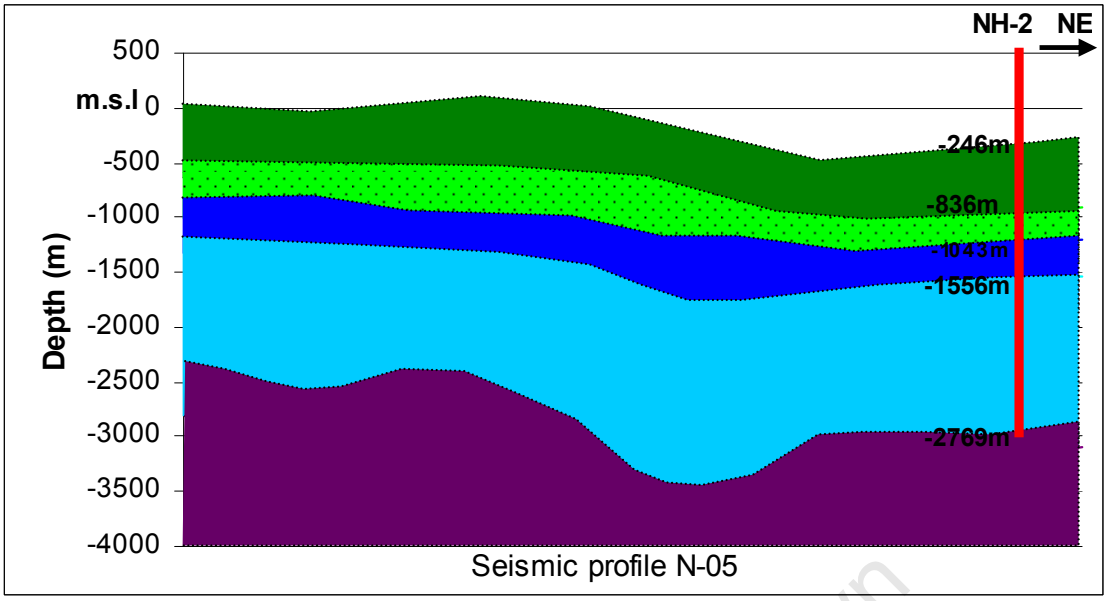

Figure 2-53: Depth (m) variations along seismic profile N-05 (length is about 29 km)

Figure 2-54 displays thickness increase in the Triassic sequences toward the south along profile N-57.

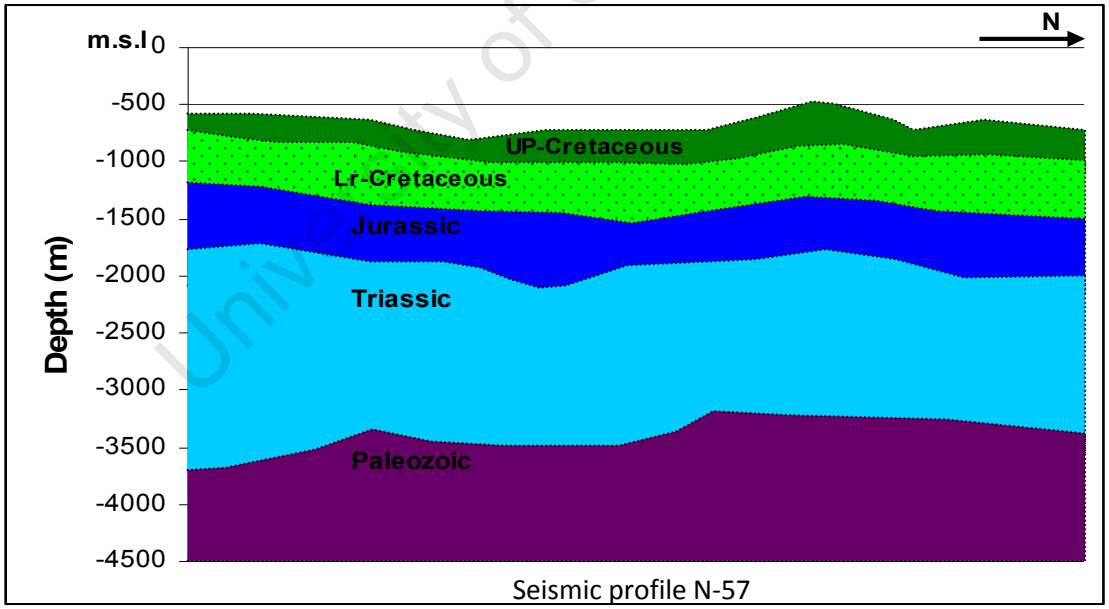

Figure 2-54: Depth (m) variations along seismic profile N-57 (length is about 22 km)

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2.5. SEISMICITY DATA INTERPRETATION

The regional earthquake catalogue, provided by the Jordan Seismological Observatory at the Natural Resources Authority, includes all events between 1907 and 2003. The interpretation concentrated on analyzing earthquake events within the study area.

Magnitudes, hypocenter depth (Km), time of occurrence, and location have been chosen as the analysis parameters. Classification of all events concluded to four classes of magnitudes: EQ1 1ML to 3.9 ML (Local Magnitude), EQ2 (4M to 4.9 ML), EQ3 (5ML to 5.9 ML), and EQ4 (6ML to 6.9 ML) (Figure 2-55).

Figure 2-54 presents a regional tectonic map showing the earthquake events that subjected the southeastern Mediterranean region since 1927, which conveys that the Jordan Dead Sea Transform (DST) is the major source of the earthquake activity in the region. Large destructive earthquakes have occurred; the latest one was in the 1927 earthquake with a magnitude of 6.25.

The region has low focus; having 90% of the events with magnitudes 3-3.9 ML and focal depths range of 10-50 kms for 85% of the events characterize level of seismicity the region along the DST and the Red Sea, along the borders between the Arabian Plate and the African Plate, while the seismicity magnitudes of 4-4.9 ML are about 10% and are dominating the region along the southern portion of the DST. The seismicity magnitudes higher than 5.5 ML are less than 5%. The seismicity is controlled by the activity of the DST and the Red Sea, along the eastern borders of the Arabian Plate.

The overall seismicity of Jordan is influenced mainly by the Dead Sea Transform Fault System; the eastern boundary of the Arabian Plate. More detailed accounts for Jordan's seismicity is given by Isa (1991)

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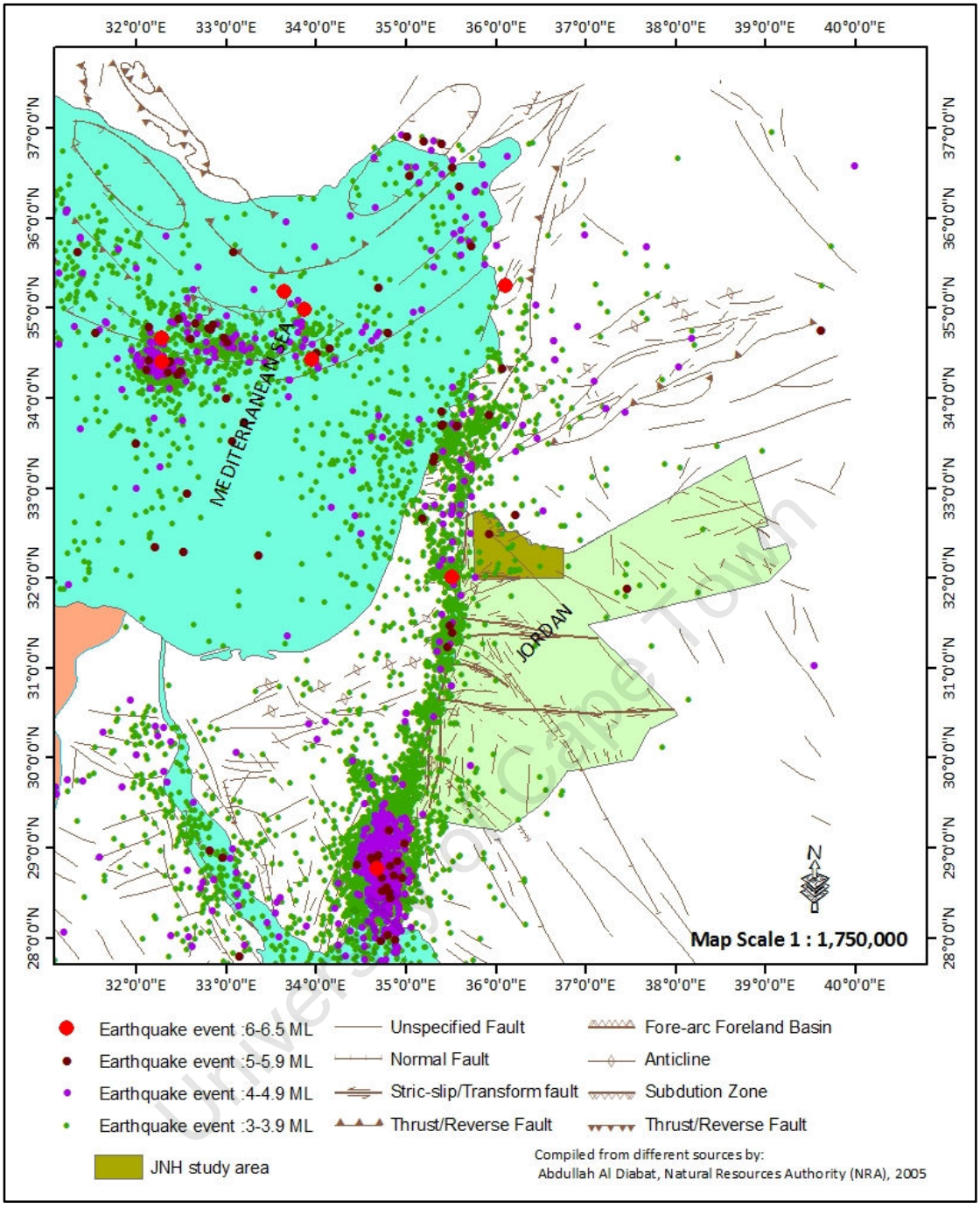

Figure 2-55: Regional tectonic-seismicity map of Jordan and vicinity of the DST, Red Sea, and the SE- Mediterranean showing the seismicity activity since 1927, after Diabat, 2005

The seismicity events analysis of the study area concludes that the majority of events located in the study area were of magnitudes between 1ML to 3.9ML (EQ1). 40% of them located across the southern parts within the Zarqa Fault System and Ramtha Sirhan Fault System vicinity, north of Zarqa town at depths ranging from 4 Km to 39 Km. The deepest was

at 39 Km in the year 1987 northwestward of Zarqa town at ~8.7 Km distance. The shallowest occurred in the year 1983 at about 14.7 Km northeast of Zarqa town. Several earthquakes, from class EQ1, characterized the area north and east along the borders with Syria with depths of about 10 Km, whereas toward the central regions, hypocenter depths become shallow with an average of 6 Km. Two events that occurred in the year 1928 had 4.0 magnitude at depth of 10 km within the northwestern and southwestern corners of the study area. Moreover, the map also presents that the highest magnitude in the study area region was of 5.5 magnitudes that occurred in the year 1957 at 10 Km depth south of Irbid and Ramtha towns (Figure 2-56).

The seismological map of the JNH, (Figure 2-56), is constructed using the available seismic events, tectonic, and geological information that were compiled from different resources by Diabat (2005). These resources were listed in section 1.1.2.2. The map shows the homogeneous distribution of seismic events along the E-W and NW-SE major faults, whereas to the west towards the Jordan Valley, the non-homogeneous seismic activity is revealed. This may indicated direct effect of the DST activity and the Arabian Plate movements along this portion.

The overall seismicity of JNH is influenced mainly by the Dead Sea Transform Fault System; the eastern boundary of the Arabian Plate, which formed its complex structural style. More detailed accounts for Jordan's seismicity is given by Isa (1991)

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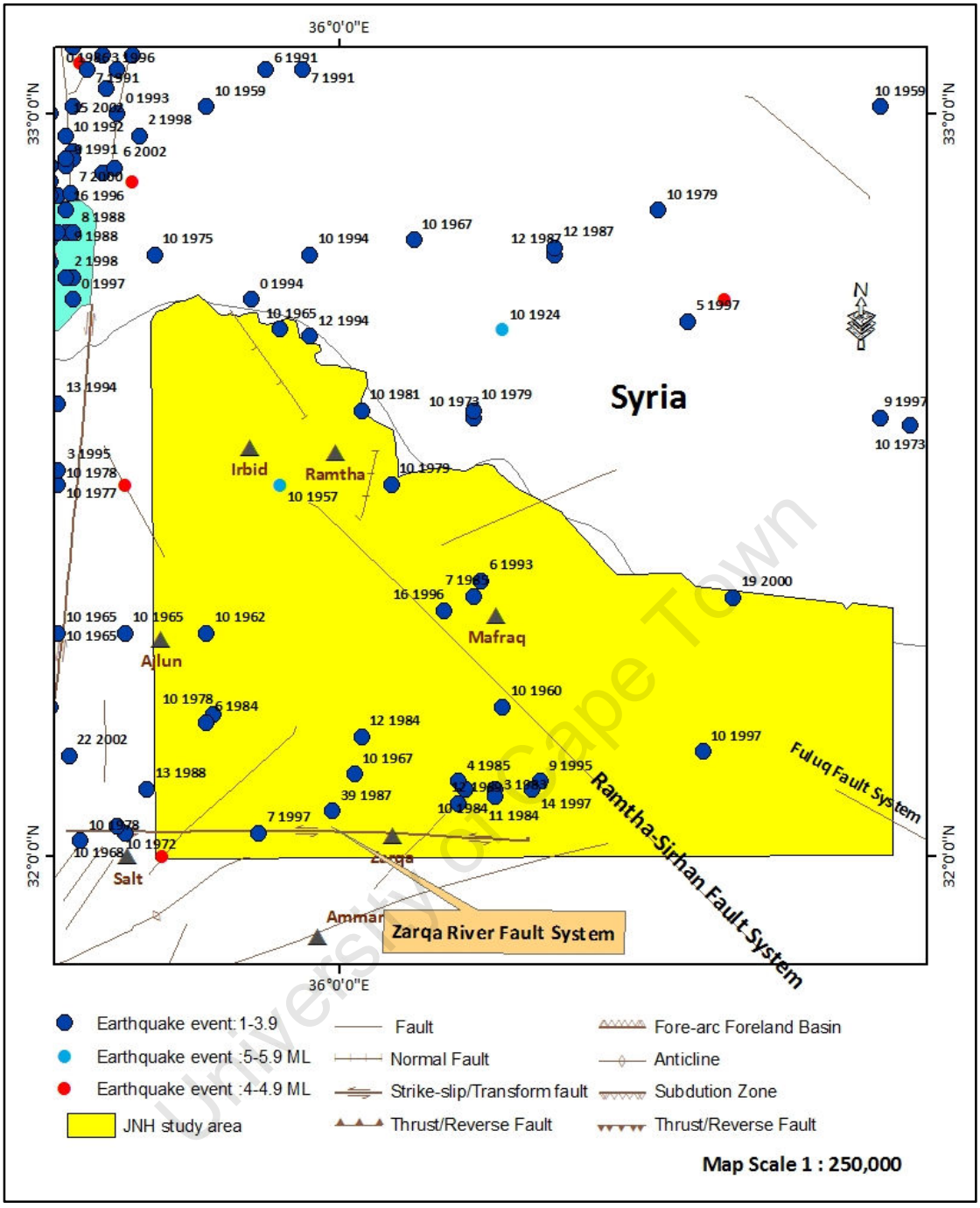

Figure 2-56: Location map of the seismicity events in the study area showing their magnitude, hypocenter, and time of occurrence

3. STRUCTURAL AND STRATIGRAPHIC INTERPRETATION OF THE JNH STUDY AREA

ABSTRACT

This chapter will put forward the outcome of the integration between all analyzed surface and subsurface geological and geophysical information that were used to shed light on the General surface and subsurface geological setting of the JNH area.

The integration processes present the outcome of the analysis of the surface geology, gravity, 2D seismic, the available boreholes, and the geomorphology in order to identify the General geological framework. In this respect, structural depth and thickness distribution maps for the major stratigraphic sequences were constructed. In addition, a 3-D stratigraphic model was produced based on the data of the key borehole data in order to depict the geology and stratigraphy of the subsurface in three dimensions. The integration was also supported by a set of three arbitrary cross sections; surface geology, topography, gravity, and depth to basement.

Geographic Information Systems techniques were used for data entry and building a geospatial database for data analysis, integration, and correlation. Rockware software was used to carry out the development of correlation cross sections, thickness maps, and the 3-D stratigraphic model. However, development of a structural stratigraphic model was not possible due to lack of information. All correlation results were presented in the form of cross-sections and maps at an appropriate scale.

The General structural setting of the JNH area is considered complex due to its distinguished location in the northwest corner of the Arabian Plate and adjacent to the eastern margin of the Dead Sea Transform Fault. The JNH area is characterized by a maze of complex structural systems of three major trends; NW-SE, NE-SW, and E-W cut a remarkable folding belt. The surface and subsurface stratigraphy play a key role in the formation of the General geological setting of the JNH. In addition, it was found that the surface elements including the topography are without any doubt a mirror for its subsurface structural and stratigraphic setting.

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3.1. MAJOR SURFACE GEOLOGICAL SETTING AS A RESULT OF DATA INTEGRATION

3.1.1. MAJOR SURFACE STRUCTURAL TRENDS

3.1.1.1. FAULTING

Integration and correlation with existing geological information conveyed that the JNH area has a complex structural setting characterized by a maze of distinguished structural faulting systems. These systems are mostly of major trends: (1) NW-SE to NNW-SSE, (2) NE-SW to NNE-SSW, and (3) E-W to WNW-ESE (Figure 3-1).

Among those of NW-SE trend, there is a complex of faults that by correlation revealed that it is part of the Ramtha-Sirhan Faulting system, which extends from Saudi Arabia into the JNH with a remarkable downthrown to the east. In addition to this system, the analysis revealed another NW-SE trend extends into the area along the eastern borders with Syria. Correlation showed that this trend is part of the Fuluq Faulting System.

A sequence of three NE-SW fault trends intersects the major Ramtha Sirhan fault system as shown in figure 3-1. The first one, in the south, is correlated to the Amman Hallabat structure. The second one (in the middle) extends from the southwest of Suwelih structure toward the east near the borders with Syria and intersects the Ramtha-Sirhan Fault system. The third one crosses the area east of Ibbin town and extends toward the east close to the borders. It is found that this type of trend increases in the north and northwest and locally changes its direction to NNE-SSW and cross cut the folded structures across the area of Ajlun Dome where folding and faulting become extensive.

A major E-W trend accompanied by a series of distinctive folding structures is restricted mainly to the south and southwest of the area. It was correlated to the Zarqa fault system.

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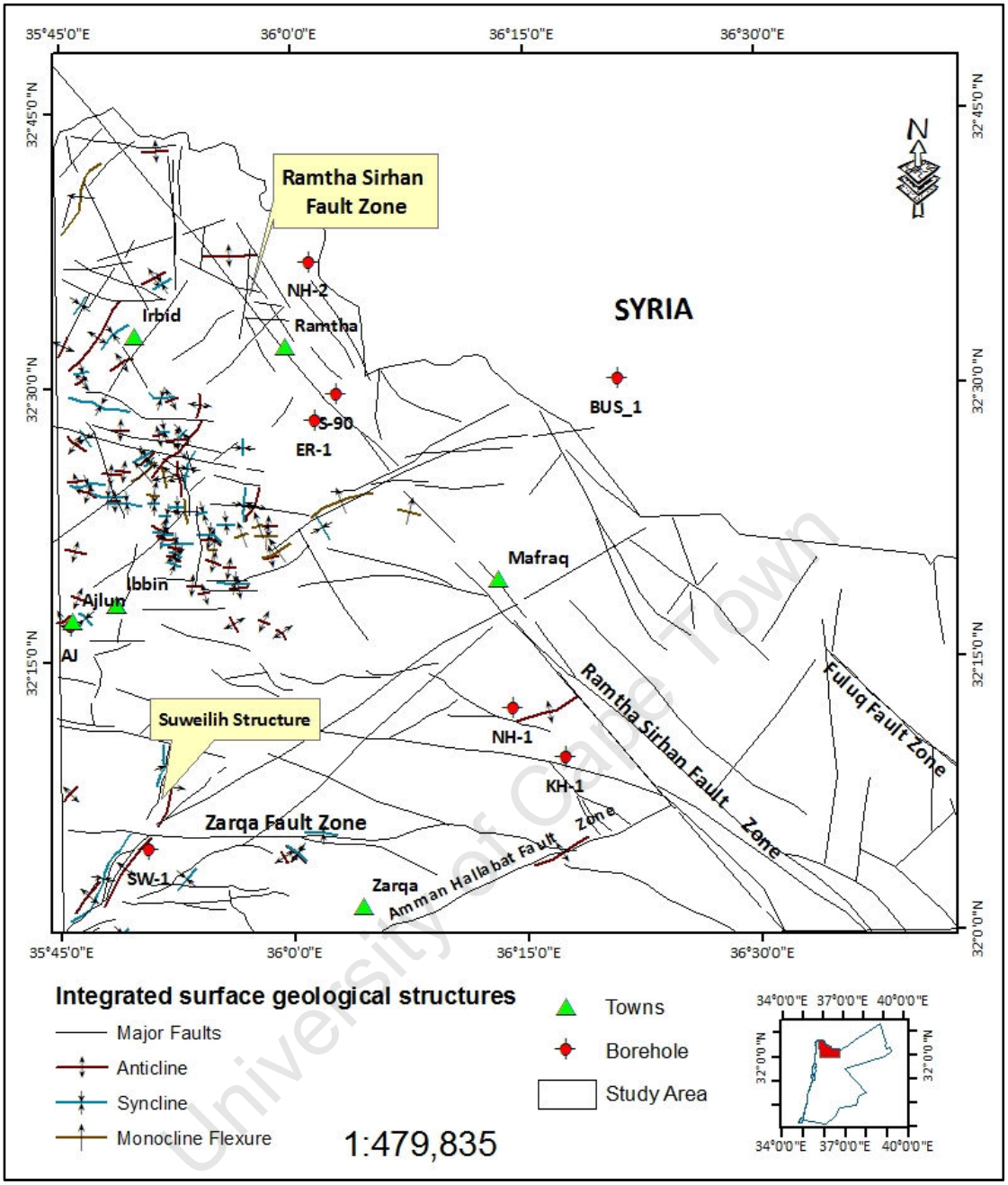

Figure 3-1: Major surface geological structural elements as integrated from existing geological studies; 1: 50,000 National Geological Mapping Project 1985-1992, Bender 1985, and Beicip 1981 and 1975

3.1.1.2. FOLDING

The integration revealed existence of a significant folding belt that extends from Amman Hallabat structure across the western margin of the Ramtha-Sirhan Faulting System. Toward

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the west and northwest, it becomes highly folded cut by several NW-SE and NE-SW major faults. This folding belt is characterized by a series of anticlines, synclines, and monocline flexures with NNE-SSW and NE-SW axis trend.

3.1.1.3. TOPOGRAPHY OF THE JNH AND ITS SURFACE GEOLOGY

The surface geology and the geomorphologic analysis revealed a distinguished structural geomorphologic setting in the JNH area. In this respect, it is found that the major structural elements of the area have controlled its General surface relief and terrain. Terrain classification revealed that low elevated areas (basins or depressions) coincide with faults such as Zarqa River while high elevated areas form as uplifts and folded zones. Figure 3-2 presents the major terrain classes and their relation to the surface structural elements of the area.

Low areas and wadies coincide with 1, 2, 3, and 4 fault trends. In the areas of Zarqa River and Yarmouk River Basin, the faults control the pattern and shape of the dominant drainage network.

In addition, the faulting network shows a particular pattern very close to the topography of the area. For instance, the Ramtha-Sirhan Faulting System extends through a major basin (low elevated area with intermediate slope) from the southeast toward the northwest where it declines. The highly folded zones comprise the high-elevated area such as Ajlun Dome in the west adjacent to the Dead Sea Transform Fault and the areas in the east adjacent to the borders with Syria, along the eastern margin of the Fuluq Faulting System.

This leads to a result that the topography of the area is controlled by the structural elements, due to regional tectonic movements.

The JNH area can be subdivided in terms of geomorphology into High elevated areas resulting from compression activity accompanied by erosion and sedimentation processes forming uplifts or dome features (Ajlun dome in the west) (Figure 3-3).

Low areas with apparent steep degradation (wadi areas), such as Zarqa and Yarmouk Rivers, the aforesaid major trends cut it and caused its present shape.

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Low areas with intermediate slope mark depressions and basins such as Ramtha-Sirhan Faulting System. A fold belt of multi series of anticlines, synclines, and monoclines comprises the western margins of the Ramtha-Sirhan trend and close to the eastern margin of the Dead Sea Transform Fault (Figure 3-3).

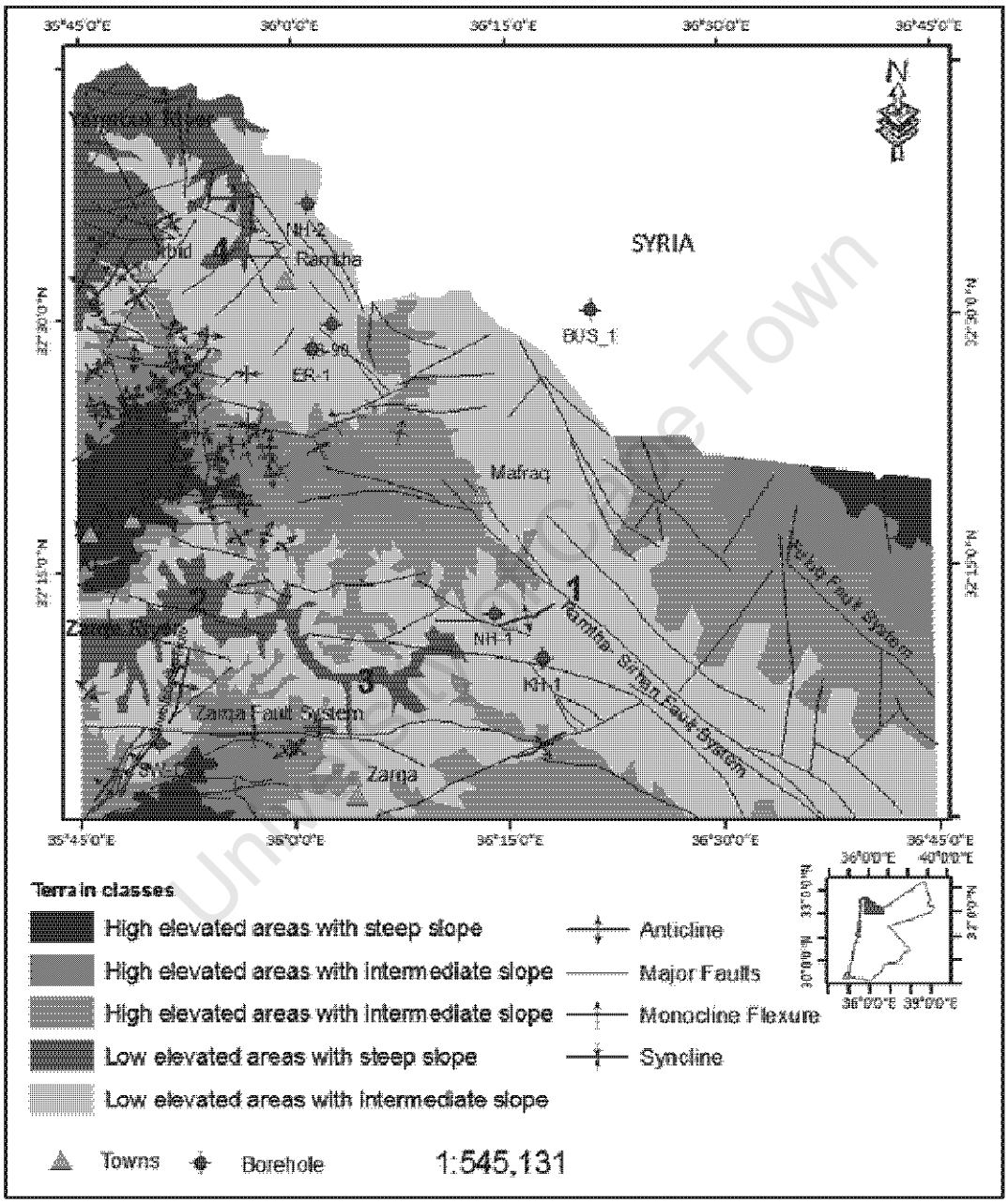

Figure 3-2:The major surface structural elements and the main terrain classes

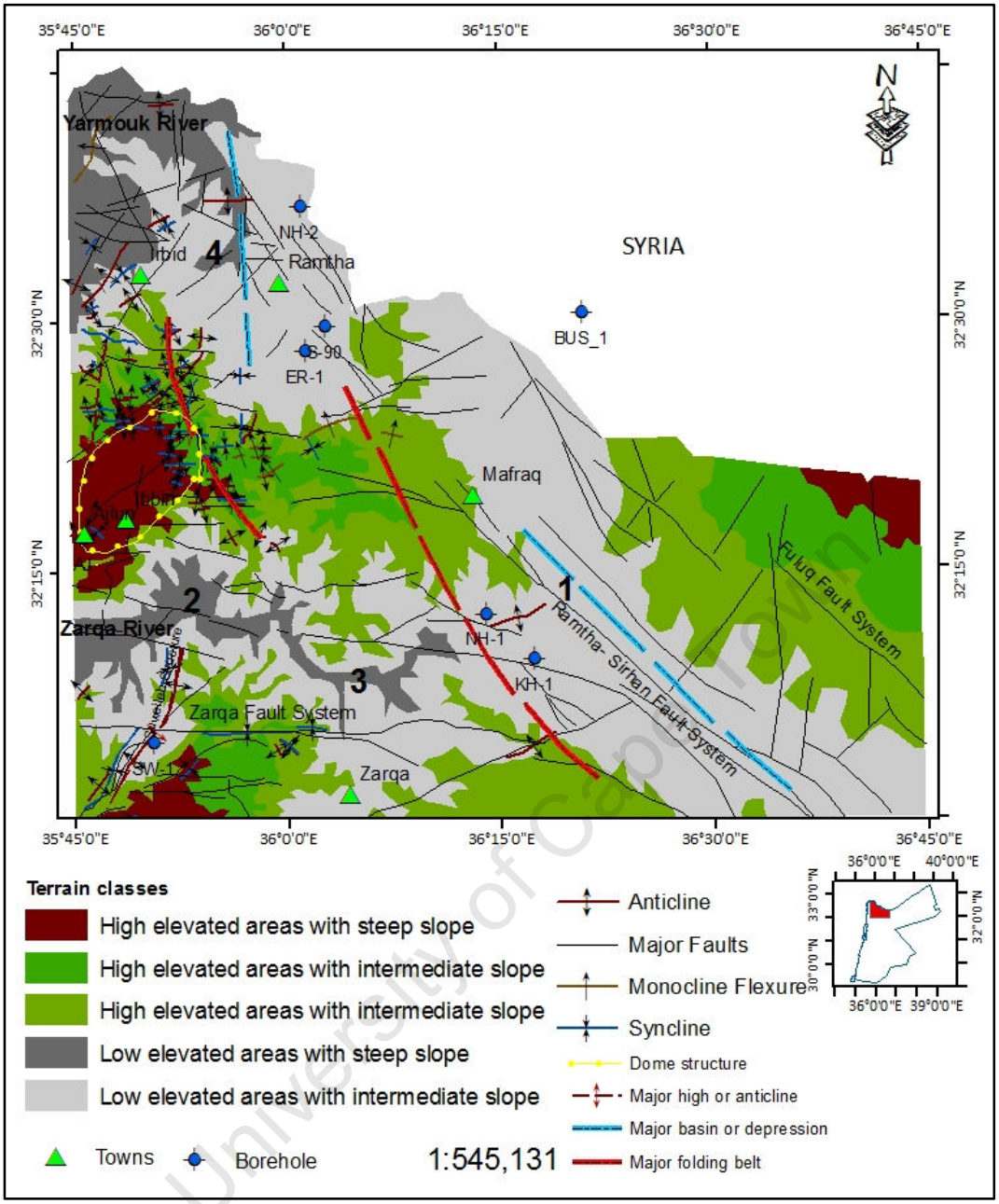

Figure 3-3: The major surface geological elements as a result of integration with the geomorphology and topogrphy of the JNH area

3.1.2. MAJOR SURFACE STRATIGRAPHY

Integration between all available existing geological surveys revealed that the majority of the rocks cropping out in the JNH area are of sedimentary origin ranging from Jurassic to Quaternary ages (Figure 3-4).

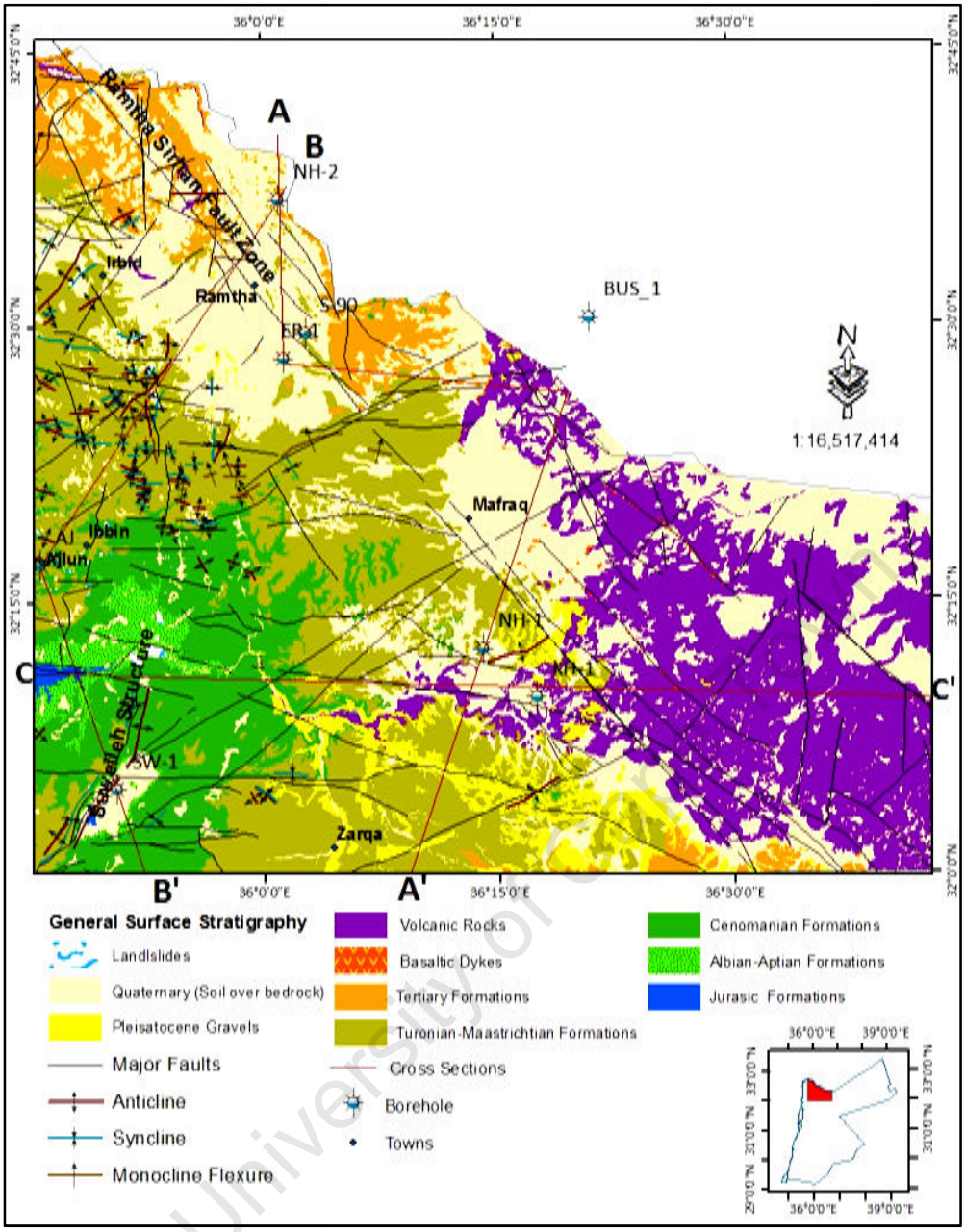

Figure 3-4: Geological base map of the JNH area showing the main stratigraphic unit distribution

3.1.2.1. MESOZOIC ERA

JURASSIC PERIOD

The oldest rocks that outcrop in the study area are of Jurassic age (Azab Group) is fully exposed in the vicinity of Zarqa River (thickness ≈400 m).

CRETACEOUS PERIOD

Rock sequences of the Lower Cretaceous; Albian-Aptian (Kurnub Group) are unconformably overlying the Jurassic sequences (Abdelhamid *et al*., 1991). Thickness is about 300m

The Ajlun Group; Cenomanian-Turonian sequences, attains about 500-600m thickness sequences and covering remarkable part of the JNH. They attest to a very well preserved and continuous marine transgression over the dominantly continental Albian-Aptian sediments. This resulted in the deposition of platform carbonates within lagoonal. Tidal, and open marine environment.

The Belqa Group; Upper Turonian-Maastrichtian (Upper Wad esSir Massive limestone Formation, Amman silicified-Phosphorite Formation, Ghareb Chalk Marl Formation cover most of the map area.

3.1.2.2. CENOZOIC ERA

TERTIARY-QUATERNARY- RECENT PERIOD

This Group of sedimentary rock belongs to Belqa Group, which is subdivided into Taqiyya Chert Limestone Formation (Paleocene-Eocene) at base; attains about 200 m of thickness. This Formation is overlain by Chalk Marl Formation (Eocene and upper most of Oligocene age) which attains about 40 m thickness. Tayibba Limestone Formation, Waqqas Conglomerate Formation (Oligocene-Miocene-Pliocene) overly the marine Taqiyya Formation with a thickness of about 152 m. Pleistocene to Recent sediments covers most of the north, northeast and south east parts of the JNH. These sediments are divided into soil, calcrete, Pleistocene gravels, wadi sediments, and fluvial sediments (Khalil, 1997).

3.1.2.3. VOLCANIC ACTIVITY

Basalt flows of Tertiary and Quaternary age are abundant to the east and southeast parts.

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3.1.3. MAJOR SURFACE GEOLOGICAL SETTING AND ITS RELATION TO THE TOPOGRAPHY, GRAVITY ANAMOLY, AND BASEMENT DEPTH VALUES

Three arbitrary composite cross sections were constructed in order to give a comprehensive view regarding the relationship between the subsurface and the surface structural setting (Figure 3-5). These cross sections illustrate the surface geology, topography, gravity, and depth to basement variations across the JNH area.

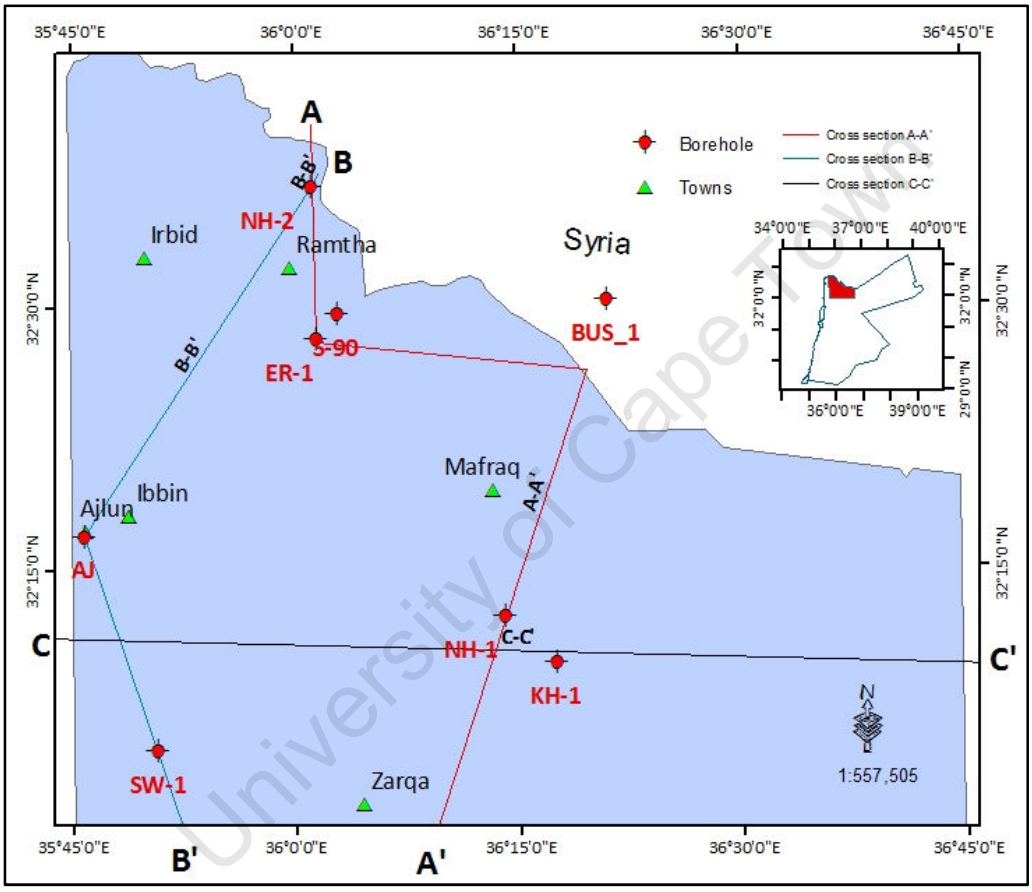

Figure 3-5: Geology, topography, gravity, and depth to basement composite cross section index map

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3.1.3.1. COMPOSITE CROSS SECTIONS

COMPOSITE CROSS SECTION A-A' (FIGURE 3-6)

This section displays the Ramtha-Sirhan Fault System as a major structural system composed of a group of normal step faulting trends with a General Downthrown toward the east forming significant horsts and grabens. Tertiary and Turonian – Maastrichtian sequences are outcropping along this section and overlain by soil and Pleistocene gravels. Volcanic rocks cover the eastern parts of the JNH. It also exhibits a major low magnitude structure between Amman-Hallabat Fault System in the southeast and Ramtha-Sirhan Fault System in the north east, where strata clearly decline and dip toward the northwest. In addition, an apparent degradation in altitude as well as thickness of outcropping rocks from the southeast to the north-west was exhibited. For instance, Turonian rocks outcrop at an altitude of 550-700 m in the southeast while it outcrops at 100-150 in the northeast. This section also exhibits a major deformation structure with NE-SW trend, where the left flank; the formations are steeply dipping northward towards the Syrian borders in the vicinity of NH-2 well. The significant variation in thickness and dipping indicates a NW-SE major faults crossing between ER-1A well and Mafraq town area

The gravity profile shows a distinguished consensus with the surface geology and topography. The gravity values indicate deposition of a thick sedimentary cover across the area between the Amman-Hallabat Fault System and the Ramtha-Sirhan fault system (between NH-1 and ER-1 wells). As evidenced by the depression or basin in this area. Depth to basement across the center of this depression is between-4.5 to-4.9 Km.

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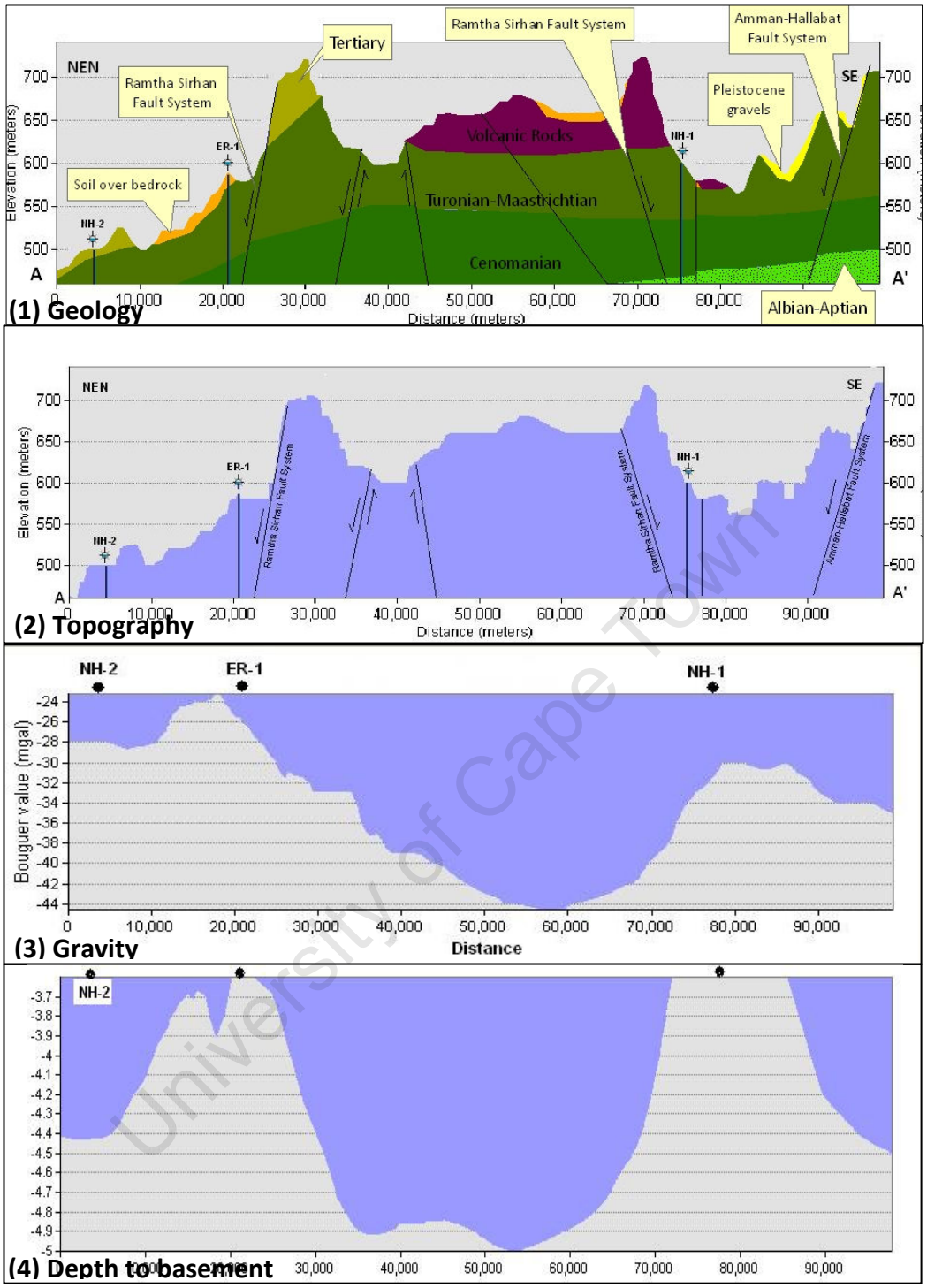

Figure 3-6: Composite cross section A-A' illustrating the geology, topography, gravity, and depth to basement along this section (Horizontal scale= 2-5 vertical scale)

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COMPOSITE CROSS SECTION B-B' (FIGURE 3-7)

This cross section shows a clear change in dip and thickness of the outcropping rock and also illustrates the major stratigraphic column of the area.

Turonian-Maastrichtian sequences comprise the Yarmouk River Basin. They are over lied by the Tertiary sediments, which are covered by soil. The Ramtha-Sirhan Fault System crosses this area forming a complex system of horsts and grabens with an eastern downthrown increasing toward the north east where the dip also increases remarkably toward wadi Kufrinja. Toward wadi Kufrinja, Turonian-Maastrichtian rocks disappear gradually and the Cenomanian outcrop with distinct thickness overlying the Lower Cretaceous (Albian-Aptian) sequences. Toward Wadi Zarqa, the stratigraphic column is completed with the Jurassic sequences where Zarqa Fault System cut it. Lower Cretaceous (Albian-Aptian) sequences comprise Suwelih structure center.

What distinguishes this section is the Zarqa Fault System, cutting the Zarqa Wadi. This indicates that this fault system contributed in the formation of the shape and patterns of this wadi. Accordingly, this evidenced that the topography of the area was the result of a successive regional tectonic movements which have affected the region. In addition, this section shows Ajlun structure as a major anticline with a NNE-SSW axis. The rock sequences along its eastern margin are dipping toward the east forming a major folding belt with a major NE-SW axis trend cross cut by major NE-SW and NW-SE faults.

The topography along this section appears to be a reflection of the gravity. The gravity profile shows that the Ramtha Sirhan fault system and the Zarqa Fault System are deep-seated faults. Also, gravity values across the Yarmouk River Basin indicate an increase in the sedimentary cover, where the gravity values are-30 mgal--25 mgal and the depth to basement reaches-4.5 Km. Toward the west, the basement rises to about-2 Km, and then it declines toward the southwest close to Suwelih structure. Across the area lies between 12-23 km distances along the profile, a horst structure is identified.

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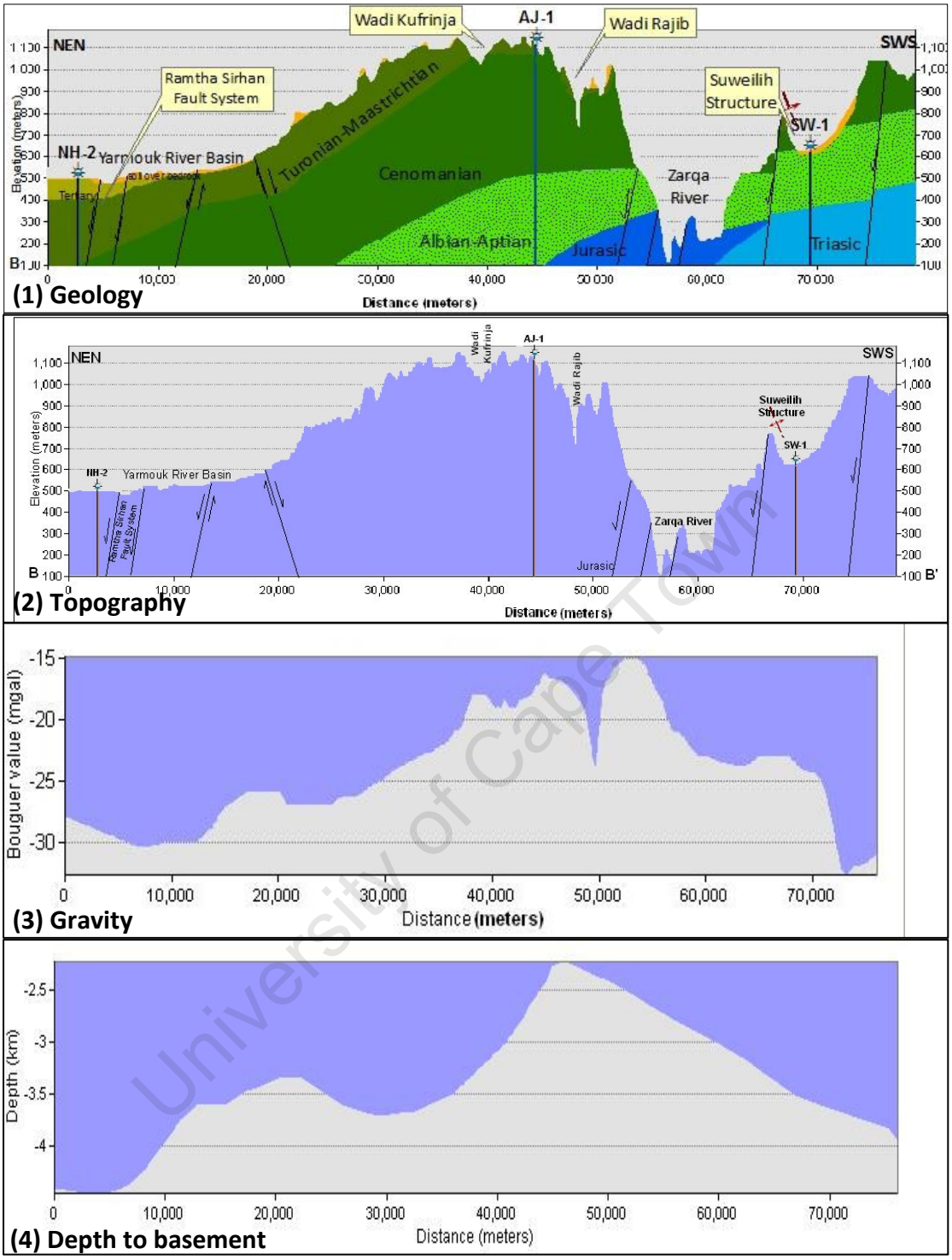

Figure 3-7: Composite cross section B-B' illustrating the geology, topography, gravity, and depth to basement along this section (Horizontal scale= 2-5 vertical scale)

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COMPOSITE CROSS SECTION C-C’ (FIGURE 3-8)

Cross section C-C' illustrates Jurassic outcrops distribution across the Zarqa wadi whereas, toward the east Lower Cretaceous (Albian-Aptian) sequences are outcropping followed by the Cenomanian, Turonian, and then the Tertiary sequences. In the east, they are all covered by volcanic rocks

This section displays a major normal step faulting system with a major downthrown toward the east. The influence of the Fuluq Fault System is clear on the eastern margins of the area. It is worth mentioning that there is a noticeable thickness in the rock sequences within the limits of the Ramtha Sirhan fault system. Along the gravity and the depth to basement profiles, the sedimentary sequences appear dipping toward the east where the basement declines to less than-5 Km.

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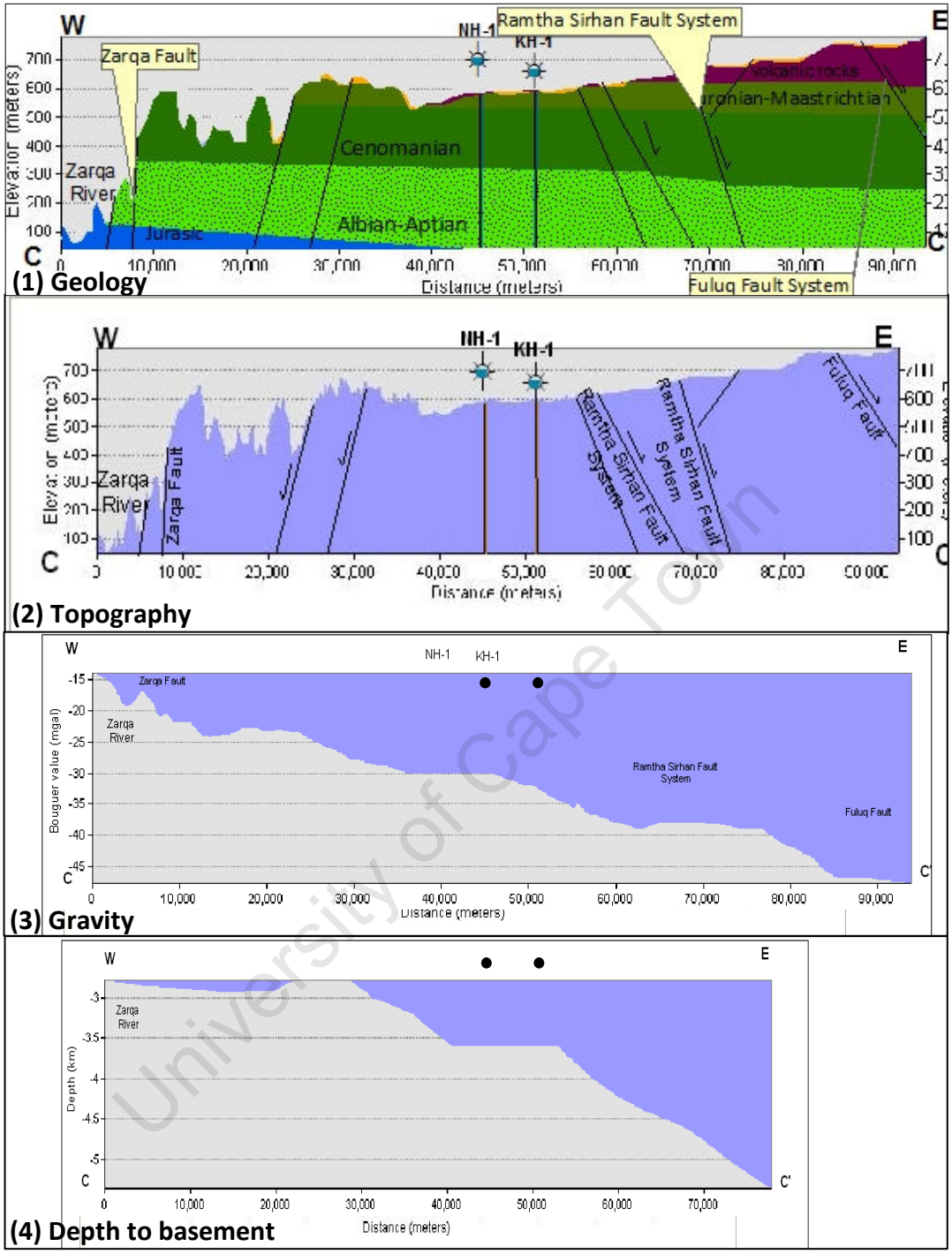

Figure 3-8: Composite cross section C-C' illustrating the geology, topography, gravity, and depth to basement along this section (Horizontal scale= 2-5 vertical scale)

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3.2. MAJOR GEOLOGICAL SETTING BASED ON DATA INTERPRETATION AND INTEGRATION

The subsurface geological setting was studied in terms of major subsurface structural elements and subsurface stratigraphic distribution across the JNH area, in relation to the surface geological setting, in order to identify the dominant structural framework. Therefore, an effort was made to integrate both the gravity and the 2D seismic results with the surface geology.

3.2.1. MAJOR SUBSURFACE STRUCTURAL TRENDS

3.2.1.1. INTEGRATION OF SURFACE GEOLOGY AND GRAVITY INTERPRETATION

Gravity and surface geology integration emphasized the complexity of the structural setting of the JNH area. It revealed that there are three major fault trends: (1) NW-SE, (2) NE-SW, and (3) E-W which have controlled the area (Figure 3-9). The dominant faults trend, such as Ramtha-Sirhan Fault, is of NW-SE.

The interpretations exhibited it cut crossing two major structures; the first one (HI & L1) is a system of High and Low structure located within the vicinity of Al Mafraq town. This structure is bounded by two major NE-SW and NNE-SSW; apparently they seem to intersect at some point into the east in Syria.

The second major structure is a system of two Low and High (L2 and H2) structures situated within the vicinity of the southern parts of the Yarmouk River Basin between the S-90 and ER-1 wells and the NH-2 well north of Ramtha town. Those high and low magnitude structures are bounded by Ramtha-Sirhan Fault system and another major NW-SE fault system that is believed to be an extension of the Fuluq Fault System. Another important NW-SE fault extends from the southeast near Zarqa town and extends to the northwest between Ibbin and Ajlun towns intersecting Zarqa Fault System.

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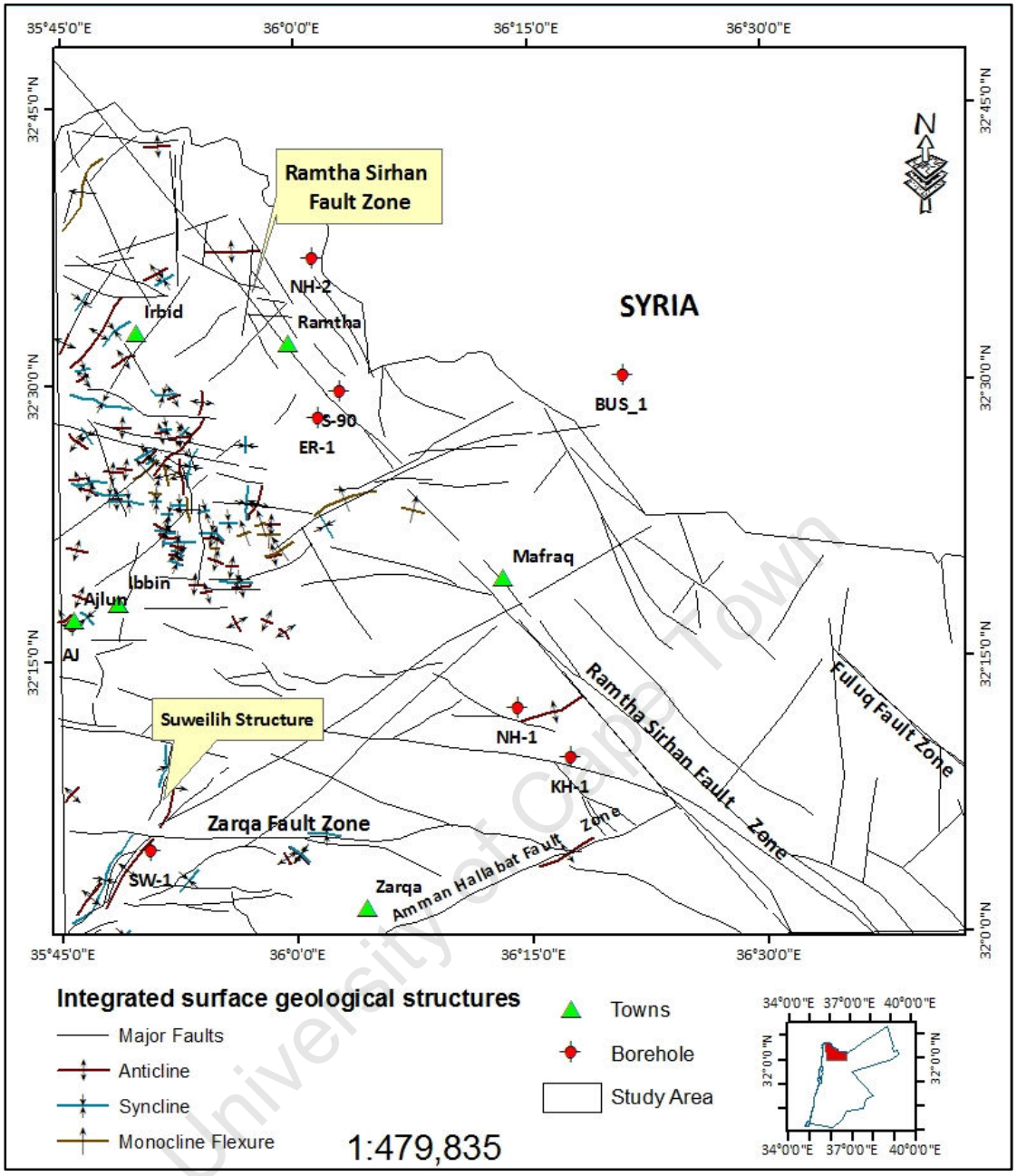

Figure 3-9:Major structural elements based on integration between gravity and surface geology

The NE-SW fault trend is more clearly exhibited in the northern parts of the area than in the south. To the north and northwest parts, the trend direction changes into NNE-SSW. One of those trends is a major fault that intersects the Ramtha Sirhan Fault System in the area between Al Mafraq town and the S-90-ER-1 wells.

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Integration revealed an important E-W fault trend that crosses most of the southern parts of the area passing the SW-1 well in the west and extends to the east where it plunges into the southeast south of the NH-1 well. This fault is intersected by two N-S faults where it changes its trend direction toward the southeast and also intersects the Ramtha-Sirhan Fault System. The correlation linked this major E-W trend to the Zarqa Fault System.

3.2.1.2. INTEGRATION OF SURFACE GEOLOGY, GRAVITY, AND 2D SEISMIC INTERPRETATION

It is found that the major fault trends delineated from the surface geology and the gravity, are mostly deep-seated that had played a key role in the formation of the General structural setting of the JNH area and had controlled its topography.

The interpretation of the seismic data conveyed that the JNH is being controlled by three major fault systems of NW-SE, NE-SW, and ENE-WSW trends cut that in General cut all stratigraphic horizons up to the surface (Figure 3-10).

Ramtha-Sirhan Fault System (NW-SE trend) is found as a deep-seated fault that cut all identified stratigraphic horizons. However, its influence on Cenomanian, Triassic, and Palaeozoic strata was stronger. There are two important NW-SE trends; one extends along the Syrian borders in the east. The other one is to the west of Ramtha-Sirhan Fault System that forms with a group of minor and major faults a complex structural system that reflects the tectonic activity that had occurred in the region as well as the effects of the tension and pressure forces.

A series of high and low magnitude structures were identified by gravity interpretations. The 2D seismic interpretation, emphasized their existence especially at the Cretaceous, Jurassic, and Triassic levels. They appear to be cut by several NE-SW fault trends, especially across the area around Al Mafraq town, forming distinguished horst and graben structures.

ENE-WSW fault trends characterize the northern and western margins of the JNH. They appeared to be intersecting by the major NW-SE causing slight deviation from their trend.

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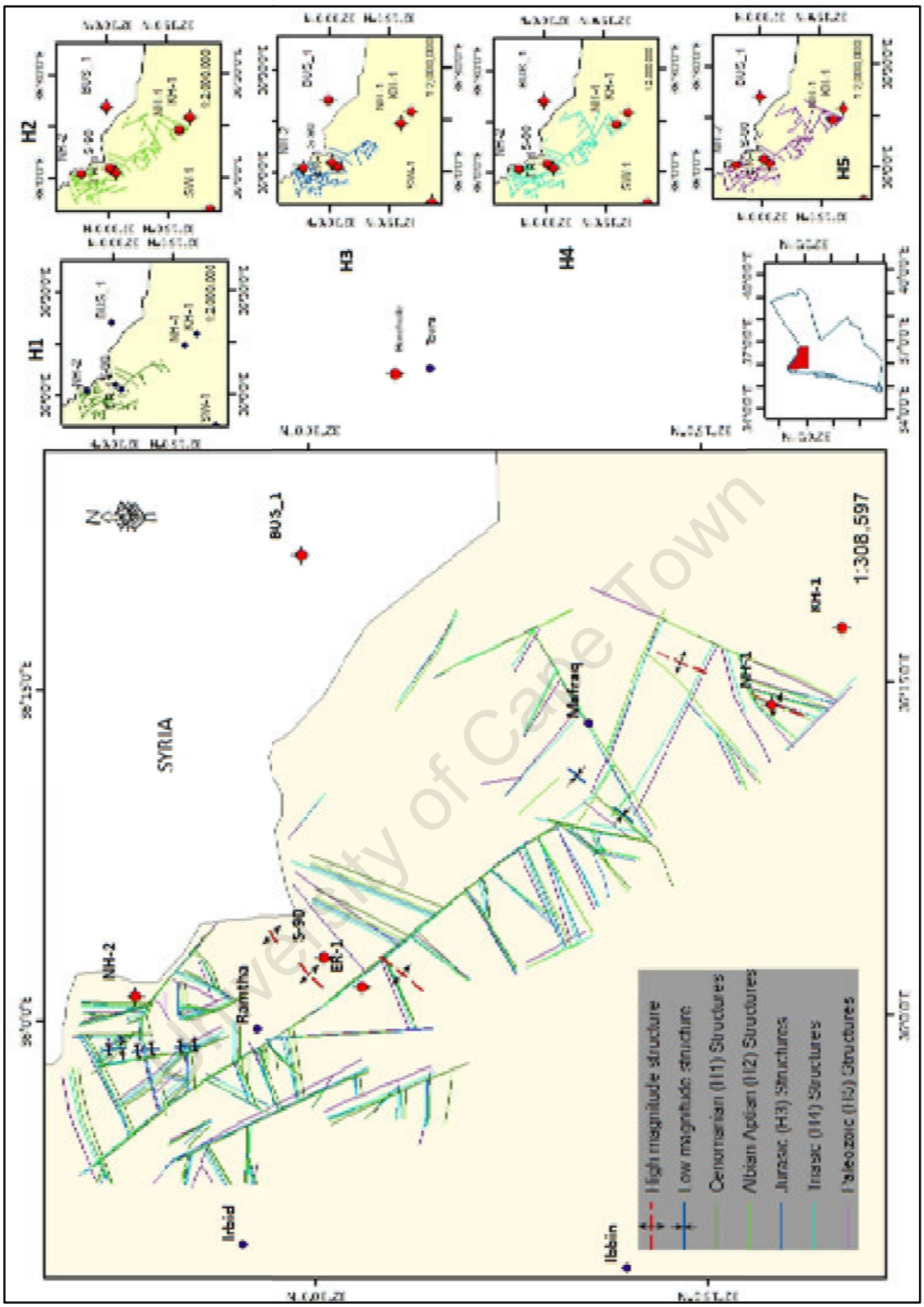

Figure 3-10: Major sub-surface structural elements of all identified stratugraphic horizons (Paleozoic-Cenomanian) interpreted from the 2D seismic reflection data

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It was evident that gravity, surface geology, and the seismic interpretation results were highly correlative. They emphasize the complexity of the structural setting of the JNH (Figure 3-11). In this figure, it was obvious that several NE-SW and E-W faults intersect the main NW-SE fault system (Ramtha Sirhan Fault System); this confirms that this fault system is young and was formed after the Cenomanian.

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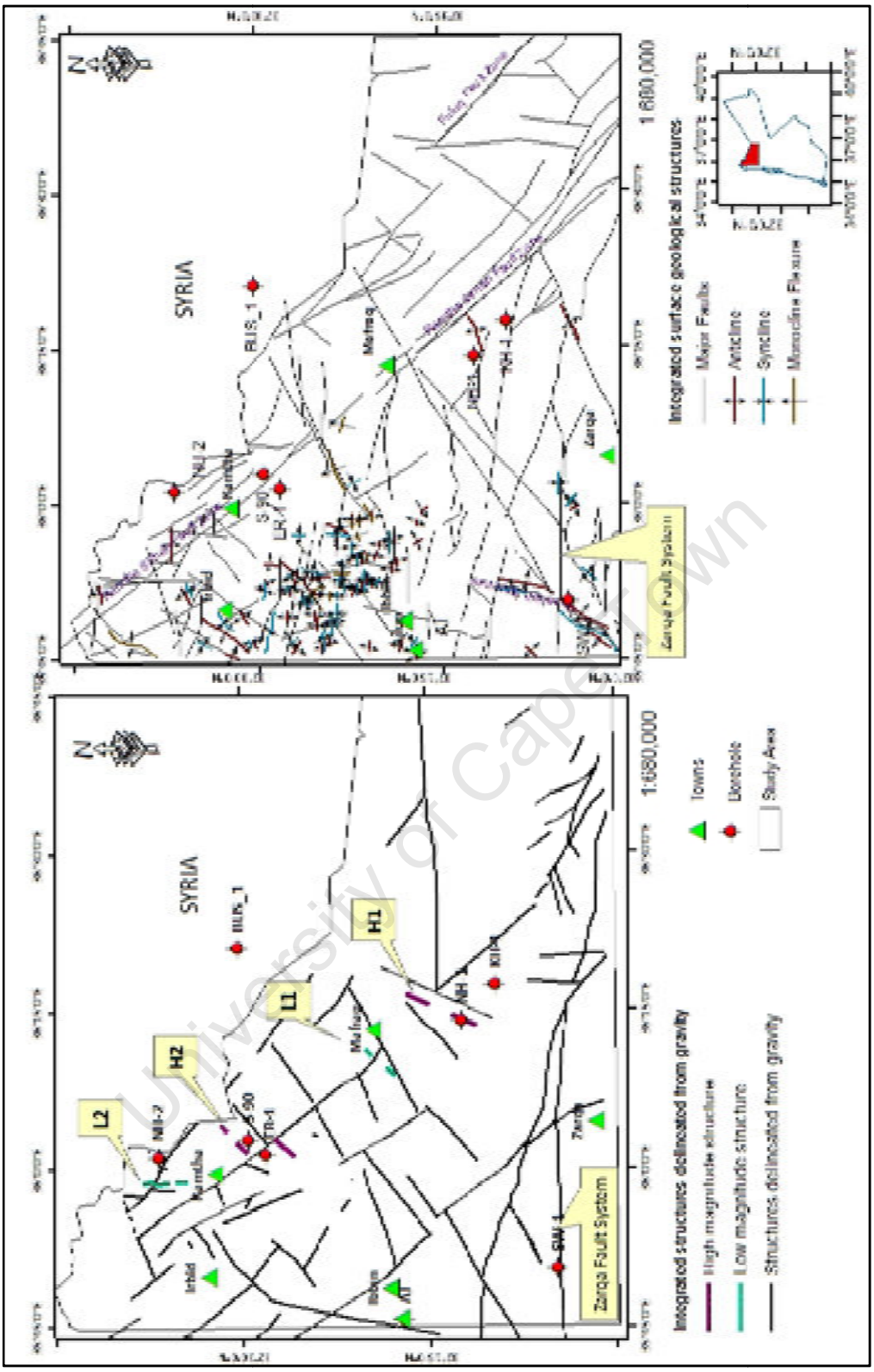

Figure 3-11: Major faults and fold structures as delineated from the gravity data and surface geological maps

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3.2.2. SUBSURFACE STRATIGRAPHY

The major subsurface stratigraphic distribution was studied in terms of identification of the main subsurface stratigraphic units and their structural depth and thickness variations as calculated from the 2D seismic profiles and the key boreholes across the JNH area.

3.2.2.1. STRUCTURAL DEPTH AND THICKNESS VARIATIONS OF THE MAIN STRATIGRAPHIC HORIZONS AS CALCULATED FROM THE 2D SEISMIC AND THE KEY BOREHOLE DATA

Integration between the borehole and seismic data was carried out in order to study the depth and thickness variation of the identified stratigraphic horizons. This was achieved by development of grids from the calculated depth values for the horizons. 2D thickness maps were also constructed. ARC GIS and Rockware software were used for the construction of the isopach and structural maps as well as analysis and correlation. This gave much insight into the subsurface geological setting across the JNH area.

THE CENOMANIAN SEQUENCES HORIZON (H1) (FIGURE 3-12)

This horizon was only identified in the central and northern parts of the JNH. The structural depth map (Figure 3-12) shows that it plunges toward the north and northwest where depth reaches about-900 m below sea level forming a low magnitude structure.

Across the south-western vicinity of NH-2 well, map depth shows apparent variation from about-600 m to about 325-500 m above sea level. This confirms the existence of a major NW-SE fault that passes between S-90 AND ER-1 as seen on the isopach map and extends toward the northwest north of Irbid town. To the west, this horizon keeps rising until it reaches about 150m above sea level and it may continue to rise until Ajlun Dome. However, there is no seismic coverage available to confirm or deny that.

Isopach map shows thickness increase of the Cenomanian sequences toward the north and northwest where it reaches about 460-600 m. while toward the southeast thickness decreases to about 300-280 m. It is worth mentioning that the highest thickness value was detected within the vicinity of S-90 well (about 700 m). Sudden change in thickness was evidenced within the vicinity of the ER-1 well, which confirms major structure existence.

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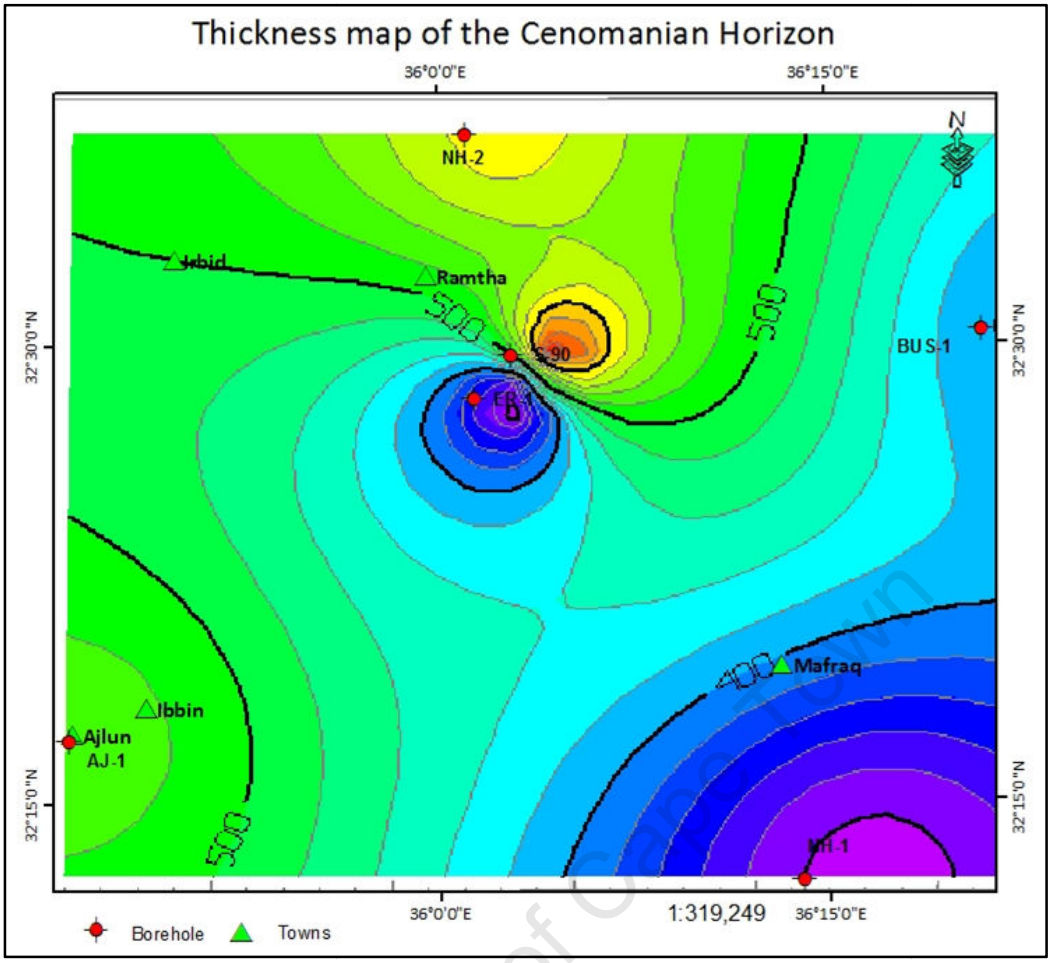

Figure 3-12:Isopach maps of the Cenomanian sequence as calculated from the 2D seismic reflection and the key boreholes data

THE ALBIAN-APTIAN SEQUENCES HORIZON (H2) (FIGURE 3-13)

This stratigraphic horizon was identified at a depth of about 400 m across the area around Al-Mafraq town forming a distinguished high structure. West of Al Mafraq town, the horizon suddenly declines to about -200 m, while toward Ajlun Dome it rises to about 400 m.

Across the area between Irbid and north of Ramtha towns, there is a distinguished low structure where depth reaches to about-900 m. The isopach map shows a significant NW-SE trend of thickening where it reaches about 250-300 m. The area around ER-1, S-90, and NH-1 present the highest thickness. Whereas, toward the north and west (close to Ajlun Dome) thickness decreases.

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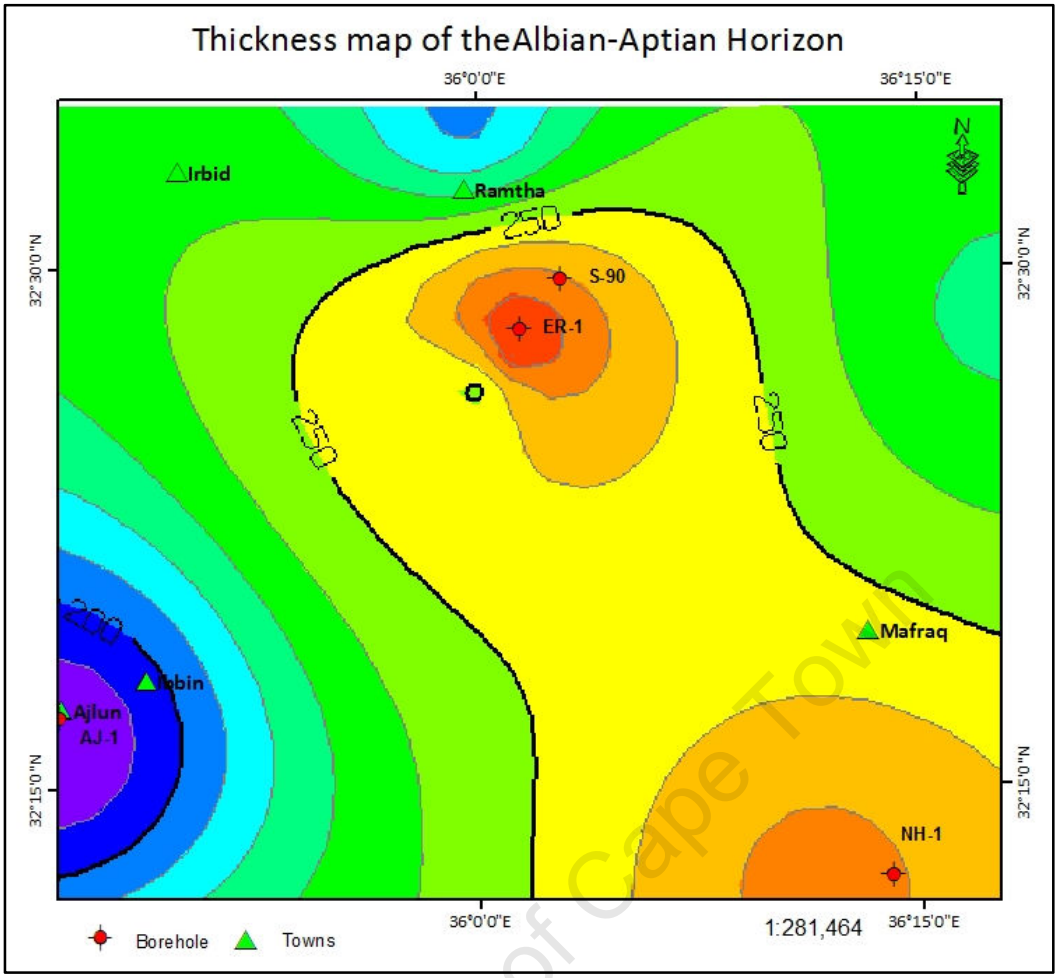

Figure 3-13: Isopach maps of the Lower Cretaceous (Albian-Aptian) sequence as calculated from the 2D seismic reflection and the key boreholes data

THE JURASIC SEQUENCES HORIZON (H3) (FIGURE 3-14)

This horizon exhibited a remarkable low magnitude structure cut by a major NW-SE fault (Ramtha-Sirhan Fault System) with a major east downthrown as shown in Figure 3-14. To the east of Al-Mafraq town, the horizon rises to about 237-400m forming a high magnitude structure. While to the west, it declines suddenly to about-575-413m. Thickness increases to about 460-580 m across the southwest and north of the JNH unlike toward the east and southeast, where it decreases to about 240m.

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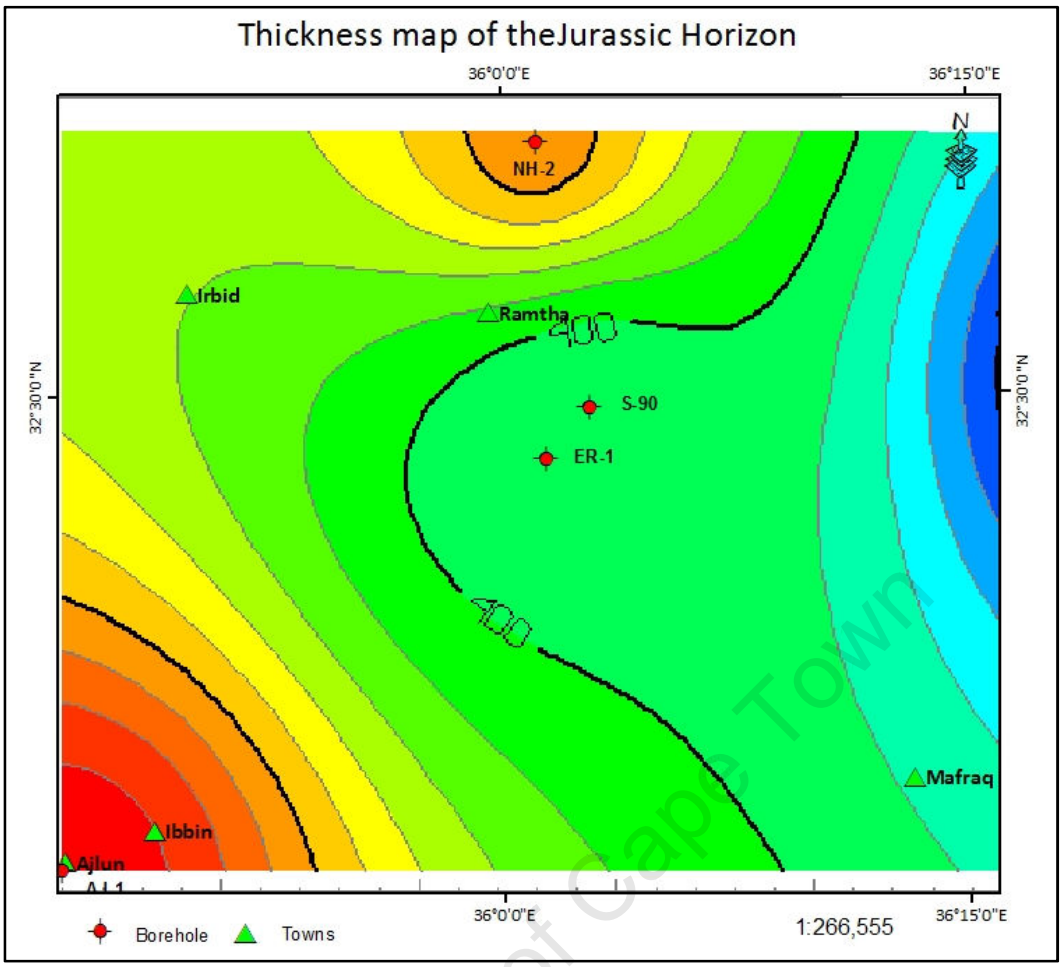

Figure 3-14: Isopach maps of the Jurasic sequence as calculated from the 2D seismic reflection and the key boreholes data

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THE TRIASIC SEQUENCES HORIZON (H4) (FIGURE 3-15)

This horizon deepens toward the north and northwest to about -2000--1825 m. unlike toward the southeast, north of the NH-1 well it rises to about -200 m forming a high magnitude structure around the Al Mafraq town.

The influence of the NW-SE and NE-SW faults is significant especially between S-90, ER-1, and BUS-1 wells. Thickness variations of these sequences reflect the influence of the dominant structural framework. It increases in the north and northeast unlike in the south, southwest, and southeast.

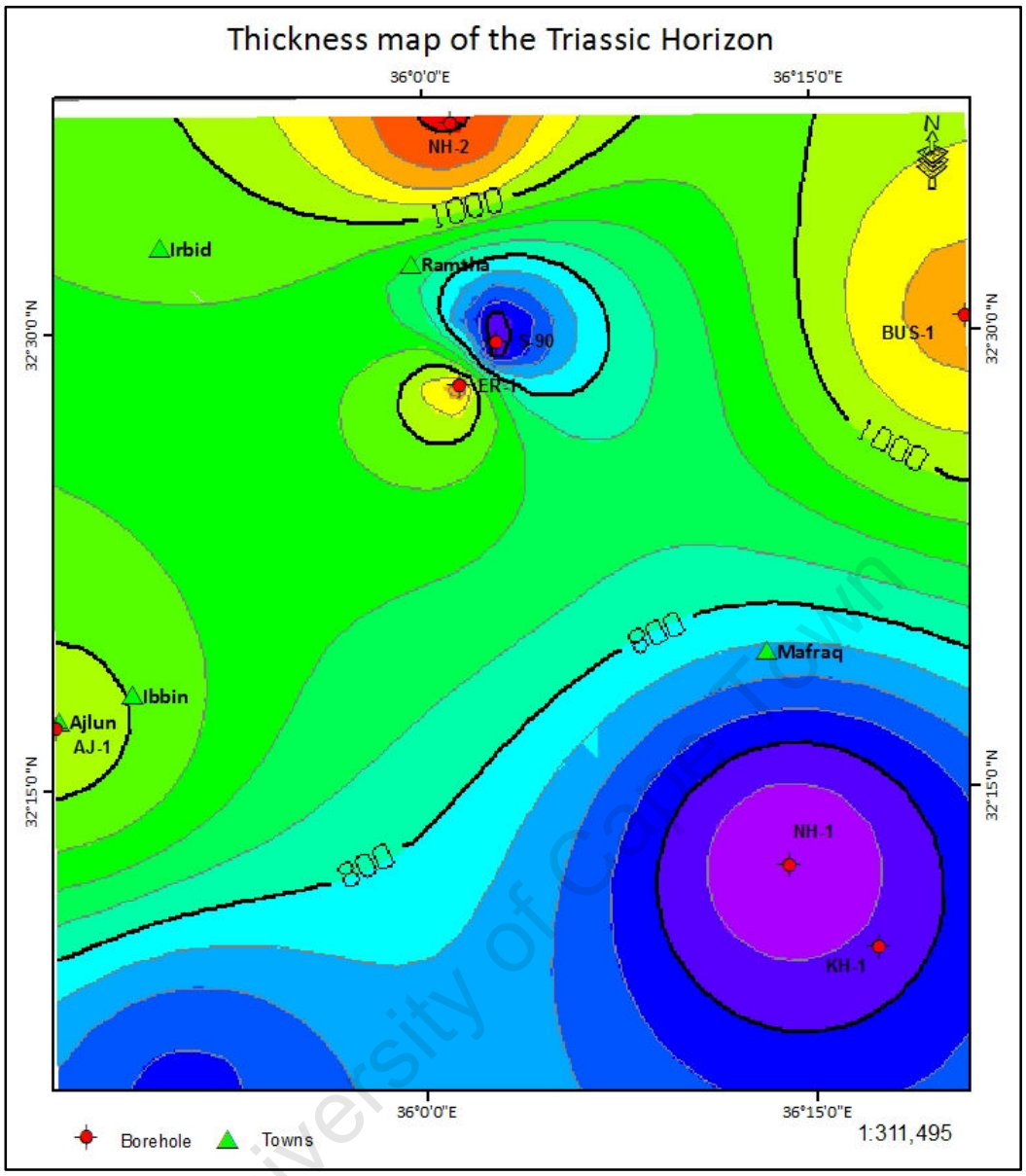

Figure 3-15: Isopach maps of the Triassic sequence as calculated from the 2D seismic reflection and the key boreholes data

THE PALAEOZOIC SEQUENCES HORIZON (H5) (FIGURE 3-16)

The structural map displays a declination of the top of the Palaeozoic horizon toward the northwest unlike toward the southeast (Figure 3-16).

The top of the Palaeozoic appears to be subdivided into two blocks disrupted by several deformations; the northern block is highly deformed where the major fault trends cut it into several low structures. A major one is composed of two minor ones separated by the

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Ramtha-Sirhan Fault System around the S-90 and ER-1 wells where the depth declines to about -3200-3600m. Another one is located between north of Ramtha town and NH-2 well where the depth declines to about -3200-3400m. A third main one lies in the northwest of Irbid town where the depth declines to about -3200-3400m. The southern block toward the west, southwest, and southeast depth rises to about -1200-1000m forming a high magnitude structure across Al Mafraq town. An apparent thickness variation is noticeable from about 3000m southeast to about 200m north and northwest.

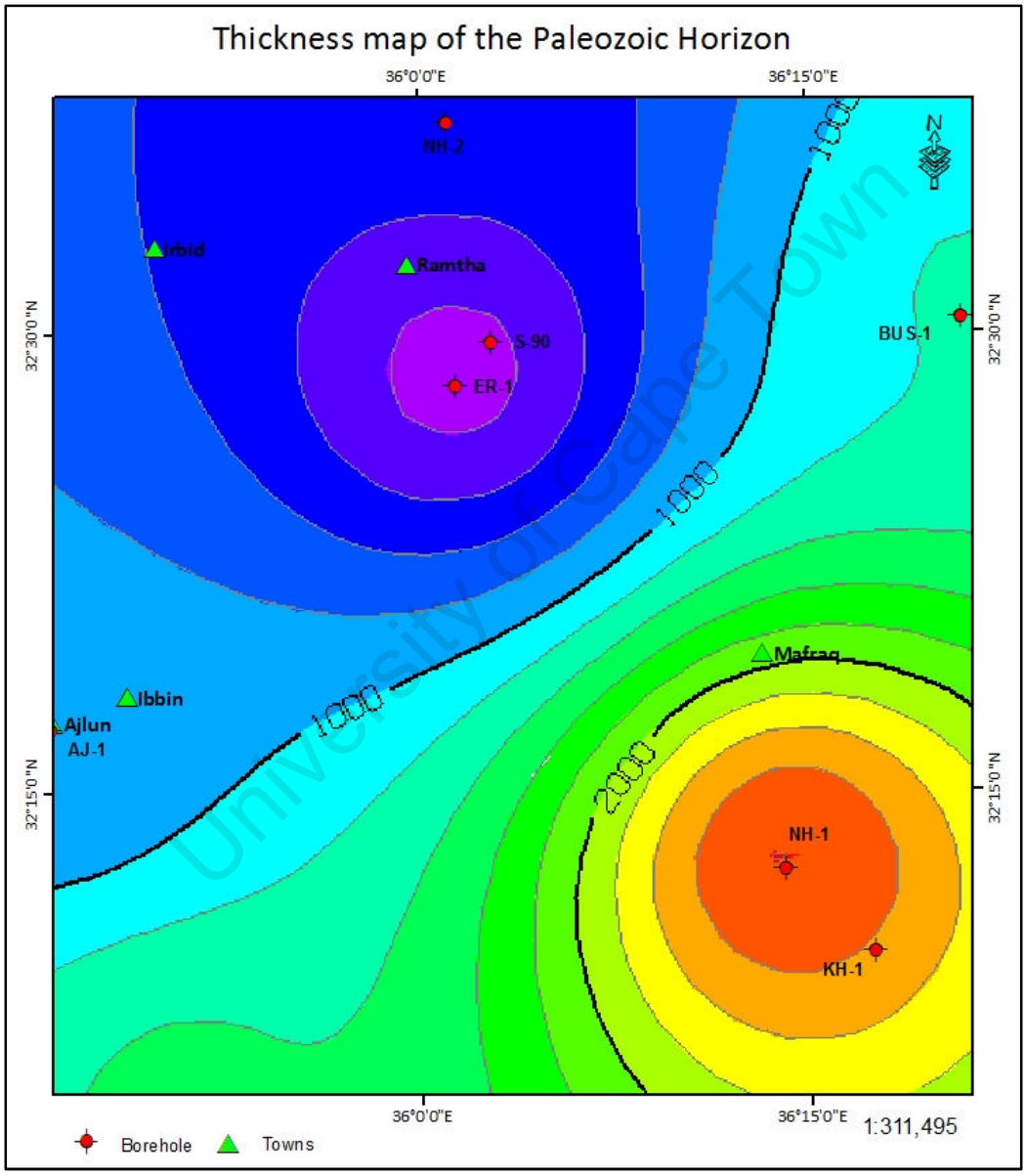

Figure 3-16: Isopach maps of the Top of Paleozoic sequence as calculated from the 2D seismic reflection and the key boreholes data

An effort was carried out to study the thickness variations of the Tertiary and the Turonian-Maastrichtian sequences as calculated from borehole data in order to give a complete picture of the entire stratigraphic column; however, these horizons could not be identified due to difficulty in identification of these horizons on the available 2D seismic profiles. Figure 3-17 displays the thickness map of the Tertiary sequences, which increases toward BUS-1 well in the east to about 480-520 m. While to the west, near the S-90 well, it decreases to about 100-140 m.

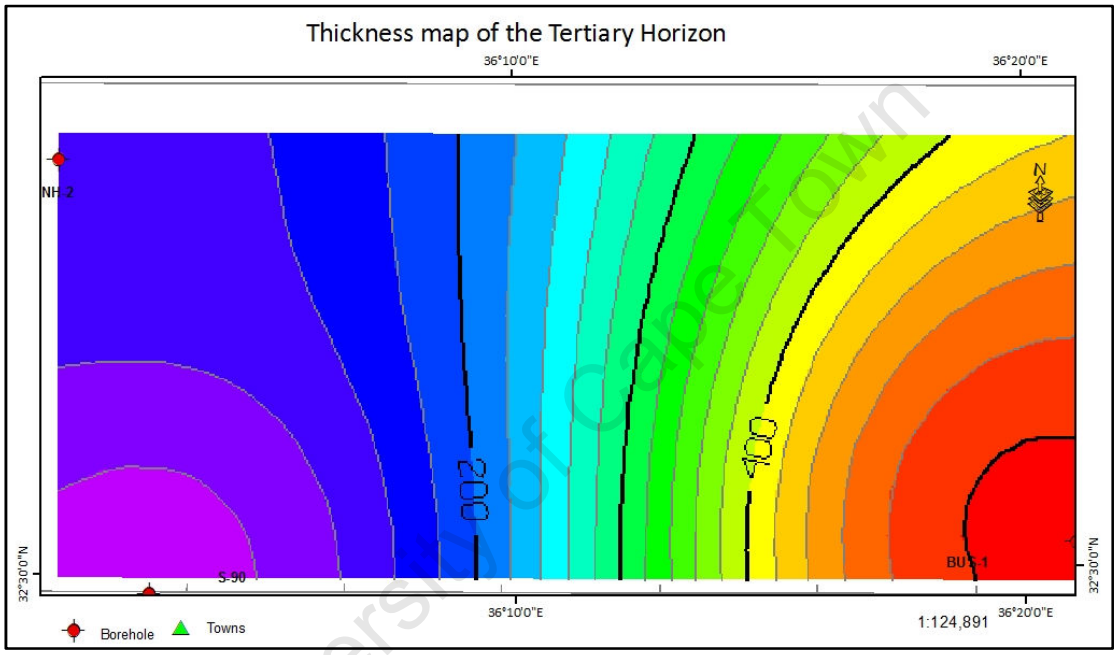

Figure 3-17:Isopach map of the Tertiary sequence as calculated from the key boreholes data

The Turonian-Maastrichtian thickness (Figure 3-18) increases toward the northeast to about 650m close to the NH-2 well. Across the vicinity of S-90 well, thickness decreases to about 200-300m. While across the ER-1 region it increases to about 550-600m. Close to Ajlun Dome and Al Mafraq town these sequences are thinning. The analysis of this thickness map suggests the presence of a major fold belt with an axis of NE-SW to NNE-SSW cut by major NE-SW and NW-SE fault systems.

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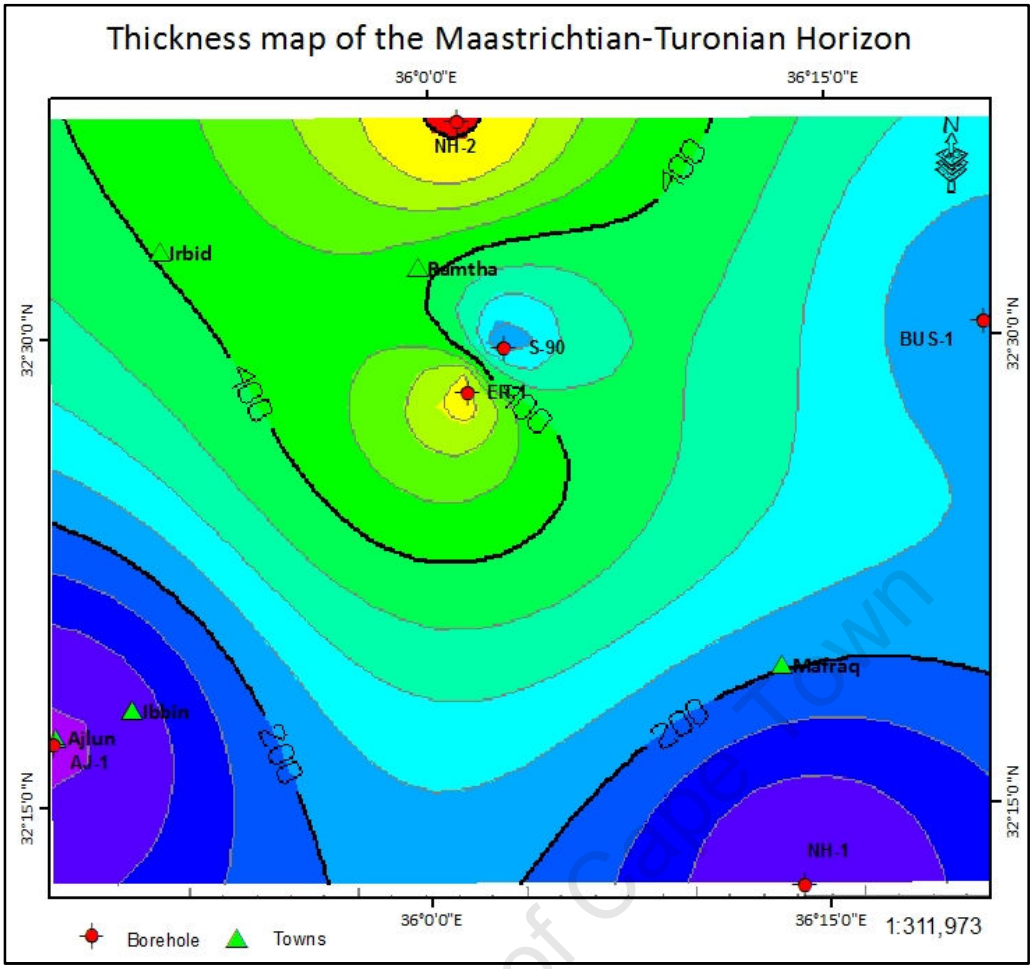

Figure 3-18: Isopach map of the Turonian-Maastrichtian sequence as calculated from the key boreholes data

3.2.2.2. SUBSURFACE STRATIGRAPHIC DISTRIBUTION BASED ON THE KEY BOREHOLES

The six wells drilled in the JNH show that, JNH area has thicker, more complete Jurassic and Triassic sections than are present in the rest of Jordan. Lower to Middle Eocene carbonates are exposed at the surface except in the deeply incised wadies where section down to the Triassic is exposed. Roughly 1500m of Tertiary and Cretaceous carbonates overly 1500m of Jurassic and Triassic mixed carbonates and clastics which in turn overly more than 2500m of Paleozoic clastics. The thick Jurassic-Triassic section seen in the JNH extends to the north into the Damascus Basin in Syria (Maccullough *et al*, 1988). In Jordan, the Jurassic and Triassic sediments are progressively truncated by Albian-Aptian Kurnub Sandstone Group unconformity to the south and thin from 1500m in NH-2 to 0m at Wadi Al Mujib (east of the

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Dead Sea, Central Jordan) (Powel, 1989). Throughout the Mesozoic, marine transgression originated from the north and west of Jordan. The provenance area for clastics lay to the south on the Arabian shield and to the east on the Hail Arch. The carbonates in the north change to clastics in the south as Triassic sediments approach the southern strandline of Triassic seas (, Jawzi et al., and 1994).

3D FENCE DIAGRAM OVER THE JNH

The main stratigraphic horizons from the Precambrian to the Tertiary were correlated in a fence diagram started from the northeast toward the west, southwest, southeast, and east of the JNH area in order to shed light on the subsurface stratigraphy

Figure 3.19 displays a 3D fence diagram between the key boreholes as. This correlation profile enables clarification of the stratigraphic distribution across the JNH area and south of Syria (Hauran area). It shows a significant thickening in the Paleozoic sequences toward the southeast as well as the absence of Jurassic. Jurassic, Triassic, and Cretaceous sequences show thickening toward the northeast and northwest. Tertiary sediments mainly comprise the northeast parts of the JNH area

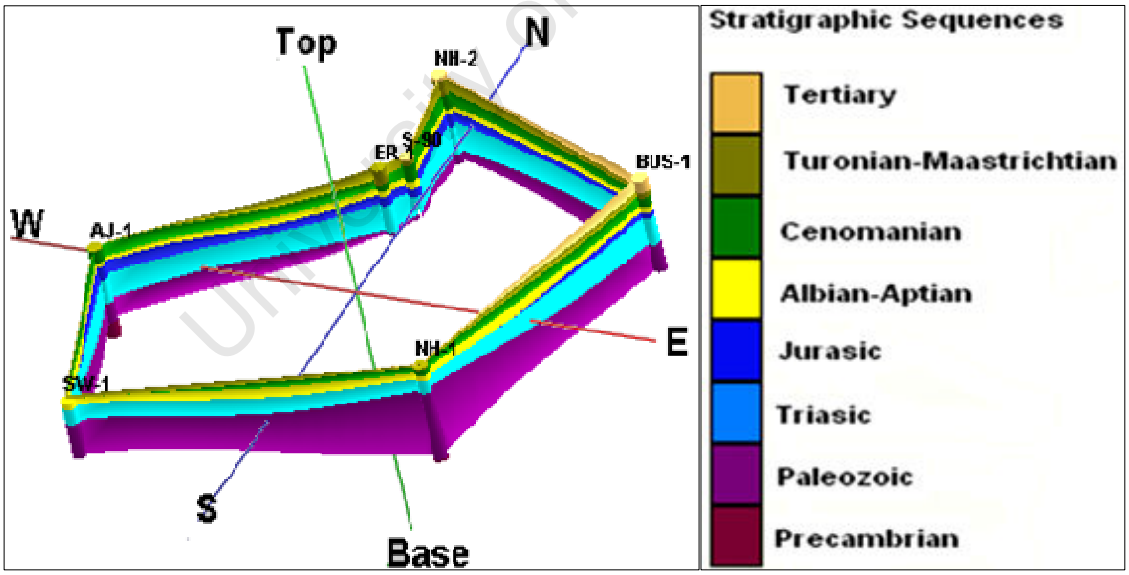

Figure 3-19:A 3D fence diagram between the key boreholes showing the sub-surface stratigraphy distribution

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3D STRATIGRAPHIC MODEL OVER THE JNH

A three Dimensions (3D) stratigraphic model was developed from the data of the key boreholes (Figure 3-20). It enables more clarification of the structural and stratigraphic distribution across the study area.

PALEOZOIC SEQUENCES

Figure 3-20(A) emphasizes a remarkable thickness of the Paleozoic sequences in the southeast direction and the absence of the Jurassic.

MESOZOIC SEQUENCES

Triassic, Albian-Aptian, and Tertiary show noticeable thickening in this direction, however, upper Cretaceous is missing. Toward the southwest, the dome structure of Ajlun structure is noticeable with a NE-SW major axis. In this direction, Suwelih structure shows a significant sedimentary cover of Albian-Aptian (Lower Cretaceous) sediments.

Toward the northeast, Triassic, Jurassic, Cretaceous, and Tertiary exhibit a significant thickening, forming a remarkable low structure (Figure 3.20.B).

Albian-Aptian sediments show a gradual increase in thickness in the southwest direction, in comparison to those in the northeast and in the west (Figure 3-20.C). Within the vicinity of AJ-1 well a considerable uplifting structure is observed which is believed to be part of Ajlun Dome structure (Figure 3-20.D).

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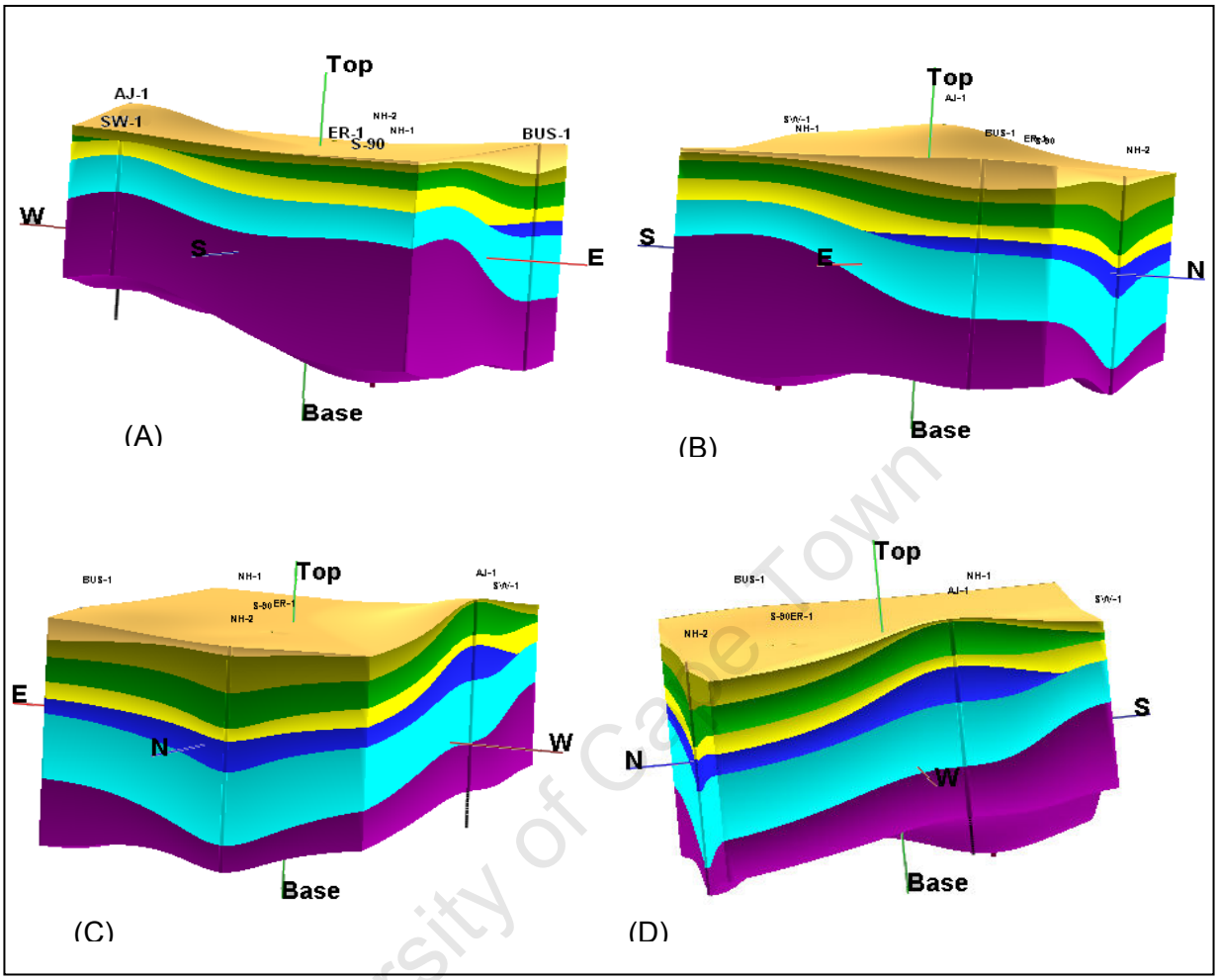

Figure 3-20:The developed 3D stratigraphic model from the key boreholes. A, B, C, and D illustrate different view scenes

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3.2.2.3. STRUCTURAL-STRATIGRAPHIC CORRELATION BETWEEN THE KEY BORHOLES IN THE JNH

The outcome of the 3D stratigraphic model was supported by further detailed structural correlation between AJ-1, SW-1, NH-1, and NH-2 wells which revealed the following points:

(1) Formation top of Shueib-Na'ur formation (Cenomanian) in well AJ-1 is structurally higher than NH-1 and NH-2, by 554 m and 1353 m respectively.

(2) Top of Kurnub formation (Albian-Aptian) in well AJ-1 is structurally lower than SW-1 by 57 m and higher than NH-1, NH-2 by 310 m , 1409 m respectively.

(3) Formation top of Huni Formation (Middle Jurassic) in well Aj-1 is structurally higher than NH-2 by 1434 m while Huni Formation in SW-1 and NH-1 is missing.
(4) Top of Abu-Ruweus Formation (Late Triassic) well AJ-1 is structurally lower than SW-1 and NH-1 by 573 m, 174 m respectively, and higher than NH-2 by 1372 m.
(5) Top of Hudeib Formation (Early Permian) in well AJ-1 is structurally higher than NH-2 by 1562 m while Hudeib formation in Sw-1 and NH-1 are missing.
(6) Disi / Umm Ishrin and BURJ Formations (Middle-Late Cambrian) in well AJ-1 are missing due to faulting or erosion.
(7) Top of Salib Formation (Early Cambrian) in AJ-1 is structurally lower than SW-1 by 271 m and higher than NH-1 by 352 m.

Another structural and stratigraphic correlation between ER-1 and S-90 with a borehole located towards the ESE of Ramtha town was conducted in order to give much insight into the major unconformities between the Paleozoic and Mesozoic sequences. The NRA studies in 1978 of these boreholes indicated that The ER-1 structure is seismically defined anticlinal fold with little or no surface expression. Geological sampling of the surface beds on the culmination and flank indicate Maestrichtian age beds. The seismic survey indicate N-S orientated faults on the east and west flanks, between which a gentle fold plunges slowly to north and south. There is an estimated closure of 150 m. The increasing thicknesses down flank suggests some folding movement during deposition , but this thickening appears to be slight and may be due to changes over a subtle topographic high caused by an early forming structure . Possibly, each uplift and erosion/non-deposition phase gave rise to a small tectonic accentuation of the original fold.

Towards the ESE of Ramtha town in the vicinity of S-90 and ER-1A wells, there appears to be a considerable amount of thickening in the Paleozoic sequence as well as the lower Mesozoic formation; the Triassic-Jurassic sequence. Further towards NH-1 well in the southeast, there is a big gap in the stratigraphic sequence at the where the late Cambrian is under the lower Triassic and a considerable reduction in the Paleozoic series occurs. In the Ramtha ER-1 , as well as the S-90 the Triassic-Jurassic group was reported to be considerable thick which marks a remarkable boundary between the two sub-basins; Azraq and JNH , where the Triassic-Jurassic group was not reported at the Wadi Ghadf (WG-1) to the west of Azraq (Nowaihed, 1982) .

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Nowaihed in 1982 referred to a correlation between the Safra (ESE Ramtha town within the Azraq Basin), S-90, Er-A wells which led to the conclusion that the stratigraphic sequence in the Northern highlands is recognized by the lower Mesozoic (Triassic-Middle Jurassic) groups and overlain by the Middle-Upper Cretaceous and very restricted lower Tertiary. The unconformity between the two sequences is quite evident by the thinning and pinch out of the Tertiary series to the west and northwest of Azraq.

The correlation of NH-1 well with the ER-1 well which is located about 35 km northwest revealed that several major and local unconformities have been encountered in the NH-1 well. The most significant unconformity has been identified at the Mesozoic-Paleozoic boundary which resulted in the truncation of considerably thick section of these ages. Therefore, the tops of Triassic and Paleozoic sequences were formal much higher than the prognosis (180m and 1098m respectively) (Rabi, 1987)

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4. DISCUSSION

ABSTRACT

JNH area has, for many decades, had drawn the attention of many researchers and investigators as well as oil companies for its distinctive geological setting, because of its location in the northwestern corner of the Arabian Plate within the eastern margins of the Mediterranean Sea Basin. The JNH area lies in the middle of an important group of tectonic provinces; Rutba Uplift, Jordan Uplift, Dead Sea Transform, Palmyrides, and the Sirhan Depression.

This study was designed to give a comprehensive geological picture of this part of Jordan in an attempt to understand the relationship between its structural setting and the adjacent regional tectonic and structural elements. Hence, this study is considered the first of its kind in terms of the scientific approach and the technology used in the collection and analysis of all surface and subsurface geological data about this remarkable geological province of Jordan. This approach enabled delineation of the General geological setting in terms of main structures and rock distribution by age and thickness.

The area of prime interest, JNH, lies in the northwestern corner of the Arabian Plate within the eastern Mediterranean margins, and adjacent to the eastern margin of the Dead Sea Jordan Valley Graben. Consequently, this has contributed to its General structural and tectonic setting. The General structural setting of the area under consideration is characterized by the existence of compression and extensional features; major folding zones of anticlines, synclines, and monocline flexures. These folding zones are either accompanied or cut by major faulting systems striking NW-SE, NE-SW, NNE-SSW, E-W, and N-S. The major faulting systems form with the minor secondary faults a distinguished structural style of horsts and grabens striking mainly NS and NNE-SSW which many authors considered as structures of significant importance.

The geological structural setting of the JNH shows the effect of episodes of deformation that affected Jordan and the northern Arabian Plate since the Cambrian period. The Arabian Plate northward motion and its counterclockwise rotation (Burdon, 1959; Panikarov *et al*.,

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1967) has resulted in gentle, regional tilting, uplift and subsidence and a combination of faulting and folding (Burdon, 1959; Quenelle, 1959; Fruend, 1965; Bender, 1974; Quenelle, 1984; Johnson, 1998). Such movement is accompanied by compression and strike-slip faulting along the Bitlis and Zagros zones, where the Arabian plate collides with and sub-ducts beneath the Eurasian plate. Collision with Eurasia caused folding and thrusting in the Zagros and Bitlis zones along the northeastern and northern margins of the Arabian plate, and concurrent strike-slip faulting on the Dead Sea transform which caused the development of pull-apart basins and en echelon folds. This chapter will discuss the major structural elements of the JNH area and some related major elements adjacent to it, taking into consideration most of the previous studies.

Several stress episodes affected Jordan since the Cambrian are believed that it formed the present geological setting of the JNH. Ramtha-Sirhan Fault System, Zarqa Fault System, Fuluq Fault System, Irbid Ramtha Basin, Bala'ama Fold Structure, Amman Hallabat Structure, Suwelih Structure, and Ajlun Dome. All these major elements are witnesses to the compression, tension, and compression-tension combination of deformation episodes that took place in this area. In addition, Dead Sea Transform Fault System formation is the main tectonic event that affected the JNH.

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4.1. GEOLOGICAL SETTING OF THE JNH

4.1.1. GENERAL STRUCTURAL STYLE

The interpretation revealed a complex structural setting of the JNH which suggests that the area has been subjected to several phases of compression and tension forces while episodes of deformation since the Cambrian time. Syrian Arc stress and Jordanian Arc stress which were defined by several previous studies are believed to be strong indicators of these processes of deformation that show the effects of the Arabian Plate motion.

The interpretation clarified the following characteristics of the previously mentioned structural style of the JNH:

(1) Complex structural style; which is composed of a maze of complex structural systems of faults and folds
(2) Three major structural trends are dominating the area; NW-SE, NE-SW, and E-W
(3) Existence of series of fold belts of lows and highs which are mainly striking NNE-SSW, N-S, and NE-SW, and cross cutting by major faulting systems
(4) Remarkable fold belts are comprising the western margin of the JNH along the eastern ridge of the Jordan Valley where the northern part of the major DST extends in Jordan from the north of the Dead Sea northward towards Lake of Tiberias, however, these deformations decreases eastward
(5) Significant strata dipping is toward the east and north forming a major northward plunging anticlinal element that is believed to extend into Damascus Basin in Syria. This structure is disrupted by faulting systems which cut it into blocks
(6) Ajlun Dome is part of this major plunging anticline that borders the eastern margins of the study area
(7) Major subsidence is striking NW-SE along the Ramtha Sirhan Basin and separating the JNH from the Azraq Basin in the eastern Platform of Jordan
(8) Borehole data induced significant structural system of combination of major synclines and anticlines

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(9) Existed faulting systems are mainly of normal faults accompanied with secondary normal faults

(10) The General geomorphology and topography of the JNH is highly controlled by its structural setting

(11) As a matter of fact, the present geologic setting of the study area is as a result of the geologic events subjected the Arabian Plate throughout the geologic time. Thus, aging of the Palmyrides , Rutba Uplift , and the DST formation indicate the tectonism of Ajlun Dome

4.1.1.1. DISSCUSION JNH STRUCTURAL STYLE; ITS CAUSES AND ORIGIN

The complex structural style of the area suggests that the area has been subjected to several phases of compression and tension resulted from episodes of deformation that affected Jordan and the northern Arabian Plate, since the Cambrian times. As mentioned in the above, JNH is characterized by combinations of faulting and folding which may took place into stages. According to Burdon in 1959, "Folding and faulting deformation took place in two phases"; minor compression forces affected the area during the Maastrichtian and resulted in minor folds. Combination of folds and faults developed as these compression forces became more intense. Later, the compression stresses contributed counterclockwise rotation of the Arabian Plate, which caused major deformation, and displacement along what is now the Jordan Rift Valley. Then, sinistral movement continued and produced tension where the block opened, and produced the Rift. In addition, Swartz and Arden in 1960 assumed that the developed tension in the Red Sea, simultaneously with compression in Lebanon by counterclockwise rotation of the Arabian Plate. Fruend in 1965, emphasized the hypothesis that compression folding developed since the Upper Cretaceous in the Zagros-Taurus ranges, Palmyra, Lebanon, Judea, Negev, and northern Sinai simultaneously with tensional faulting in the Red Sea, Gulf of Suez and Northern Israel.

Mikbel and Zacher, 1981, 1986; Mikbel and Atallah, 1983; Mikbel, 1985 studied the JNH structural style of high intensity folds and faults close to the Transform, and decrease eastward. They claimed that the eastern margin of the Dead Sea Transform Fault is controlled by northward motion of the Arabian plate with respect to the Sinai Palestine

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plate. This movement induced SE-NW and N-S horizontal stresses that generated this type of deformations

The effects of another major tectonic stresses in the region which caused by the Arabian Plate motion affected the JNH and resulted its present structural style;

Eyal and Reches in 1983 defined two major tectonic stresses in the region; each is uniform both in time and space:

(1) The Syrian Arc stress is a stress field with dominating horizontal compression trending W to NW in the Late Cretaceous to Eocene rocks in the folds and plateaus west of the DST.
(2) The Dead Sea Transform (DST) stress field, with dominating horizontal extension trending E to ENE.

This was supported by a Paleostress analysis by Diabat *et al.*, 2004 who conducted a Paleostress analysis study of the Cretaceous rocks in the eastern margin of the Dead Sea Transform (DST) in Jordan. The study led to the identification of three Paleostress fields:

- A field stress of WNW-ESE compression and NNE-SSW extension which includes two Paleostress regimes; one is restricted mainly to the JNH area, predominantly strike-slip faulting and dip-slip normal faulting regimes. It could be associated with formation of the Syrian Arc fold belt that started during the Turonian or it may be due to an anticlockwise rotation of the stress field. Eyal and Reches in 1983 suggested that it is the older stress that is responsible for the formation of the Syrian Arc
- A field stress of NNW-SSE compression and ENE-WSW extension; it includes two stress regimes, one with dominating strike-slip faulting and the other with normal faulting. It is associated with the 105 km sinistral displacement along the DST and the opening of the Red Sea. Therefore it was suggested to be younger than the first one and responsible for the formation of the DST(Eyal and Reches, 1983)
- A local Paleostress field, which is characterized by nearly N-S orientation, is responsible for the formation of E-W trending normal faults. This is the youngest event as these faults cut the previous ones, and it may have been active since the post Middle Pliocene (Ron and Eyal, 1985).

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(3) In addition to the above mentioned study, several previous studies and surveys emphasized an important stress element; the Jordanian Arch stress which shows the effect of the Arabian Plate motion as well as the effects of the DST stress. This type of stress is highly obvious on the General structural style of the study area. Filon in 1975 clarified that this tectonic stress is characterized by a large northerly plunging structure, disrupted by faulting systems which cut it into blocks forming significant structural elements. This describes and agrees with what the study has revealed from the interpretation regarding the major structural elements of Ajlun Dome that borders the western margin of the JNH. Filon (1975) also indicated that gravity and magnetic data suggests that the Jordanian arch is a basement ridge plunging into Damascus basin. Apparent thickness variations of the Mesozoic and Cenozoic sequences toward the north are also indications of this plunging.

JNH lies within the Eastern Mediterranean Platform. Consequently, the structural elements of JNH are believed to be related in origin to those identified within the Eastern Mediterranean Platform. Many studies stressed the existence of a sequence of uplift, rifting, subsidence, and shortening elements that have taken place since the creation of the Arabian Plate and formation of the great Dead Sea Transform Fault (Mitchell, 1959; Mikbel, 1985; and Occidental, 1991). Interpretation of surface and subsurface geological information as well as correlation to the geology of the adjacent areas shows the existence of a series of compression and extensional structural elements. Compression elements manifest in broad folding belts and uplifts whereas extensional elements manifest basins and normal fault type. Abu Jaber *et al*. in 1989 studied the relationship between the opening of the Eastern Mediterranean Sea and the development of the adjacent Levantine Platform (Jordan, Syria, and Israel) structures during the Mesozoic and Paleocene-Middle Eocene. This study showed that the compression and tensional stress that affected the Mediterranean Sea and caused its deformation development is responsible for the formation of the Levantine Platform phases. In accordance, a sequence of uplifts, rifting, subsidence, and shortening are concluded because of induced fluid migration within marginal marine basins in the Levantine Platform. Sirhan Depression and Palmyra Basin are the first manifestation of this relationship. Basaltic flows and volcanic deposits mark the western convergence of these basins.

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Kazmen in 2002 conducted a study on the sedimentary basins and rifts of North Arabia. This study illustrated a long history of intraplate deformation: rifting and inversion from the Late-Paleozoic to Cenozoic times. The major rifting episodes took place during the Late Carboniferous-Permian, Middle-Late Triassic and late Early Cretaceous followed by periods of post-rift subsidence and accumulation of sediments. This is evidenced by the existence of several rifts and basins across the Eastern Mediterranean margins. Sirhan Depression and the Jordanian Arc elements in the JNH area are strong indicators of these processes of deformations. (Figure 4-1) illustrates those major Late-Paleozoic-Mesozoic rift related structures north the Arabian Plate and Eastern Mediterranean Basin according to Kazmen, 2002. These structures were described as inverted intercontinental rifts or aulacogenes; Palmyrides, Sinjar Trough, Euphrates, and Druze Depression.

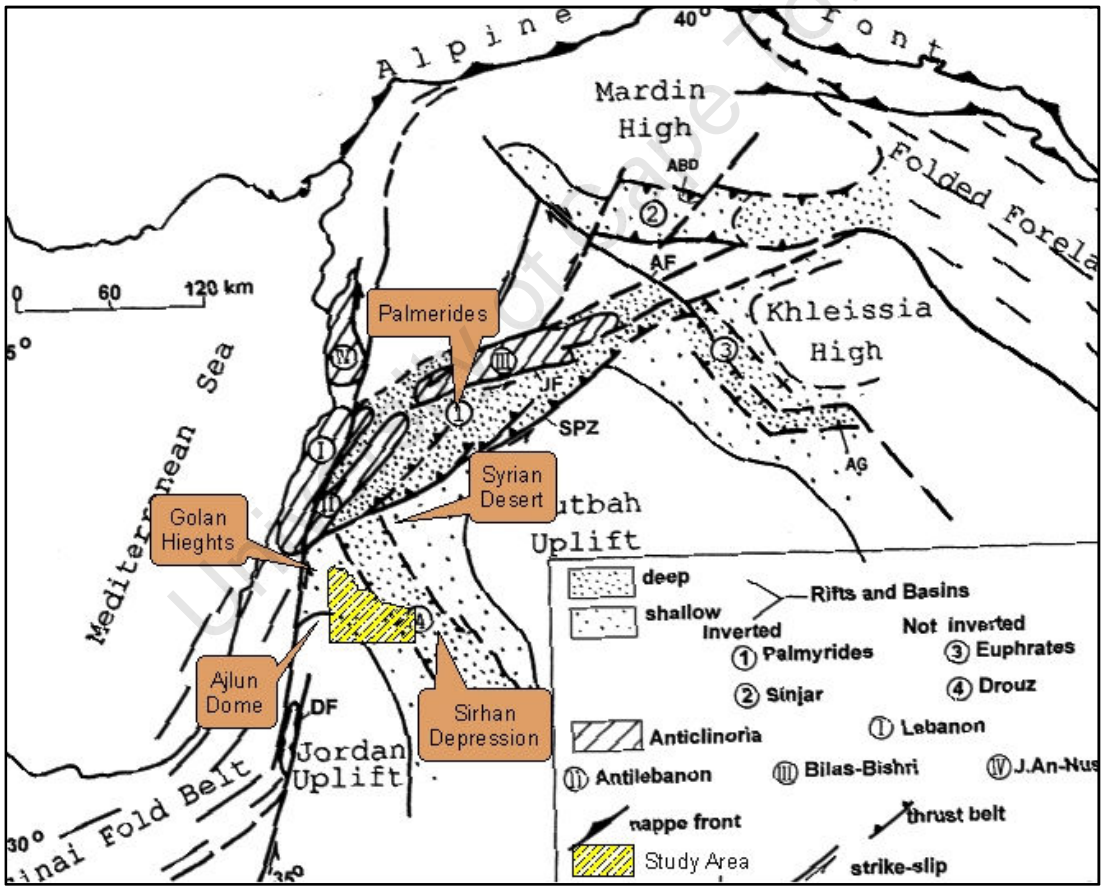

Figure 4-1:Rifts and Basins OF North Arabian Plate, after Kazmin 2002

Panikarov *et al.,*1967 *;* Occidental, 1991; Al Saad *et al*., 1992; Kazmin, 2002 described the region as a major Levant platform where Rutba Uplift and Jordan Uplift are the two main tectonic elements that characterize it.

Rutba Uplift comprises the largest uplift to the northeast and east of the Sirhan Depression; where Triassic rocks are brought up to the surface in its central part. In addition, there is Jordan Uplift, which is situated east of the Dead Sea Transform where Ajlun Dome comprises its center with Cretaceous rocks.

Euphrates Neogene Depression bounds Rutba Uplift from the east and the Jordan Uplift bounds it from the west. JNH area lies between these two Uplifts and the Druze Depression (Sirhan Depression) and occupy most of it in a NW-SE direction. The growth of the folds across the Jordan Uplift can be traced from the Late Cretaceous or early Palaeogene (Kazmin, 2002)

4.1.1.2. REGIONAL TECTONIC ZONES OF THE NORTHERN ARABIAN PLATE THAT ARE IN RELATION TO THE JNH STRUCTURAL STYLE

(1) RUTBA UPLIFT

Rutba Uplift, where Triassic rocks are brought up to the surface in its central part (Kazmin, 2002), comprises the largest uplift to the northeast and east of the Sirhan Depression (Figure 4-1).

A study to examine the crustal structure of the northern Arabia platform beneath Syria was carried out by Al Saad *et al*., 1992, who described the Rutba Uplift as one of three major tectonic zones of the northern Arabian platform in Syria that are crossed by a transect. This transect is surrounded by the major plate boundaries of the middle east; DST, the Bitlis suture and the East Anatolian fault to the north, and the Zagros collision belt .

The Rutba uplift is a broad, basement-cored dome located in central Southern Syria Desert near the Jordan-Iraq border with a thick Phanerozoic (mostly Paleozoic) cover of 6-7 km. subsurface studies indicate that this uplift was an early Paleozoic depocenter (Lovelock 1984; Al Saad *et al*., 1992; Sawaf *et al*., 1993). Paleozoic rocks consist of interbedded sand/shale sequences, deposited in a near shore to shallow marine environment.

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The Mesozoic section comprises the northern flank of the uplift facing the Palmyrides belt, indicating subsequent uplift relative to the Palmyrides in the early Triassic (Best, 1991). Four major Paleozoic unconformities dip gradually northward and disappear beneath the highly deformed Palmyrides belt (McBride *et al*., 1990) with significant Mesozoic and Cenozoic thickness to the east in the Euphrates depression

(2) SIRHAN DEPRESSION

Sirhan Depression or Druze Depression was mentioned in many studies by different nomenclatures; Sirhan Depression, Sirhan Basin, Ramtha-Sirhan Basin, Sirhan Trench, Sirhan Graben, and Druze Depression (Mitchell, 1959; Panikarov *et al.,* 1967; Occidental, 1991) **.** To avoid confusion, we will refer to it here as Sirhan Depression.

Sirhan Depression is considered to be one of the basins that extend from the Nefud in Saudi Arabia to the Euphrates River in Syria, which structurally represents arms of relative subsidence formed between Rutba-Hail Uplift, Jordan Uplift, and Aleppo Uplift (Khouri, 1982), (Figure 4-1)

A system of NW-SE faults bound Sirhan Depression along its western and eastern margins. Bouguer and depth basement profiles (Figures 3.6, 3.7, and 3.8) emphasized that these faults are deep and may have penetrated into the basement. Panikarov *et al.,* 1967 clarified that they appear faulted at depth. These faults seem to be controlling the position and the strike of the Sirhan Depression. In addition, they have contributed much to the formation of thick sheets of basic effusive rocks that were erupted in the Neogene and Quaternary times (Panikarov *et al.,* 1967; Occidental, 1991). On the surface, basaltic flows reaching its maximum thickness of about 1500m in the Jebel Druze cover the depression. Gharaibeh in 2003 addressed presence of basaltic dykes along the Fuluq Fault System (east of Sirhan Depression) and Ramtha–Sirhan Fault system, forming positive topographic features and linear ridges. These volcanic ridges rise up to about 1600m above sea level in the axial zone of the Depression. A thick sequence of Palaeogene, Cretaceous and possibly older sediments fill the depression (.Panikarov *et al.,* 1967).

Fractures of the northwesterly trend marked by chains of volcanic cones controlled the Early Miocene to Recent basaltic eruptions on the Jebel Druze and Hauran Plateau. As in other parts of Arabia, these fractures are most probably re-activated basement faults, which could

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control subsidence. To the north of the area, a major depression of multiple synclines was delineated within the vicinity of Yarmouk River Basin, around Ramtha and Irbid towns.

(3) THE SOUTHERN SYRIAN DESERT

The Southern Syrian Desert borders the northern margins of the study area, (Figure 4-1). The structural style of the Southern Syrian Desert is highly related to that dominated in the JNH area. A system of elongated regional faults extend for a long distance cut by systems of secondary faults and fractures characterizes its structural style. Consequently, groups of grabens and horst blocks are formed. The framework of the major and secondary faults is grouped into NW and NE striking systems. This style is an indication of the effects of several compression and tension forces affecting the area in phases. Panikarov *et al.,* in 1967 and Quenelle in 1984, addressed that these dominant fractures seem to be associated with tension forces acting during the growth of the large uplifts. This may explain the formation of high magnitude folded structures, which were delineated on the surface and subsurface data along the western margins of Sirhan Depression and adjacent to Ajlun Dome.

(4) THE PALMYRIDES

The Palmyra thrust-fold belt or the Palmyrides is considered as one of the most important tectonic elements within the Eastern Mediterranean margins in Syria that forms the northeastern arm of the "S"-shaped Syrian Arc that includes the Negev folds in central Sinai. It is a NE-SW striking intercontinental mountain belt, which acts as a mobile tectonic zone between the relatively stable Rutba uplift to the south and the less stable Aleppo plateau to the north, (Figure 4-1).

The evolution of the Palmyrides has been influenced by the surrounding Arabian plate boundaries, including the Red Sea and Dead Sea Transform System to the west; the Bitlis suture zone and left-lateral East Anatolian fault to the north, and the Zagros suture zone to the east. Specifically, it appears that uplift in the Palmyrides can be attributed to oblique compression stresses transmitted from the northern Arabian plate boundary into the interior of the Arabian platform (Chaimov *et al*., 1991; Al Saad *et al*., 1992). These stresses mainly affected the northern Syria unstable platform (Aleppo Plateau)) across the east Anatolian Transform Fault (Al Saad *et al*., 1992) causing dextral distortion on the Lebanon-Palmyra zone and creating mountain ranges of two styles (Quenelle, 1984).

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Uplift of the Palmyrides is a relative young phenomenon, however, during most of the Phanerozoic the zone was a sedimentary depocenter (Palmyrides / Sinjar trough), accumulating several kilometers of Paleozoic and Mesozoic strata through episodic rifting and broad subsidence (Brew, 2001).

The southwest Palmyrides are dominated by a series of short, southeast verging reverse faults that core prominent surface folding with steep dipping anticlines forelimbs (in some case overturned) and more shallow dipping back limbs toward the southwest (Brew, 2001). To the west of the folded Palmyrides anticlines the Anti-Lebanon Mountains form the highest topography in Syria where Jurassic and Triassic formation are exposed. and most of the Cretaceous section has been eroded (Brew, 2000). Walley in 1998 suggests that the majority of Anti-Lebanon uplift occurred during the second stage of the "Syrian Arc" deformation in the Late Palaeogene. The Lebanese structures were later modified as part of the restraining bend architecture of the Dead Sea Fault System during the Neogene (Chaimov *et al.*, 1990).

The structural style of the JNH is a result of multi phase compression caused by the Arabian plate motion during the last 50 Ma (Occidental, 1991). According to Freund *et al*., 1970, the overall present-day structure of Palmyrides is a result of the multistage, roughly N-S, compression caused by the Arabia-Eurasia collision during last 50Ma. In Middle Miocene to Recent time deformation was enhanced by a restricting bend of the Yammuneh fault, the western transform boundary of the Arabian plate. A sinistral transpressional component along the South Palmyra fault zone is probably related to the clockwise rotation of the Rutba block, which results from a sharp change in the amount of shortening in the Palmyrides from west (20 km) to east (1 km) (Chaimov *et al*., 1990)

(5) GOLAN HEIGHTS

The Golan Heights is a prominent tectonic element within the region of Eastern Mediterranean margins where the effects of the DST is significant. It is a typical basalt plateau formed by fissure eruptions, (Figure 4-1). The northern border of the Golan Heights is at contact with the flanks of the Hermon anticline whereas the southern part is the Yarmouk River which cuts into Senonian-Eocene beds near the southern flank of the Irbid syncline which continues beneath the Golan Heights. The eastern extension of the Golan

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Heights is the Hauran plateau, a younger basalt plateau with numerous prominent volcanic cones and fresh basalt sheets. The western border of the Golan is the Jordan rift valley. The Yarmouk River separates it from the JNH area in the south (Figure 4-2)

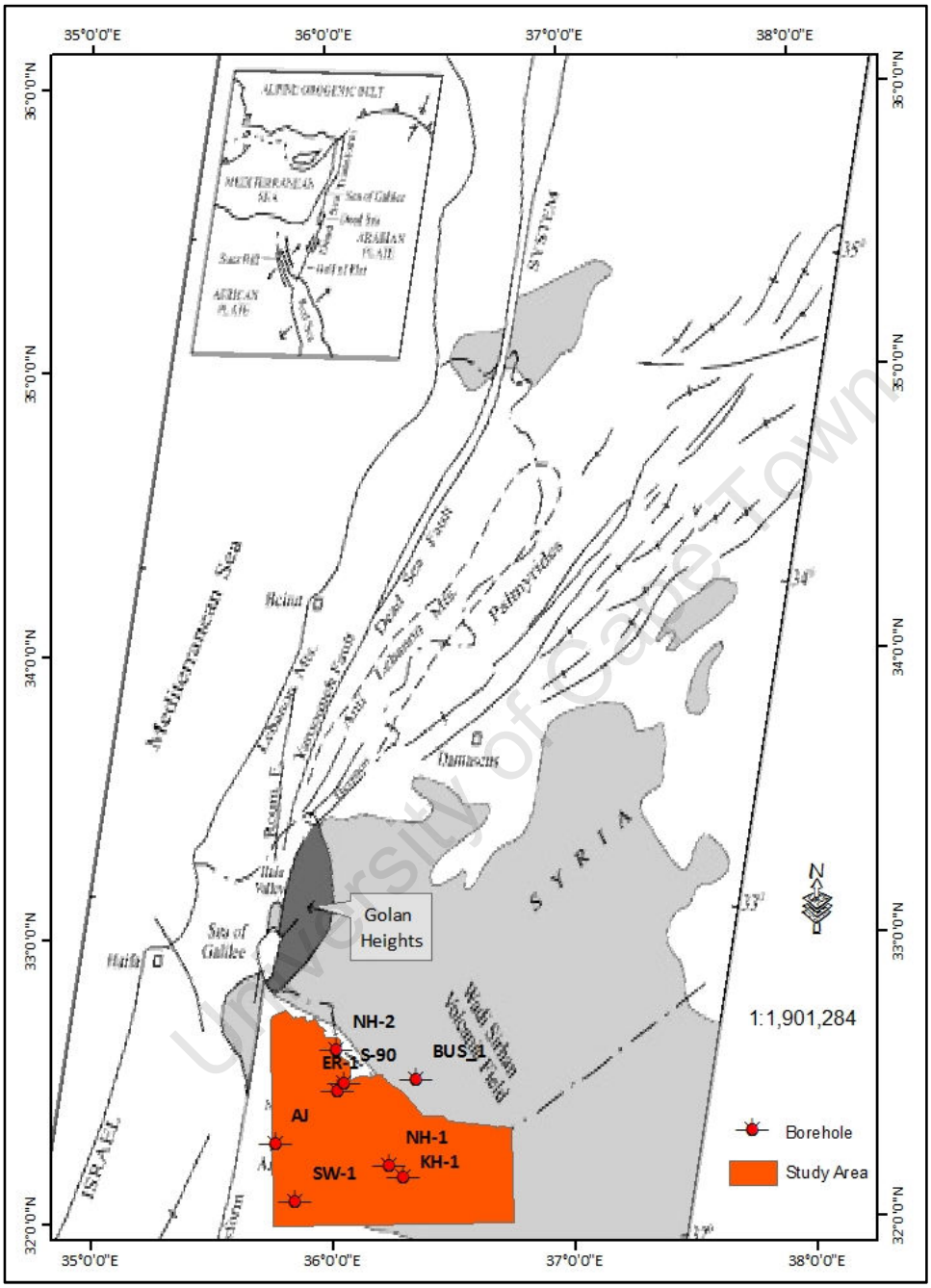

Figure 4-2: Location map of the JNH area and the Golan Heights, the Palyrides, and the DST modified after Shulman and Ben-Avraham, 2004

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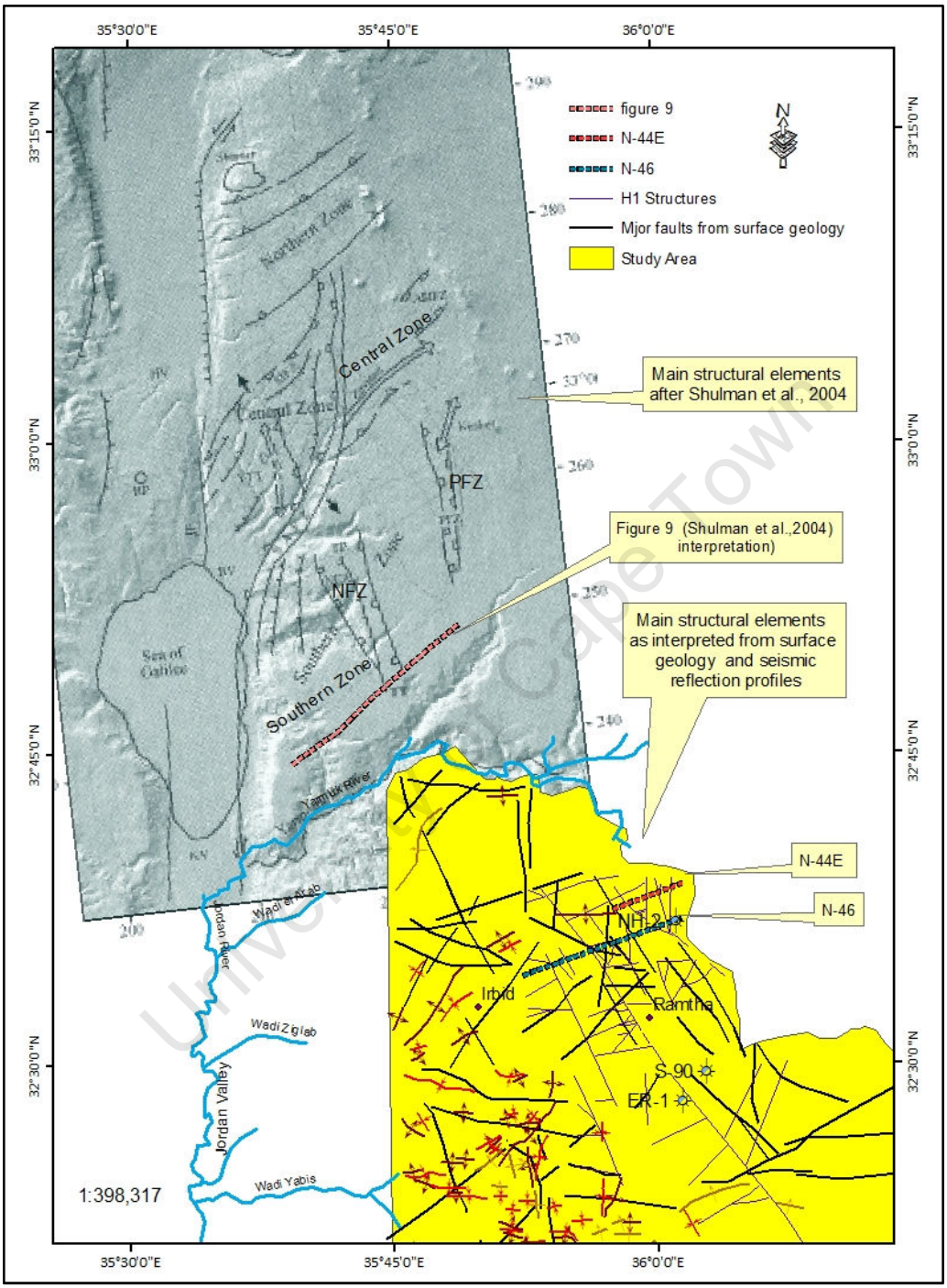
Shulman and Ben-Avraham in 2004 studied the Golan Heights and its tectonic linkage to the DST and the Palmyrides folding. In this study, Golan Heights was subdivided into three structural zones; northern, central, and southern zones. A correlation between the northern



part of the JNH and the southern zone indicates similar structural style that is, mainly, subjected to the DST activity (Figures 4-3 and 4-4)

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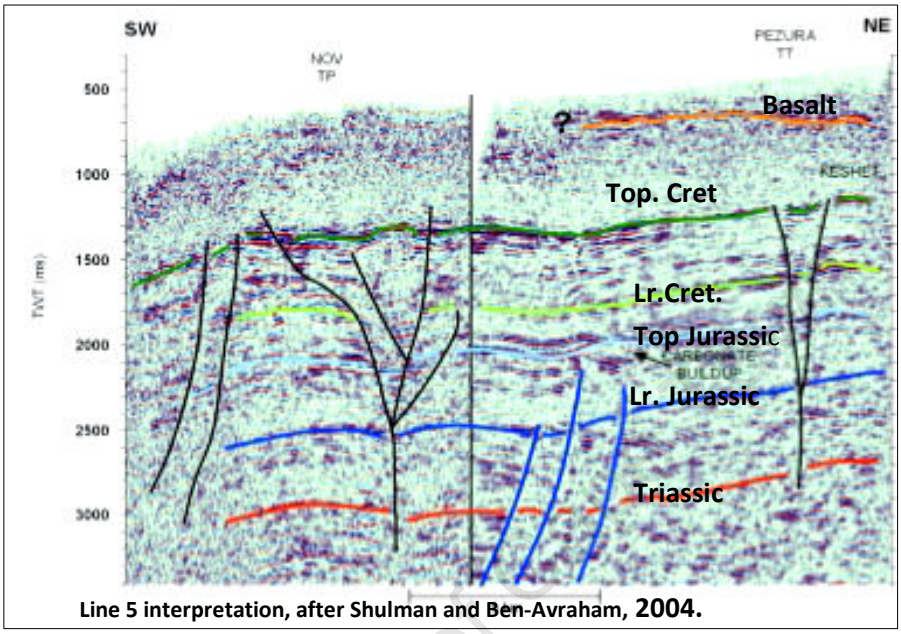
Figure 4-3:Correlation between the northern part of the JNH and the southern zone of Golan Heights. The upper map shows the main structural of Golan as interpreted by Shulman and Ben-Avraham, 2004

Figures 4-4 and 4-5 display the main structural elements as interpreted from seismic profiles N-46 and N-44E (for location see Figure 4-3) and line 5 after Shulman *et al*., 2004.



Line 5 interpretation, after Shulman and Ben-Avraham, 2004.

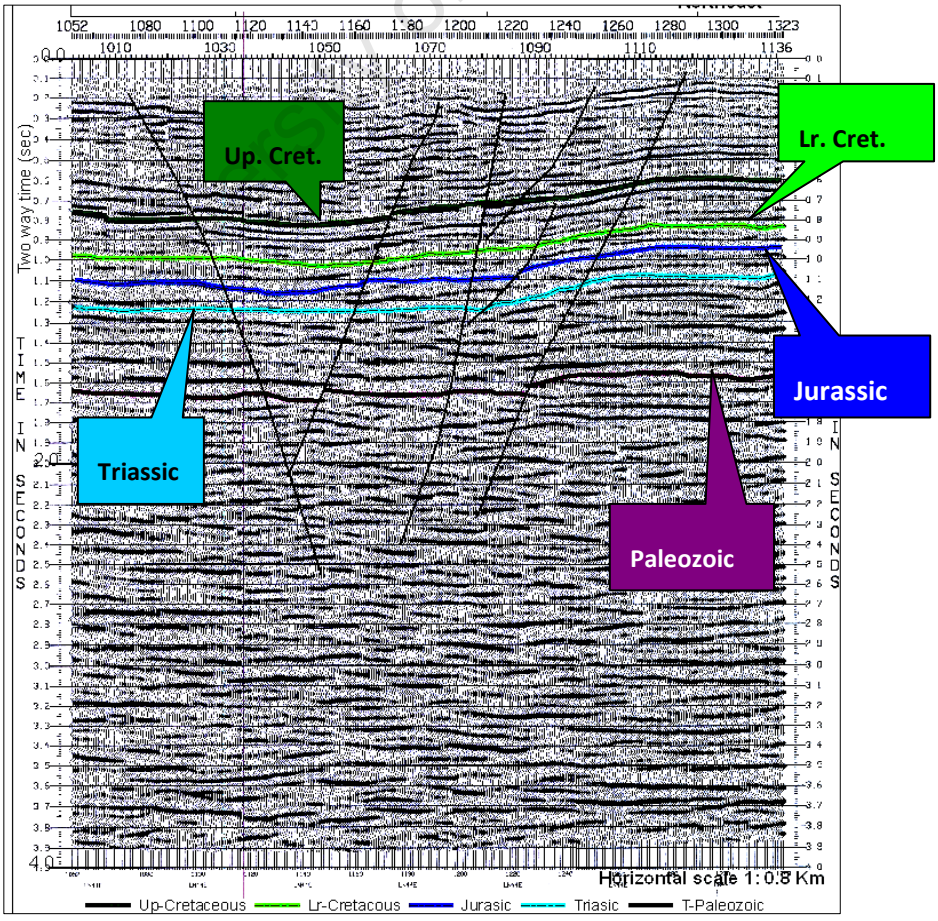
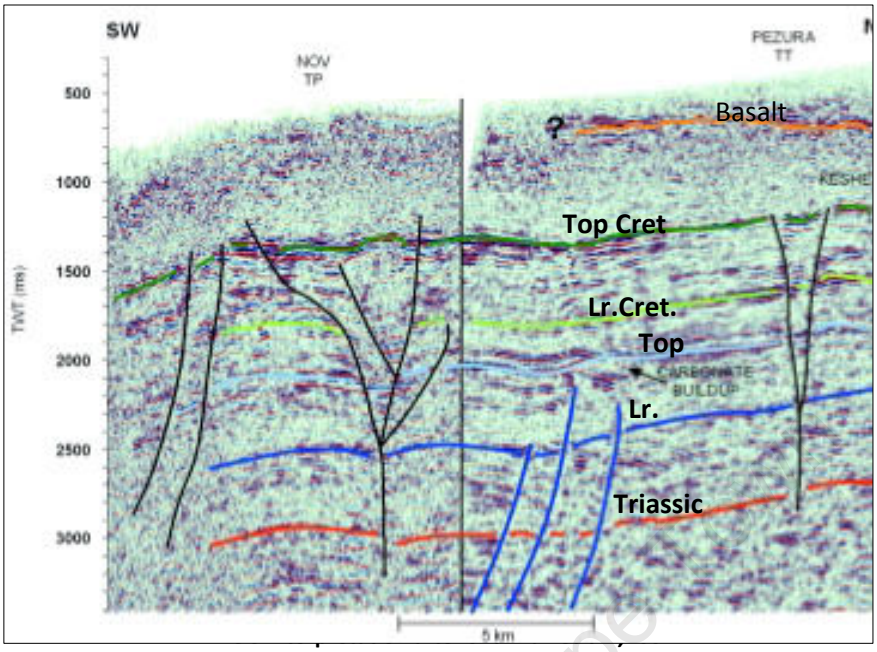


Figure 4-4: Correlation between profile N-44E (JNH) and profile 5 (Golan Heights)



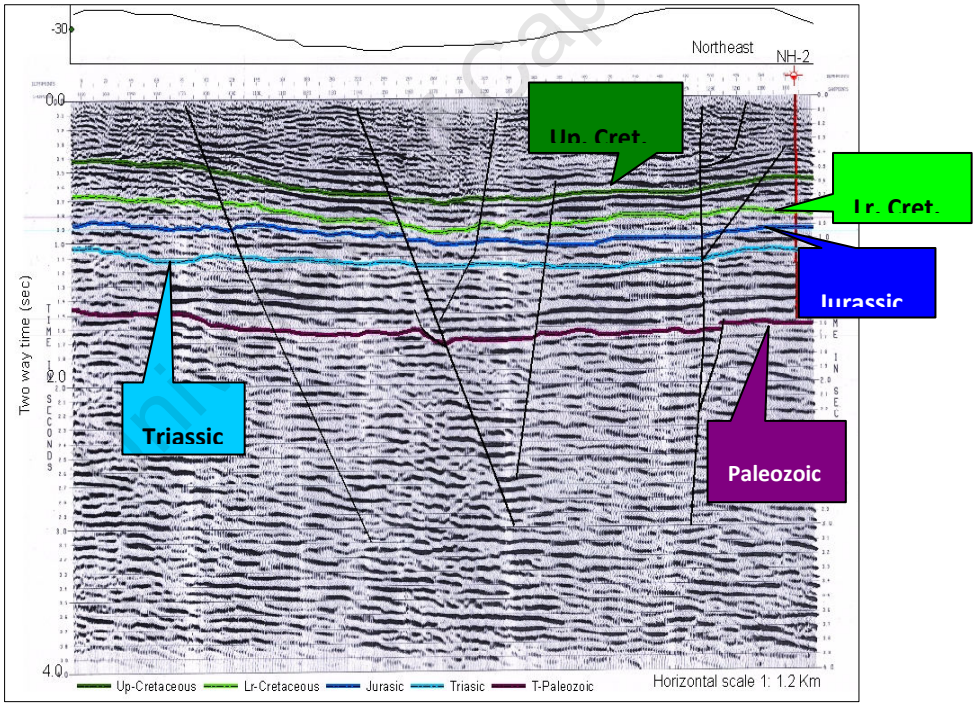


Figure 4-5: Correlation between profile N-46 (JNH) and profile 5 (Golan Heights)

" Time migrated seismic line 5 (Datum: +1200 m), composed of two en echelon seismic profiles Note the two compression mounds on the Top Judea Group level and the anticline folds on the LC3 to Triassic levels on both sides of the Nov fault zone. Jurassic faults are

marked in dark blue. Abbreviations are TP, Transpression; TT, Transtension" (Shulman and Ben-Avraham 2004)

The surface and subsurface geology interpretation of the JNH exhibits two major fault systems; NW-SE trend which is probably related to the Ramtha Sirhan Fault System. The other system is composed of two NNE-SSW trend. These faulting systems appear to be related in origin with the NFZ and PFZ main trends in the southern zone which were interpreted by Shulman and Ben-Avraham in 2004 (Figure 4-3).These fault zones are interpreted to be transtensional and have been formed in response to the strike slip motion along these faults (Shulman and Ben-Avraham, 2004).

The stratigraphic horizons comprise shallower depth than in the northern Golan Heights; however the structural style is similar. Episodes of tectonic stresses are significant.

4.1.1.3. STRUCTURAL STYLE OF THE JNH AND ITS TOPOGRAPHY

The interpretation revealed that:

(1) The dominant structural elements in the JNH area controlled its topography. This result is in accordance with previous studies (Wolfrat, 1967; Nuweihed, 1982; Mikbel, 1985; Occidental, 1991; Abu Hamideh, 2000; Nuweihed, 1982; Panikarov *et al.,* 1967); in northern Jordan, the topography and the relief across this region are subjected to tectonic events. Thus, simultaneous tectonic stresses of compression and tension led to the formation of the uplifts, synclines, grabens, and anticlines. Hilly areas are a result of uplift and tilting forces, which formed anticlines while the majority of the synclines composed basins or depressions; Panikarov *et al.,* 1967. Nuweihed, 1982 during a field survey in northern Jordan, concluded that the floor of the depressions is somewhat uplifted, the low land is replaced by an undulating plain with some slight stream cut, and thus the plateaus formed.

(2) The surface geology of the area is, to a great extent, reflects its topography. Most of the valleys correspond to structural faulting (e.g., Zarqa River) and the hilly areas comprise a series of anticlines and synclines (Ajlun Mountains). Seismic interpretation and borehole correlation implied the existence of a major dome structure in the west part of the area that extends toward Ajlun vicinity where the

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Cretaceous rock sequence overlies, unconformable, the older Triassic and the Paleozoic. Lower and Upper Cretaceous formations are exposed on the surface.

(3) Wolfrat in 1967 studied the surface and the subsurface structure and tectonics and hydrogeology of northern Jordan. He subdivided northern Jordan into four major morpho-structural zones (Figure 4-6). This subdivision agrees largely with the results of the interpretation of the surface and subsurface geology of the JNH area (Figure 4-6). In addition, Nuweihed in 1982 addressed several morpho-structural features of good interest, such as the Ajlun Dome, The Syncline of Ramtha and the Syncline of Bala'ama where the regional dip is to the ENE

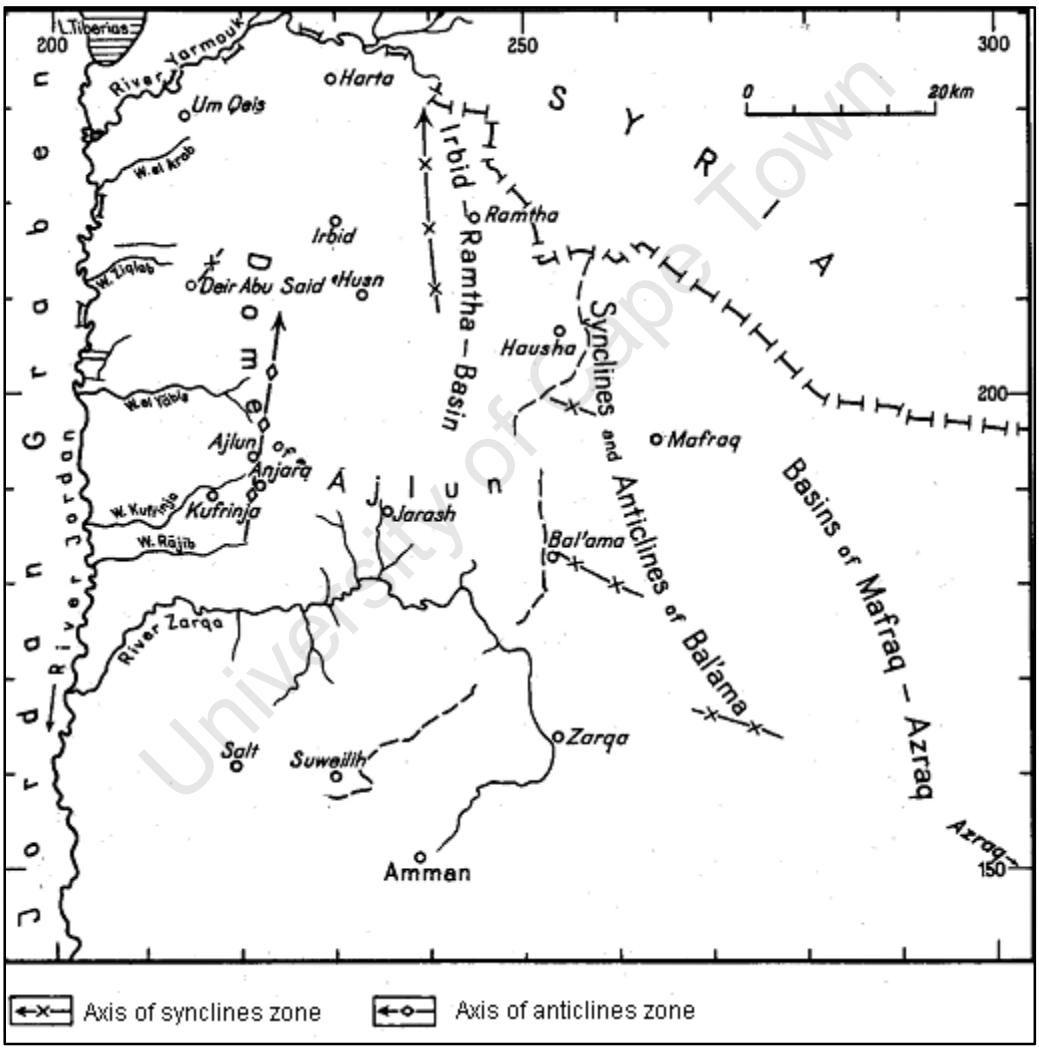

Figure 4-6: Major morpho-structural zones in Northern Jordan after Wolfrat, 1967

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THE MAJOR MORPH-TECTONIC ZONES IN THE JNH ACCORDING TO WOLFRAT AND OTHERS

(1) THE AJLUN ANTICLINE

The Ajlun Anticline (Ajlun Dome) is situated east of the Jordan Valley where it dips to the north toward the Yarmouk River. To the east it strikes E-W toward Mafraq-Azraq Zone of Basins where strata are slightly inclined. The center of the anticline is partially highly faulted. From the center of the anticline to the west, strata and slope orient toward the Jordan Valley. Many authors described it as an E-W; double plunging highly faulted anticline covering an area of 78 sq km (Amoco, 1987). Amoco in 1987 concluded that the strata are dipping to the north and south in a NS traverse. The Dead Sea Transform Fault bounds Ajlun Dome structure from the west. To the east, it is step faulted where the Ramtha-Sirhan Fault System delimits it. Zarqa Fault System terminates it from the south where the Triassic rocks are exposed and the Lower Cretaceous rock sequences overlie the Triassic formations with unconformity surface.

Nabulsi in 2000 indicated that Ajlun Dome might be considered a Paleostructure due to the absence of most of the Paleozoic section in the AJ-1 well. However, this structure lacks an adequate seismic coverage. BEICIP, (1976 and 1981) studied Ajlun Dome, and stated, “At the Cretaceous level it does not appear as an anticline fold and its actual shape resulted from several tectonic movements”. To the north, it plunges regionally northward, due to several E-W and NE-SW fault trends with down thrown to the north and NW to the north of Irbid town the regional plunge is confirmed by the occurrence and thickening of the Tertiary and Upper Cretaceous formations. The western dips particularly, developed from north south monocline flexures, which may have originated at the Eocene times. The western plunge has increased during the deepening of the Jordan Graben (BEICIP, 1976). To the south of Ajlun dome, the Cretaceous outcrops show some dip oriented to the south.

(2) THE IRBID-RAMTHA BASIN

Irbid-Ramtha Basin is part of the Yarmouk Basin. It is situated between the Ajlun Anticline and the Northern part of the Bala’ama Zone of Synclines and Anticlines (Fig. 4-6. The axis of this basin strikes N-S and dips northward. Some zones with faults and clefts are present and

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striking mainly NNW-SSE. Surface and subsurface interpretation confirmed this structure, as well as previous studies by oil companies (Nuweihed, 1982; GSI, 1985).

Abu Hamideh (2000) and Hassouneh (2003) in a geophysical survey along a profile between Irbid and Mafraq towns, showed an increase of the gravity values in the western side of Mafraq city in comparison to the eastern side. Thus, this exposes thick sedimentary cover of low density materials, truncated from the east by a major fault element. This is in accordance with the gravity profile 70 (Figure 2-10) which emphasis the existence of a major folding element in this area, traversed by NW-SE and NNE-SSW near vertical normal faults. The NW-SE trend is part of the Ramtha Sirhan Fault System. Bajjali, *et al* in 1997studied Irbid area and the surrounding area where he confirmed that this area is part of a major syncline structure that extends within the area between Zarqa River and north of Yarmouk River in the Golan Heights vicinity. To the west this syncline structure is truncated by the down faulted eastern margin of the Jordan Valley. Mikbel and Zacher, (1986) refer to this structure as Irbid Syncline.

(3) THE BALA'AMA ZONE OF SYNCLINES AND ANTICLINES

This zone is situated between the Irbid-Ramtha Basin in the west and Mafraq-Azraq Zone of Basins in the east. It is considered as an area of folds of relatively large amplitude striking WNW to NW. This structure appears as part of the Sirhan Depression (Wolfrat, 1967). Gravity profiles 02 and 70 (Figure 2-10) presents this fold zone and the effect of Ramtha Sirhan Fault System, where a tilted broad element is noticeable. This indicates the episodes of tension and compression stresses over this area.

(4) THE MAFRAQ-AZRAQ ZONE OF BASINS

This zone of basins extends from SE to NW, near the southwestern border of the Basalt Plateau of Eastern Jordan between the Ramtha Sirhan and Fuluq Fault Systems, which are believed to be caused by tension forces. This zone consists of a chain of shallow basins probably situated in the northwestern prolongation of the Sirhan Depression (Quenelle, 1959; Burdon, 1959; Wolfrat, 1967).

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4.1.1.4. JNH STRUCTURAL FRAMEWORK AND GEOMORPHOLOGY

(1) The interpretation of surface and subsurface geological information alongside the interpretation of the major morphologic units indicated the existence of a maze of regional faults striking NW-SE, NE-SW, N-S, and NNE-SSW caused by simultaneous compression and tension stresses. These fault systems run deeply into the platform basement making the slope step like, but nearly die out in the shallow sedimentary strata. The regional faults are followed by numerous minor faults breaking the large folds into blocks and forming horsts, grabens, and uplifts along the major fault systems with remarkable thickness variations.

(2) Complexity of the structural setting of the JNH area is obvious. Several authors (Mitchell, 1959; Panikarov *et al*., 1967; BEICIP, 1976; Marathon, 1988; Abu Jaber *et al.,* 1989; Occidental, 1991; Occidental, 1991; Atallah, 1992; Kazmin, 2002) emphasized this complexity. The dominant NNE-SSW anticlines and synclines in the area are similar in appearance and rotation to the Syrian Arc folds present on the west bank of the Dead Sea Transform Fault and Negev desert regions (Mcllough *et al*., 1988).

(3) The General structure of the JNH area is characterized by major folding zones associated with fault systems of reverse, normal, and a strike-slip nature caused by several phases of compression and tensional stresses (Fruend, 1965). This agrees with Bender (1975) who considered north and central Jordan as the "Province of Up warping, Tilting and Block Faulting". Rock type and thickness of the sedimentary cover controlled the structures. Some investigators characterized the JNH area as a site of an arch plunging to the north toward Damascus Basin that is dissected by horst blocks, anticline structures and elongated structurally controlled sub-basins resulting from strike-slip movements along some of these faults. Damascus Basin is a small Tertiary basin located in southwestern Syria north of the study area. Measuring approximately 1700 sq km, its boundary is controlled on three sides by faulting. It is separated from the Northern Highlands by normal downthrown to the north, east west faults (Mikbel, 1985; Nabulsi, 2000 and 2002)

(4) Figure 4-7 illustrates the General structural framework of the JNH area and the main structural elements as modified from the interpretation of the surface and

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subsurface geological information which largely agrees with Wolfrat subdivision and Nuweihed survey in 1982 and GSI IN 1985.

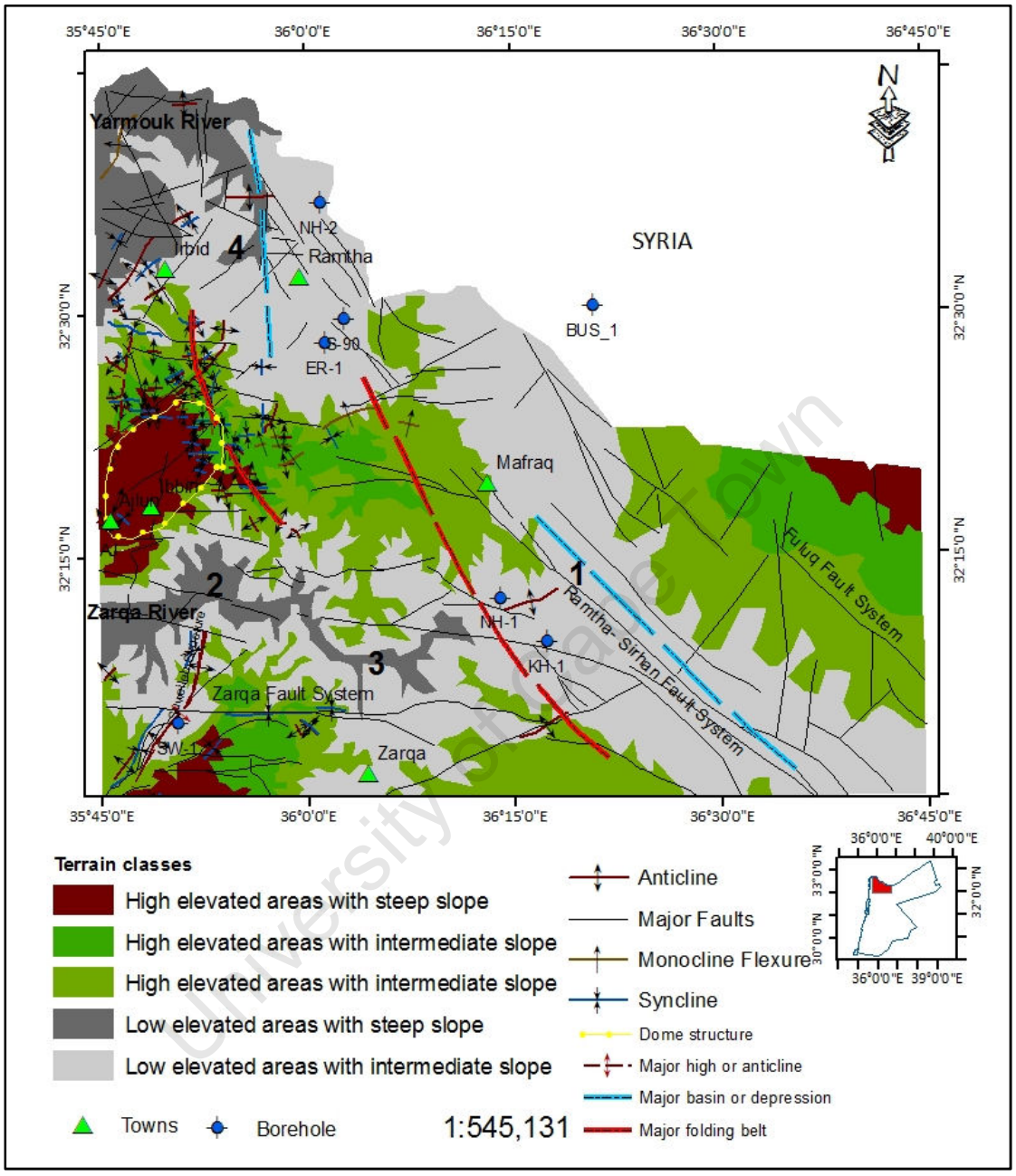

Figure 4-7: Main structural elements of the JNH area as modified from the surface and sub-surface geological data

(6) Four major folding zones of the previously mentioned major trends were identified. Major faulting systems; Ramtha-Sirhan, Zarqa, and Fuluq fault systems break these folding zones into minor blocks of horsts, grabens, and uplifts. The General dip is

toward ENE and WNE. The interpretation exhibits a major structural high toward the west where the Ajlun Dome is located. The top of this structure is to the SW of ER-1A and extends to the northeast of Ramtha town. Another two major syncline planes are observed to be plunging northward. They extend along the western margins of Ramtha town toward the northeast. A major fault plane is observed at this axis to the east of Ramtha (Nuweihed, 1982, 1982) forming Irbid Ramtha Basin according to Wolfrat, 1967.

(7) The majority of the delineated faults in this area are of the normal type with the possibility of strike slip or dip slip, horizontal movement. The area to the south of Mafraq also presents a regional dip toward the ENE and a central high with a gentler dip toward the west and southwest side. The structural depth and thickness maps of the stratigraphic horizons from the top of Paleozoic to the Tertiary exhibit these elements.

(8) The shallow part of the seismic sections exhibits relatively less faulting and the faults are smaller in magnitude than in the northern part (Nuweihed, 1982). To the west, the interpretation emphasized a highly folded domal structure within the vicinity of Ajlun. It is characterized by monocline flexures, synclines, and anticlines (Wolfrat 1967; Nuweihed, 1982)

(9) Ramtha-Sirhan Fault System appears as the dominant structural element in the JNH area. Surface and subsurface interpretation confirm its presence alongside the Fuluq Fault System. As discussed in previous sections, these Fault Systems are of tectonic origin in which simultaneous compression and tension stresses took place.. Quenelle (1959), Burdon (1959) and Bender (1974 and 1975) considered Ramtha-Sirhan Fault System as an extensional structural element.

(10) Nabulsi in 2000 conducted a study of the JNH area in an attempt to investigate the hydrocarbon potential. He found that Ramtha Sirhan Fault System is an elongated NW-SE trending element stretching from Saudi Arabia to northern Jordan (>325 km). Quenelle in 1959 and Bender in 1975 described it as a major faulting feature apparently caused by deep tensional forces. It appears on the seismic sections and the surface geological maps as a strong multiple leaner feature forming many horsts and grabens. Fuluq Fault System is another elongated NW-SE fault system that extends along the east, southeast and northwest borders.

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(11) In Jordan, where tectonic structures are mostly considered under the aspect of horst and graben tectonics, also fold structures are present (Mikbel, 1985). A narrow long extended zone, consisting of several tight fold structures, was observed along Wadi Shueib. Wadi Shueib structure is near the northeastern end of the Dead Sea. It is supposed to be because of ESE-WNW acting compression forces. The compression occurred because of the northward-directed motion and the rotation of the Arabian plate. Since it is cut by the rift faults, it must be between the Maastrichtian and Oligocene Miocene.

(12) Suwelih Compression Anticline is one of the three culminations of Wadi Shueib structure. Its NW flank is very steep and the upper cretaceous layers are nearly vertical, even locally overturned. The SE flank dips gently 5-10 degrees to the east **(**Mikbel and Zacher, 1981**).** Amman Hallabat Structure is another compressional feature which is probably part of the Late Cretaceous Syrian Arc complex that developed during the collision of the Afro-Arabian and Eurasian massifs**.** Wadi Shueib and Amman Hallabat structures are formed by stress acting on the plate boundary from SE to NW direction (Mikbel, 1985). The age of these structures is between Lower Oligocene and Miocene (Mikbel and Zacher, 1986)

4.1.2. GENERAL CHRONOSTRATIGRAPHY OF THE JNH AND ITS TECTONIC HISTORY

4.1.2.1. EFFECTS OF TECTONIC EVENTS SUBJECTED THE JNH SINCE THE PALEOZOIC TIMES ON THE STRATIGRAPHIC HORIZONS; THICKNESS, DIP, AND DEPTH TRENDS

The interpretation clarified remarkable thickness variation and dip changes, in the JNH, between NW-SE to NE-SW which indicate effect of more than one tectonic activity; this was emphasized by GSI in 1985.

A stratigraphic correlation between the key boreholes in the JNH, illustrate the distribution of the main stratigraphic horizons (Figure 4-8) and evidenced those tectonic activities since the Cambrian times. A regional stratigraphic correlation was made with the Cenozoic, Upper Cretaceous, Lower Cretaceous, and the Triassic sequences in Syria in order to study their thickness distribution trends. Brew, 2001 conducted an integration structural study for

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Syria. Thickness maps listed in figures are after Brew (2001) study. Thickness distribution trends for the same stratigraphic horizons identified in the JNH revealed agreement to a great extent. It shows remarkable thickness increase in a SW-NE and North, unlike to the northwest and southwest.

PALEOZOIC SEQUENCES

Paleozoic sequences are dipping gently eastward, and unlike westward, where it is truncated. This evidenced a regional unconformity in this direction where tilting and erosion events took place. The analysis of BEICIP, 1976, 1981; Nuweihed, 1982; and Abu Jaber *et al*., 1989 revealed a major regional unconformity between Paleozoic and Mesozoic. Structural depth (contour) maps and depth profiles of the Paleozoic and Mesozoic horizons show a regional tilting that had occurred before the Mesozoic times and possibly before Carboniferous times toward the east.

BEICIP in 1976 studied SW-1 well and Zarqa River vicinities and found that only the Cambrian was preserved from erosion below the Mesozoic unconformity. Depth contour maps showed a significant thickening of the Paleozoic sequences toward the south and southeast with distinctive high magnitude structure around Mafraq town and along the Ramtha Sirhan Fault System. This indicated that the Sirhan Basin is a transtensional feature and the bounding faults have strike–slip components. The considerable thickening in this direction indicates episodes of sedimentation since the Early Triassic.

MESOZOIC SEQUENCES

Across the Ajlun area, Lower Cretaceous Rocks overlie unconformably the Triassic formation. Thus, a major tectonic movement occurred in the late Triassic and significant erosion took place in Jurassic as evident by the absence of lower Jurassic and the unconformity surface.

The Jurassic thickness map, presents a considerable decrease in thickness toward the southeast and east, which suggests a regional tilting of the platform toward the northwest. Panikarov *et al*., in 1967 addressed that in the area of Jordan, platform sedimentation occurred during the Early Jurassic, but uplift and erosion characterized the Late Jurassic. This uplift and erosion apparently affected also southern Syria (Panikarov *et al., 1967*). In this

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area the upper Jurassic is missing, just like in the west side of Azraq Depression (southeast of the JNH) (Nuweihed, 1982).

BEICIP in 1976 and 1981 emphasized that during the early Jurassic and lower Cretaceous, the region was affected by two regionally significant uplift and erosion periods which are mentioned by Bender (1974, 1975) and Burdon, (1959). The lower Cretaceous unconformity is a more significant event as it truncates the Jurassic to Triassic sequences over Ajlun Dome in the west and toward the south east. This is supported by Panikarov *et al*. (1967) and Nuweihed (1982). This tectonic phase is known in Syria and Lebanon (Panikarov *et al.,* 1967). During the early Cretaceous, rifting apparently began in the northwest edge of the Sirhan Depression. During the Cenomanian and Turonian, rifting along Sirhan and Palmyra Basins extended eastward.

Cretaceous sequences, in General, show noticeable thickness variations and tilting features, thus this may indicate tectonic movements during deposition. The Lower Cretaceous sandstone is a marker of a major tectonic event, probably of an epeirogenic type. This boundary was also witnessed on a wider region that covers Palestine, Syria, and Lebanon where the basal Cretaceous sandstone is generally of a similar origin (BEICIP, 1976; Nuweihed, 1982). The stable middle Cretaceous platform was disrupted by a late Cretaceous faulting episode, which created local fault-controlled basins. In Jordan the Azraq Graben is the best documented basin of this episode. In the Cenomanian, as well as the Post-Cenomanian periods, transgression and regression movements are localized to a great extent and this is evident by the drastic variation in formation thicknesses (BEICIP, 1976; Nuweihed, 1982). The Late Cretaceous tectonic events are evidenced by secondary surface faulting, and volcanism as reflected by the widespread surface geology. Surface geology complexes in this area were probably Synsedimentary in origin and Warping and tilting were generated on the sides of the normal (tensional) faults (Nuweihed, 1982).

CENOZOIC SEQUENCES

A tectonic phase took place after the Eocene deposition (Upper Eocene to Oligocene times). The area was affected by the compressional tectonic phase of the late Miocene to Pliocene. This phase has been recorded in Syria and Turkey. It led to the formation of anticlinal folds

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(Palmyra range). In Jordan the effect of this tectonic phase probably occurred as well, but is difficult to assess due to lack of data in the Pliocene and Quaternary deposits. (BEICIP, 1976)

The age of the basalt flows can be correlated with the basalt of the northern extension of the Umm-Qais plateau north the Yarmouk River (Zamlat Bkhila plateau basalt) in the Golan Heights which was found to be 3.7±0.36-3-11±0.16 Ma. Flow eruptions are contemporaneous with the second spreading stage of the Red Sea during the Cenozoic over the past 5 Ma (Tarawneh, 1996)

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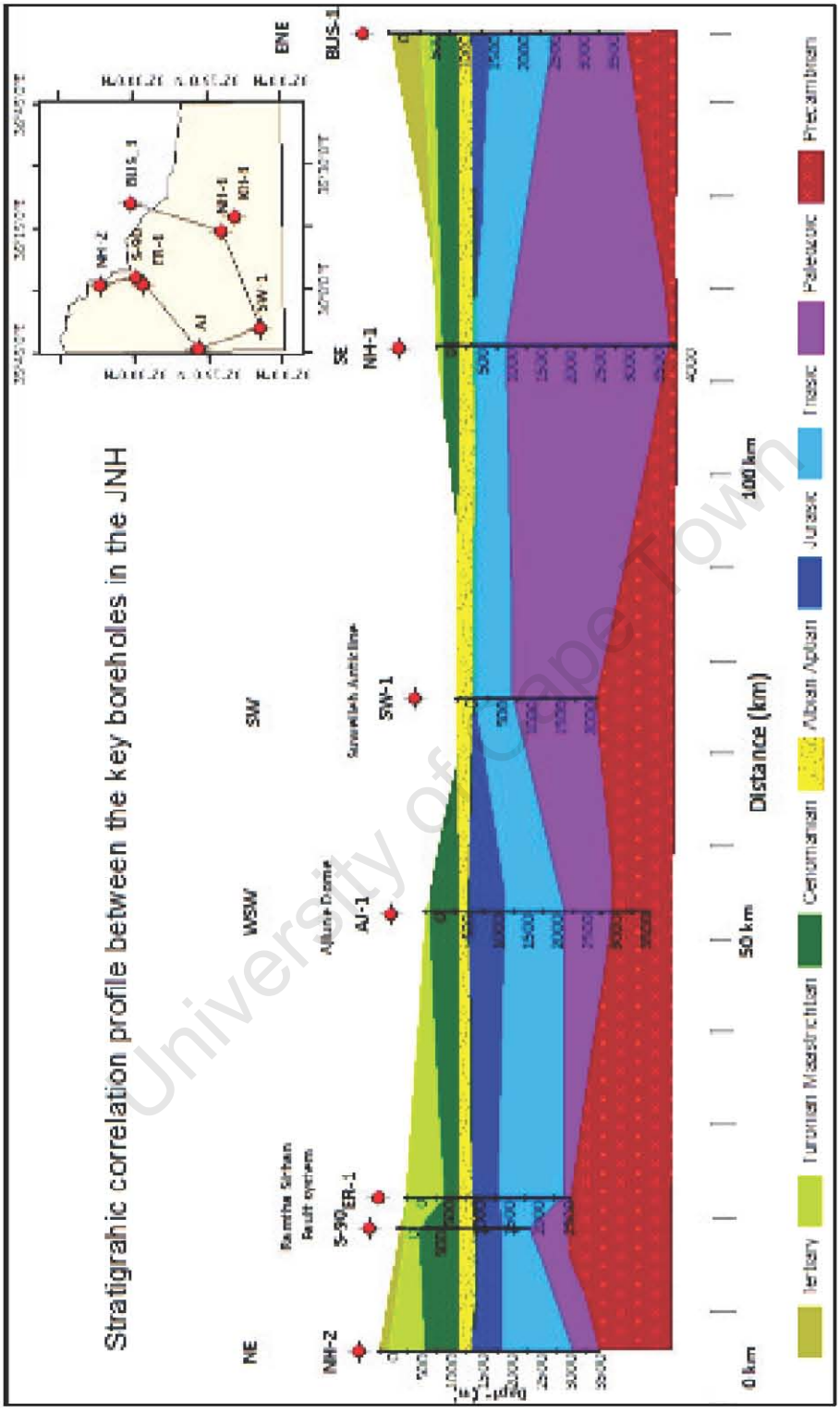
Figure 4-8: A summary stratigraphic correlation profile since the Paleozoic times between the key boreholes across the JNH area



A summary stratigraphic correlation profile since the Paleozoic times between the key boreholes across the JNH area

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4.1.2.2. GENERAL CHRONOSTRTIGRAPHY OF THE JNH

sedimentary sequence of Jordan can be divided into clastic dominated Paleozoic succession and a carbonate dominated Mesozoic and Cenozoic sequence . Figure4-9 after Occidental illustrate a regional chronostratigraphic correlation between JNH, Syria (Palmyra), and Negev; illustrate the stratigraphic distribution of the major formations. The litho-stratigraphic subdivisions and nomenclature are related as follows: Tertiary and Cretaceous Formations are according to the Natural Resources Authority Petroleum nomenclature, while Jurassic and Triassic are according to Bandel and Khoury (1989). This figure shows the main tectonic events that subjected the region since the Cambrian times. It illustrates a regional late Paleozoic unconformity separated the Paleozoic and Mesozoic sequences, resulting in significant truncation. The Paleozoic section is divided into an Infra-Cambrian to Lower Ordovician, dominantly subaerial clastic sequence, and a Middle Ordovician to Silurian clastic marine sequence. Within the overlying carbonates, regional facies and transgressive and regressive trends indicate that open ocean conditions were to the northwest. Major unconformities are characterized by clastic derived from Paleozoic clastics and possibly Precambrian units to the south.

A chronostratigraphic correlation section between JNH in the northwest to the Wadi Sirhan area in the southeast, and passing the Azraq Graben is clearly illustrated the geologic major events and lithofacies that dominated the JNH in particular and eastern plateau of Jordan in general (Figure 4-10) since the Infra-Cambrian-Paleozoic times.

Jawzi *et al*., in 1994 studied the geological setting of the Arabian Peninsula for the purpose of studying the Hydrocarbon potential, they conducted detailed geological studied that introduced various regional geologic cross sections. One of these cross sections manifested stratigraphic and structural setting along NW-SE trend passing the JNH, Azraq BSIN, and Sirhan Basin (Figure 4-11). The Jawzi et al., 1994 results are of a great extent in agreement with Occidental 1981 conclusions.

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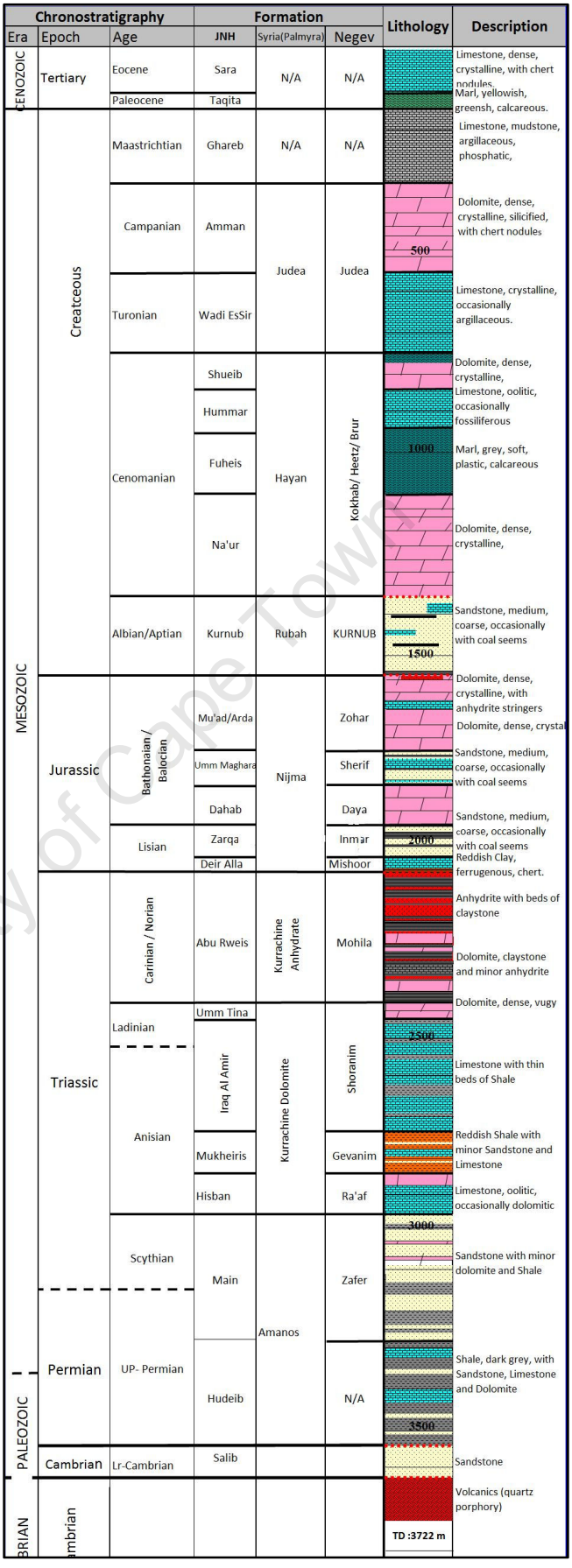
4-9 Generalized vertical litho-stratigraphic section, after Occidental 1991. Showing regional chronostratigraphic correlation- JNH, Syria, and Negev region



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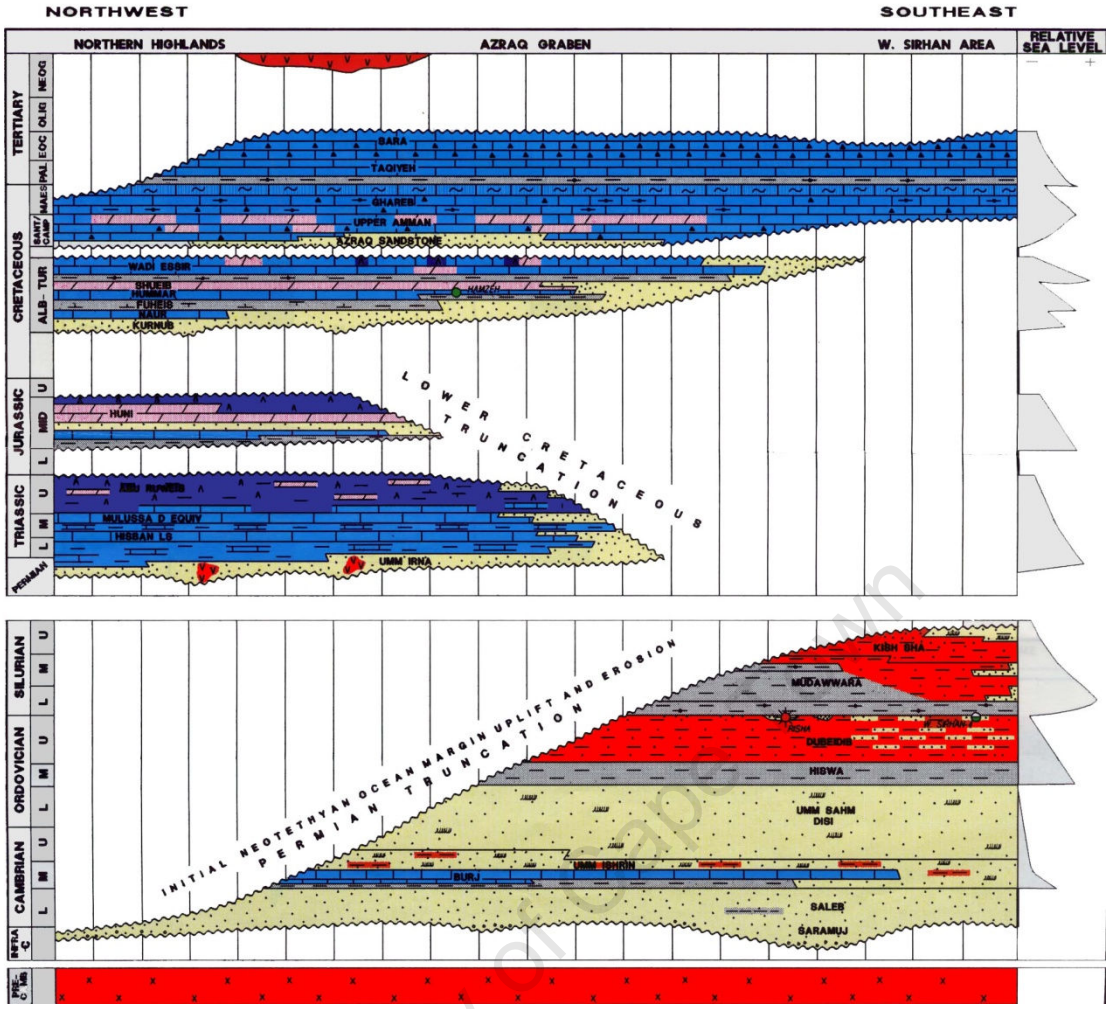

Figure 4-10 Chronostratigraphic correlation NW-SE section , After Occidental 1991

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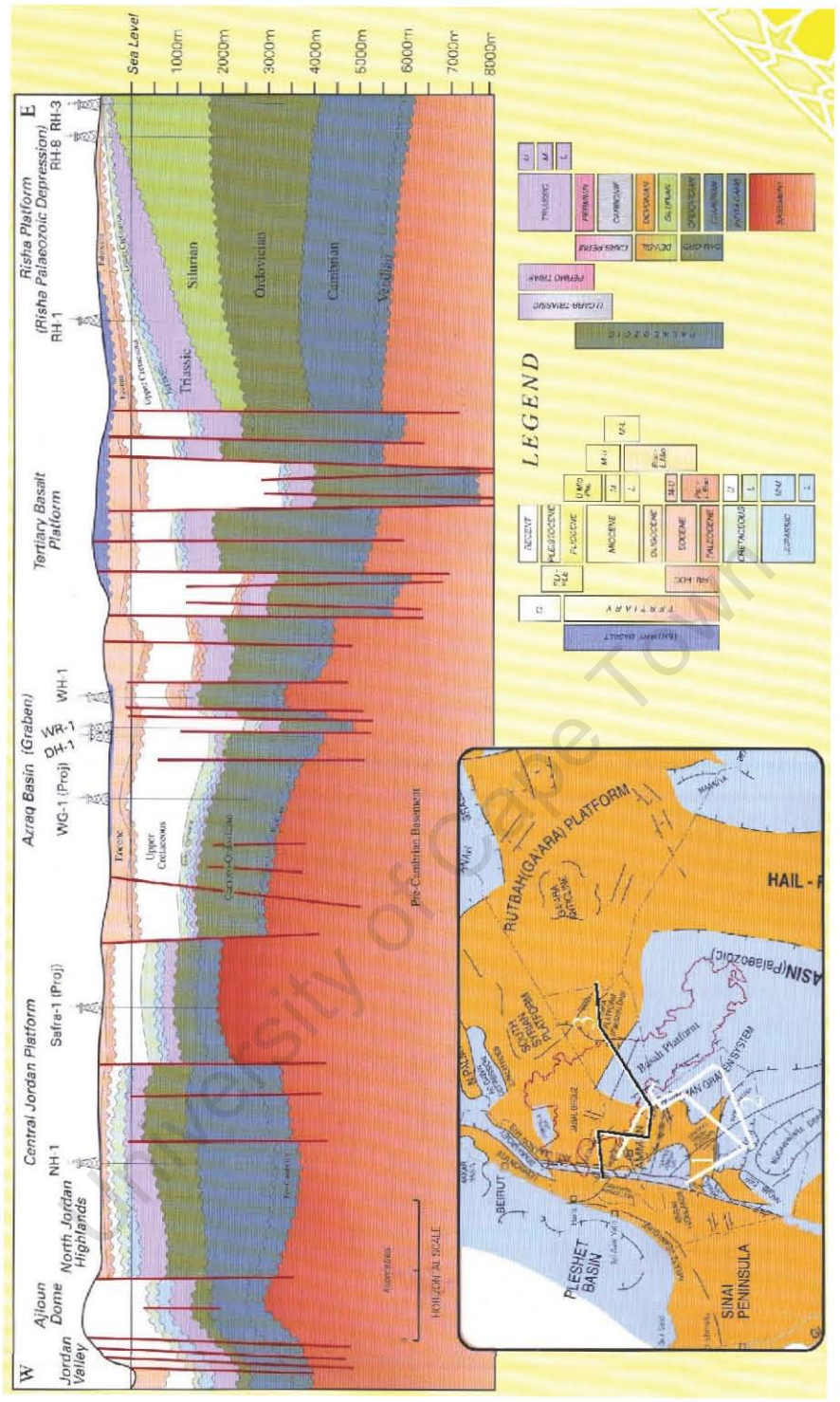

Figure 4-11 Regional Geological cross section over the JNH, Ajlun Dome towards the northeast of Jordan, after Jawzi *et al*., 1994

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4.1.2.3. THICKNESS CORRELATION BETWEEN SYRIA AND THE JNH

Brew in 2001 conducted a study in order to define the tectonic evolution of Syria using geophysical and geological analysis techniques. The study clarified thickness distribution for four stratigraphic horizons; Cenozoic, Upper Cretaceous, Lower Cretaceous, and Triassic sequences. A correlation between Brew (2001) thickness maps and thickness maps for the same horizons in the JNH revealed from the interpretation of the key boreholes and seismic profiles, resulted agreement to a great extent and clarified the regional distribution trends of those horizons. Thus, episodes of stresses affected the region and formulated its tectonic history were emphasized.

Figure 4-12 illustrated Brew's (2001) thickness maps of the above mentioned stratigraphic horizons in Syria. JNH lies to the southwest corner of Syria, south of Golan Heights.

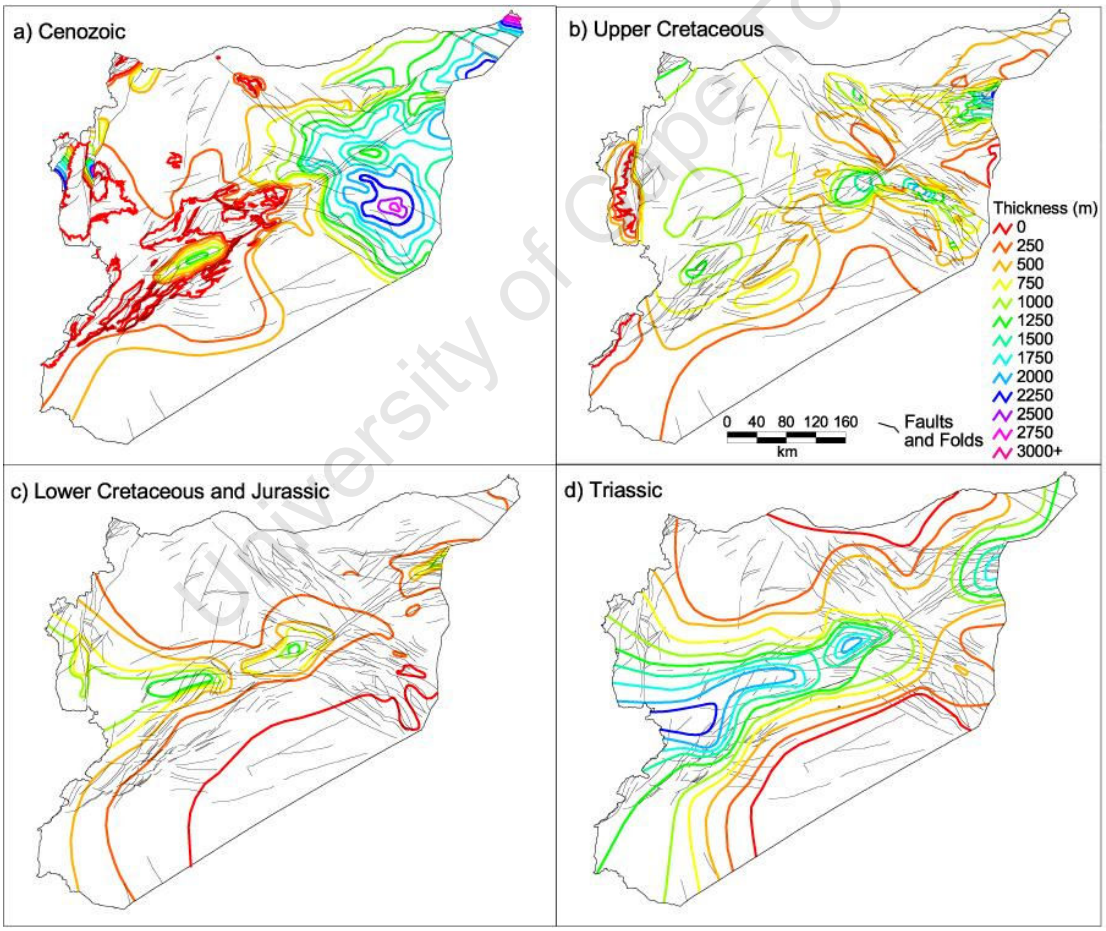

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Figure 4-12 Thickness maps of Syria, after Brew, 2001

CENOZOIC SEQUENCES

Figure 4-13 manifested a regional thickening trend towards the east and southeast; to about 500m in southern parts of Syria and northeastern parts of the JNH.

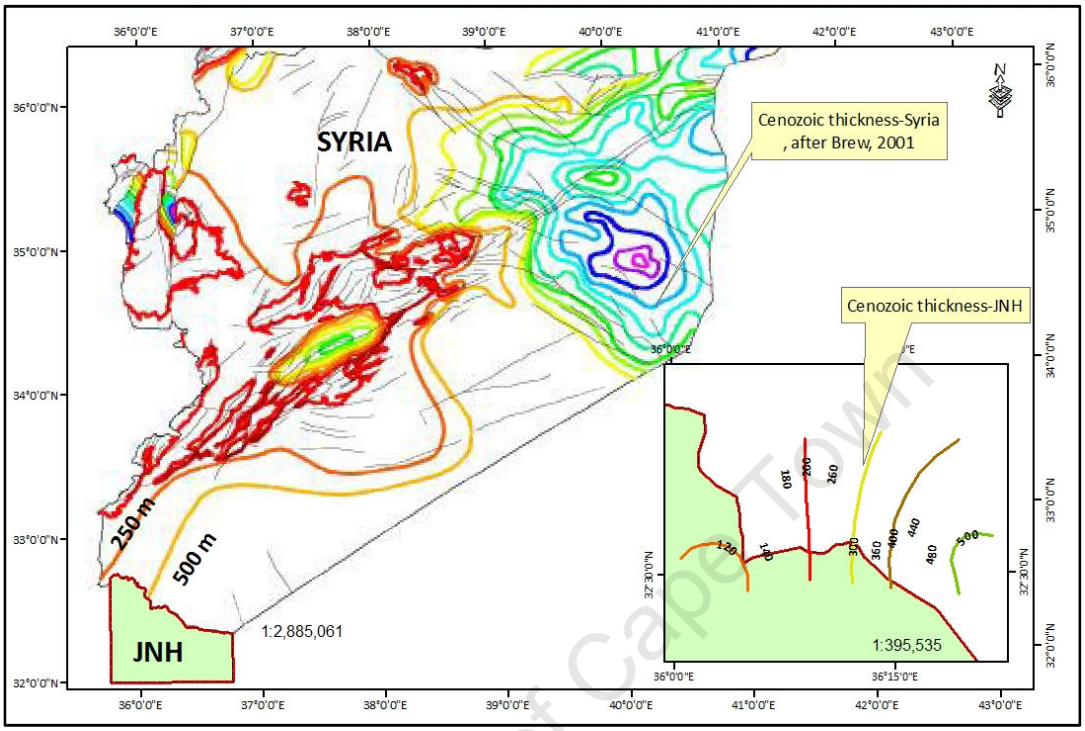

Figure 4-13 Thickness maps of the Cenozoic sequences in Syria and the JNH

MESOZOIC SEQUENCES;

UPPER CRETACEOUS, LOWER CRETACEOUS, AND TRIASSIC SEQUENCES;

Upper Cretaceous sequences show regional thickening trending SW-NE (Figure4-14).

Lower Cretaceous sequences shows regional thickening SW-NE trend, while truncates towards the east (Figure4-15)

Triassic sequences show regional thickening trends to the NW and north of the JNH, while within the vicinity of S-90 well it decreases. Further to the east of NH-2, thickness increases to about 1000 m (Figure 4-16)

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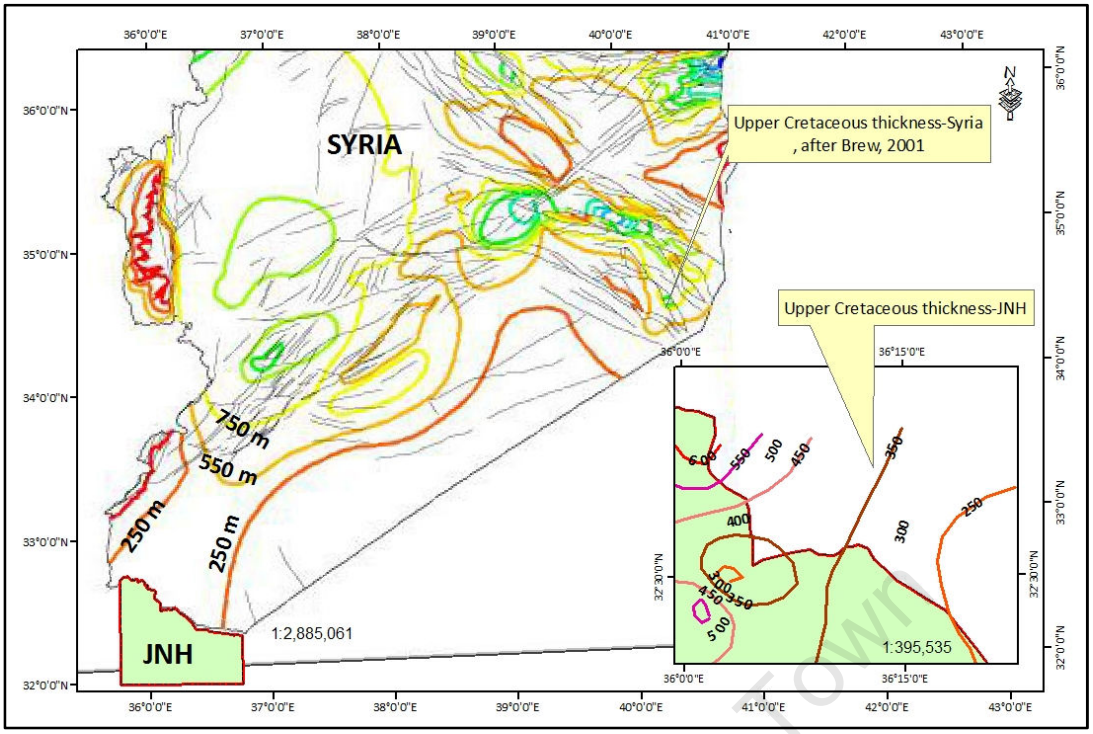

Figure 4-14 Thickness maps of the Upper Cretaceous sequences in Syria and the JNH

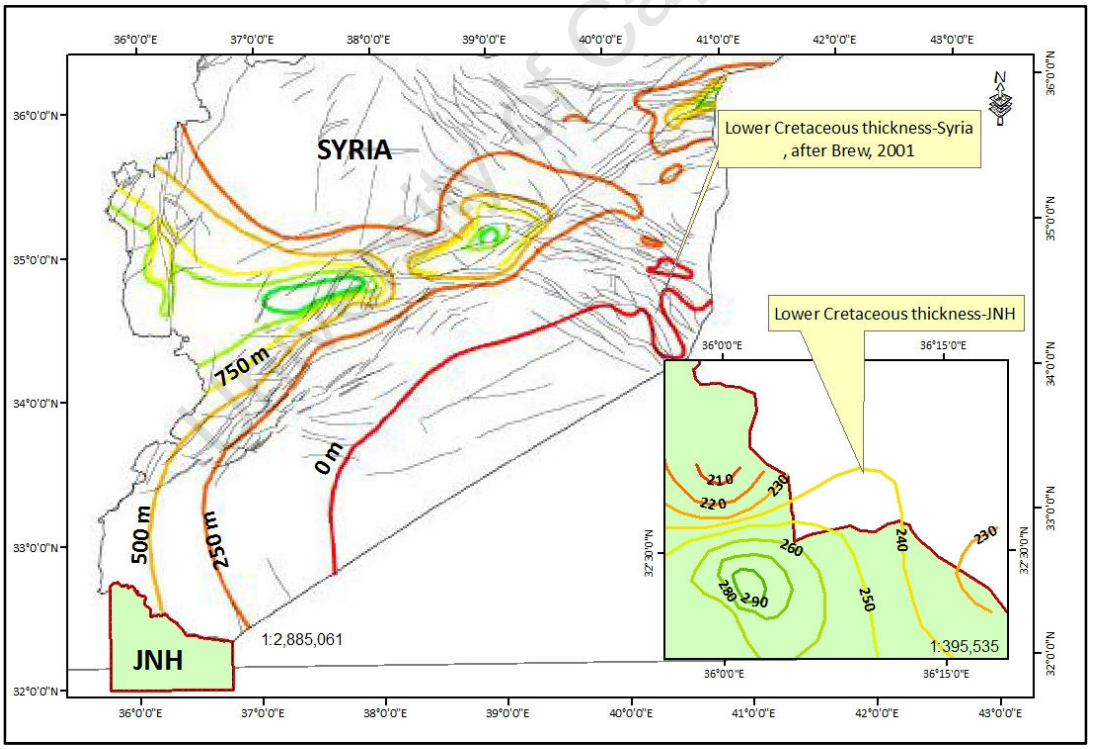

Figure 4-15 Thickness maps of the Lower Cretaceous sequences in Syria and the JNH

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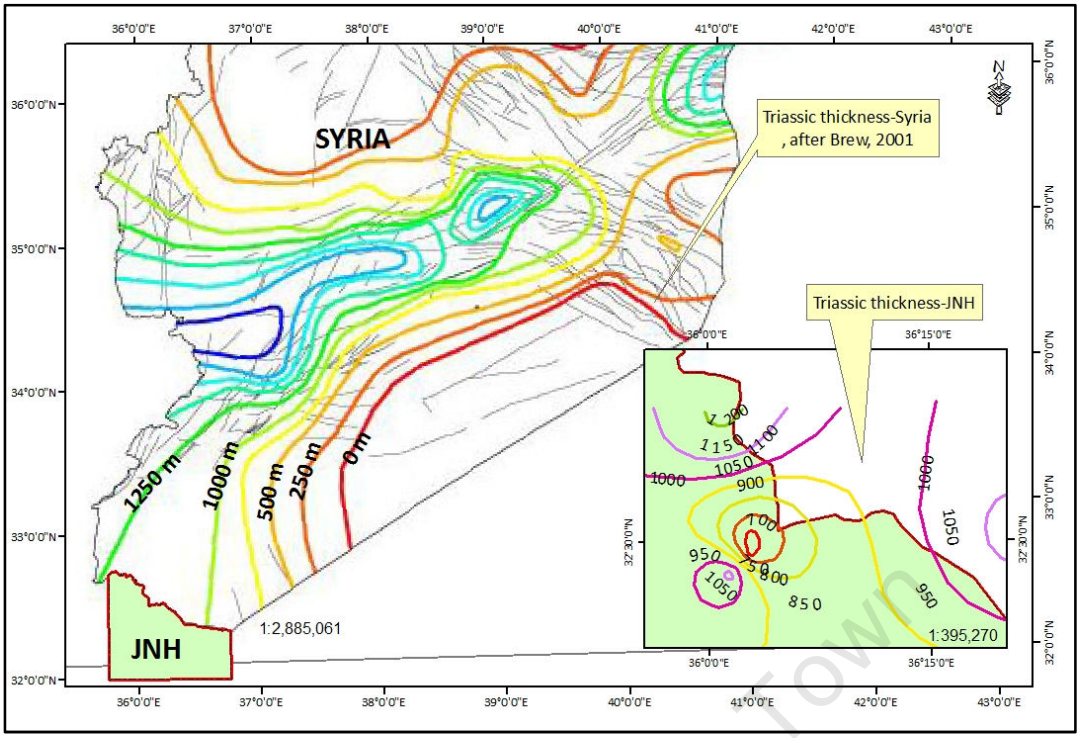

Figure 4-16 Thickness maps of the Triassic sequences in Syria and the JNH

4.2. DEAD SEA TRANSFORM FAULT AS A MAJOR TECTONIC EVENT THAT AFFECTED THE JNH AREA

Dead Sea Transform Fault System (DST) is considered as the main factor controlling the recent geology of the study area. It comprises a prominent tectonic element in the Eastern Mediterranean regions (Gomez *et al.,* 2006). The Dead Sea fault (DST) is a globally prominent, continental active left lateral transform fault (Gomez *et al*., 2006) separating African (Levantine sub-plate) from Arabian, and accommodating the different motions between them (Brew, 2001). DST extends for about 1000-1200 km from the Gulf of Aqaba (Elat) in the south to the Turus – Zagros Orogenic System in the north, (Garfunkel, 1981; Reches and Hoexter, 1981 Abu Jaber *et al.,* 1989; Occidental, 1991; Al Zoubi *et al.,* 2009). It also connects the extensional tectonic segment of the Red Sea to the compression front of Bitlis Suture Zone. The extension in the Red Sea affected the surrounding areas along the fault and gave rise to the development of N-S trending grabens in which the DST runs (also called Dead Sea Rift) (Garfunkel *et al.* 1981*,* Garfunkel 1981) (Figure 4-17)

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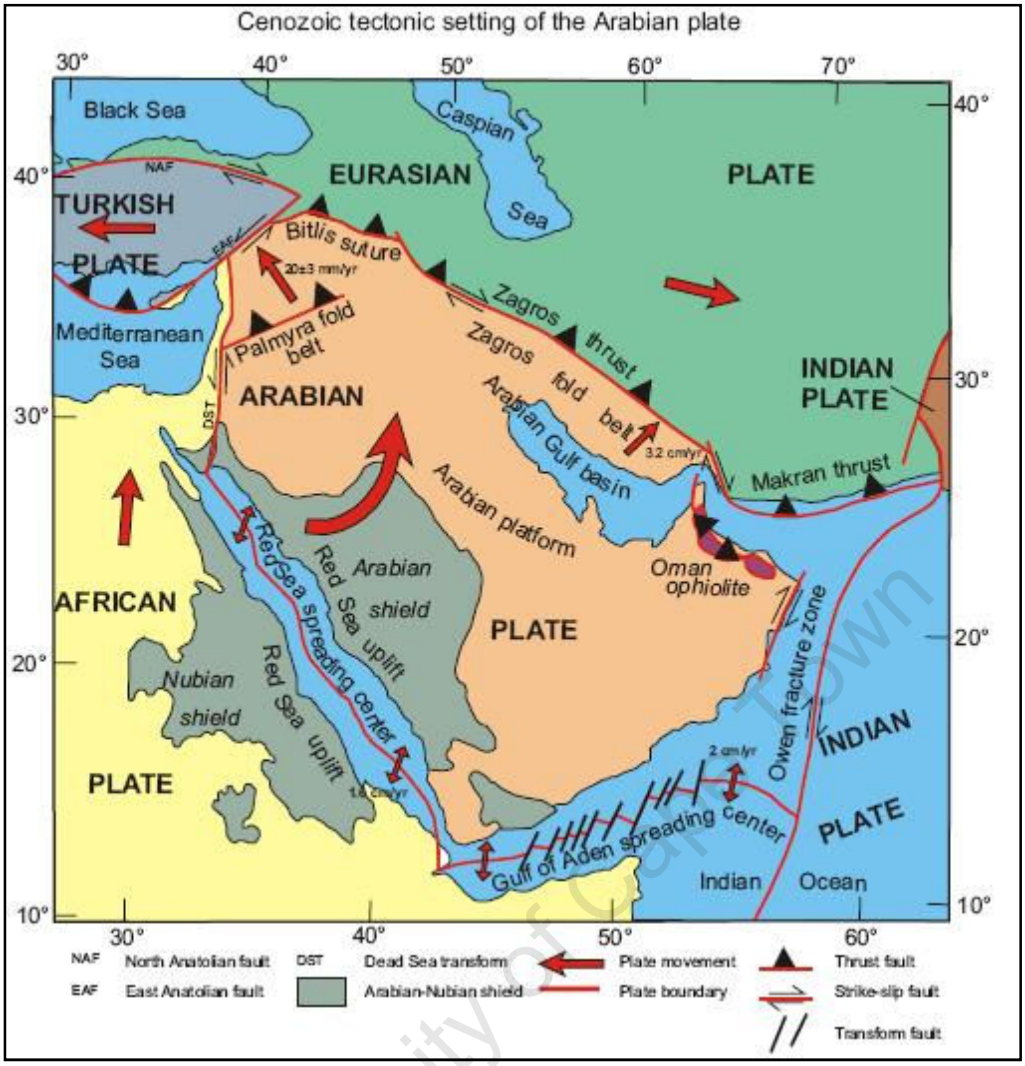

Figure 4-17: Regional tectonic setting of the Dead Sea Transform, after the Saudi Arabia Geological Survey

Several investigators suggested two phases of strike-slip motion on the DST; a Pre-Miocene-Early Miocene of 60-65 km, and Post-Miocene slip of 40-45 km (Quennelle, 1984; Freund *et al*., 1970; Garfunkel, 1981**;** Hatcher *et al*., 1981; Quenelle, 1958; Girdler, 1985). This leads to the conclusion that Jordan is situated at the transition zone between the stable part of the Arabian Plate and the unstable area of the Dead Sea Transform Fault (Al Zoubi *et al*., 2009). Lovelock (1984) suggested that the crust in the northwestern part of the Arabian Plate (beneath Jordan) has been fragmented into stable blocks separated by mobile zones.

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In the following, there is a brief discussion about the General features of the Dead Sea Transform Fault System (DST) and its implications on the surrounding regions, including the study area.

Many investigators and researchers have studied the DST; the following are some of the researchers to whom the following description is referred. Quenelle, 1959; Freund, 1970; Bender, 1974; Steinitz *et al*, 1978; Barbari *et al* 1980; Garfunkel, 1981; Kovach and Ben-Avraham, *et al*., 1990; Barjous and Mikbel, 1990; Girdler, 1990)

4.2.2. PLATE MOTION

Before the Cenozoic continental breakup, the Middle East was part of stable craton that has sediments of Precambrian to Tertiary age. The breakup was accompanied by intensive volcanism and uplifts.

The motion along Dead Sea transform has accommodated most of the opening of Red Sea. Therefore both motions were essentially contemporaneous.

A great part of Dead Sea transform is marked by conspicuous morphotectonic depressions, 10-20 km wide, partly filled with sediments that can attain huge thicknesses of 8-10 km. The Dead Sea itself is the most prominent of these depressions. Other depressions include Aqaba, Arava valley and Jordan Valley.

4.2.2. STRUCTURAL MODEL

The Dead Sea transform is associated with several internal irregularities. In the case of left–lateral motion, stepping of the fault to the left will produce a rhomb–shaped grabens or pull–apart basins. The length of such basins is usually equal the spacing between strike–slip faults which delimit them. On the other hand, if the fault is bent or stepped to the right, then local compressions will form and produce ridges, horsts, domes and folds.

The main depressions along Dead Sea transform are of en echelon arrangement. In addition, there are many small-scale rhomb grabens which produce a new surface area by crustal separation. This feature makes the Dead Sea Transform leaky, (Garfunkel, 1981). Compressional structures are less common along Dead Sea Transform. The main one is in Lebanon, which is developed in the north where the strike–slip fault bends conspicuously to

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the right. These observations led to a model of somewhat irregular plate boundary. In its simplest case, pure strike–slip occurs along some rigid portions of the boundary. When rhomb grabens predominate, a new surface area is created along the boundary. When additional normal faulting occurs, a complex boundary zone is created.

Folding elements which were delineated in the JNH area strongly revealed the effects of compression and tension stresses. Mikbel and Zacher (1981) and Quenelle (1956) studied the folding elements in northern Jordan; they concluded that the existence of broad folding system belt such as Amman-Hallabat Structure and Wadi Shueib Structure are indications of the compressional tectonics as a result of continuation of the DST which shaped the structural framework. In addition, N-S and E-W faulting trends associated with the rift resulting from a regime of transpressional stresses led a deformation process in the region throughout geologic time (Mikbel, 1986). All the folded features found in north and central Jordan reveal a major horizontal stress source from SE to NW by a second major N-S component. This fits with Burdon, 1959. The stress is controlled by movement of the Arabian plate. The compressed structures are tightly folded when they are close to the rift, while intensity of deformations decreases eastwards

Thickness and facies changes in Triassic, Jurassic, Cretaceous and Lower Tertiary rocks on both flanks of the transform in the Jordan vicinity, indicate continued structural influence of the DST (BEICIP, 1976)

4.3. TECTONIC EVOLUTION OF THE JNH

The history of the geological evolution of the JNH during the Paleozoic and Mesozoic is generally outlined from the available subsurface data obtained from the seismic profiles and the key boreholes. The interpretation emphasized the complexity of the JNH geological setting of which its structural history remains for many decades of attraction for many authors. It is believed that, JNH present day structural pattern results mostly from recent Mid-Pliocene tectonic phases. These tectonic events which led to the most striking structural feature of the Jordan-Dead Sea Graben have strongly modified earlier tectonic pattern, particularly the Mesozoic structures. Beicip in 1981 supported this idea. The following is a brief description of the main tectonic events that subjected the JNH throughout its geologic time:

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4.3.1. PALEOZOIC ERA

Within the Paleozoic deposits an unconformity was identified between the lower Paleozoic and Carboniferous. This unconformity was observed in the Syrian Desert and is probable at Safra well southeast l where the Carboniferous deposits rest upon the Cambrian series. This unconformity would reveal an ante-Carboniferous tectonic phase.

A tectonic movement happened in the late Triassic and is witnessed by the absence of Lower Jurassic and the major regional unconformity that occurred between Paleozoic and Mesozoic sequences, this agrees with GSI, 1981 and Marathon, 1988 studies

Below the Mesozoic unconformity, the Paleozoic series are more complete eastward. Regional correlation between western and eastern sides of the Dead Sea Graben conducted by Beicip in 1981 induced that from the west to east, the Ordovician, Silurian and Devonian appear successively; a regional tilting to the east occurs before Mesozoic times and possibly before carboniferous times.

At SW-1 well and Zarqa River vicinity, and probably in the whole area, it appears that only the Cambrian was preserved from erosion below the Mesozoic unconformity.

4.3.2. MESOZOIC ERA

During Mesozoic and Cenozoic, sedimentation and tectonism were controlled by the configuration of the Tethys ocean and its subsequent mountain building events as the African-Arabian plate moved northwards against the Euro-Asian plate. Wetzel and Morton (1959) and Bender (1974) noted that the Permo-Triassic sequence thin southward below the overstepping unconformable Cretaceous Kurnub Sandstone along the Dead Sea shore

It was suggested by Bandel (1981) that the relative completeness of the early Mesozoic sequence in north Jordan, as compared to the Dead Sea area, was due to the step-like northerly down faulting of the sequence in pre-Cretaceous times rather than a result of northwards tilting and subsequent erosion of the sequence prior to deposition of the Kurnub Sandstone by (Powell and Khalil, 1993)

The upper Triassic evaporates of Zarqa River (Abu Ruweis Gypsum Formation) represents this regression phases, indicating uplift of the region. At the end of Triassic times, hyper

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saline marginal marine, coastal flats covered much of the north Jordan, including central Zarqa River and further north (Bandel, 1981)

Transgression prevailed during the Jurassic, indicated by the deposition of thick carbonates and siliclastics with abundant fauna, and bioturbation (Khalil and Muneizil, 1992) which indicate deposition in an open marine environment. These authors concluded that the sand facies was caused by high terrigeneous clastic influx which probably resulted from a drop of sea level and/or tilting of the hinterland

During the late Jurassic and early cretaceous times tectonic movement and consequent erosions occur. Besides some basaltic flows indicates the effect of tensional movements. This tectonic phase is known in neighboring countries as Syria and Lebanon (Marathon, 1988, Beicip, 1981).

In the JNH, the Jurassic deposits are more and more eroded to the southeast; suggesting a regional tilting of the platform to the North West.

Deposition of mature fluvial siliclastics sedimentation (Kurnub sandstone) during early Cretaceous times, changed to marine carbonates during the early Cenomanian, following a major transgression of the Tethys Ocean, which can be traced over the eastern Mediterranean area. No regular unconformity is visible between the continental lower cretaceous and the marine Cenomanian deposits.

The second Mesozoic cycle was ended with the continental series of the Kurnub Sandstone Group (Albian-Aptian) which is also the marker of a major tectonic event (Occidental, 1991; and GSI, 1981), probably of the epeirogenic type. It is also marked by the presence of a wide variety of sandstones similar to the Nubian sand. This boundary was also witnessed on wider regional basis covering Palestine, Syria, and Lebanon where the Basal Cretaceous sandstone is generally of similar origin (Jawzi, 1994).

Carbonate sediments (Ajlun Group) were deposited on a broad platform extending from the present Mediterranean coast to southeast Jordan (Powell, 1988).

During the Senonian, some stratigraphic breaks show evidence of the tectonic movements which affected the area. It seems that earth movements during the time of deposition are the main causes of the thickness variations.

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In the Cenomanian as well as the Post-Cenomanian periods, the transgression and regression movements are localized to a great extent and this is evidenced by the drastic variation in formation thicknesses from one well to another, and also this can be observed on the seismic profiles by the thinning and wedging of the Upper Cretaceous events.

Uplift of the platform during the Late Turonian to lowermost Santonian is indicated by the presence of a disconformity at the boundary the Ajlun and Belqa Groups. The predominantly pelagic sediments of the Belqa Group indicate deposition in shallow to deep seas over a wide area of the Arabian Craton until the Late Eocene

In this area some flexures of north east direction seems too acted as soon as the Upper Cretaceous (Post Turonian), such as a flexure bounds the north western flank of Suwelih Anticline. The structure of Suwelih could have been originated at this period.

The Late Cretaceous tectonics in this part of Jordan was probably Syn-sedimentary in origin and wrapping and tilting were generated on the sides of the normal (tensional) faults. In addition to that it seems it was accompanied by several rounds of volcanic activities and eruptive activity. The probability that some of the localized wrapping and tilting is due to some igneous activity which did not reach the surface is valid.

The Post- Cretaceous tectonics events are evidenced by surface secondary faulting, known volcanism, and identification on the seismic sections or the surface is almost hindered by near surface geology complex.

From the end of Campanian, the Golan Heights were affected by several tectonic movements (Mimran *et al.*,1985), the first of which was responsible for the removal of the rock units equivalent to Ghareb Formation and most of Ajlun Group locally (Basem, 2000). There may have been a break in sedimentation as a result of uplift in the area during most of Paleocene

4.3.3. CENOZOIC ERA

4.3.3.1. UPPER EOCENE TIMES

Regional uplift and rift tectonics prevailed during the Eocene to Oligocene, with remnants of the Tethys Ocean persisting only in small parts of the Arabian Craton. The Anticlockwise

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rotation of the Arabian Plate with respect to the African Craton of about 5.6˚ around a pole of rotational located 33˚N, 24˚E has taken place in two stages (Girdler, 1983), resulting in the opening of the Gulf of Aden and the Red Sea to the west and the formation of Torus-Zagros mountains to the north and northeast.

Occidental, 1991; Beicip, 1981; and Jawzi et al., , 1994 proposed a tectonic phase that took place after the Eocene deposition (Upper Eocene to Oligocene times). During the Eocene times, only stratigraphic breaks occur. There is no evidence of the occurrence of a strong unconformity within the Eocene series.

In the west bank continental and lacustrine deposits rest unconformable on the marine Eocene deposits. They are encountered in depressed zones generally bounded by faults; their age is still doubtful but they are considered to be Mid-Pliocene deposits (Occidental, 1991, Beicip, 1981, and Jawzi *et al.,* 1994).

The various phenomena which resulted from the Post Eocene tectonic movements were summarized by Beicip structural study about Jordan and West Bank in 1981 would be:

- Individuation of the dead sea graben zone
- All along the Dead Sea fault, the left lateral horizontal displacement which has been initiated previously was probably reactivated during this tectonic phase.
- It could have been once more rejuvenated later on.

A series of faults oriented roughly WNW-SSE is visible on the northern part of the west bank. These faults are branched on the graben zone.

Along the western and northwestern parts of the JNH, numerous faults oriented northeast, west east and southeast; also appear to have some connection with the main Dead Sea Major Trend. Consequent upon left lateral shifting, these faults are considered to be secondary faults.

4.3.3.2. MIOCENE-PLIOCENE TIMES

The first deformation phase occurred in the early Miocene, and the second in the Pliocene-Pleistocene times, are related to release of crustal tension manifested in renewed sinistral shear along the Wadi Araba-Dead Sea Fault. The total estimated sinistral displacement

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slightly exceeded 100km. During the Late Miocene-Pliocene Times, It seems logical to assume that the area was affected by the compressional tectonic phase of the late Miocene to Pliocene. This phase has been recorded in Syria and Turkey where it led to the formation of anticlines folds (Palmyra Range), Beicip, 1975, 1981.

Previous studies addressed that the chronology of the post Miocene tectonic events is difficult to settle since probable continuous sinking affected the Dead Sea rift. At that time the tensional movements are predominant.

The majority of the faults, folds and flexures in the JNH have resulted from the regional uplift and rift faulting during the Neogene. Extensive erosion and deep incision, mainly along fault lines commenced during Tertiary and Quaternary times and is responsible for the present- day topography. Rapid erosion during the Pleistocene to recent, along the E-W trending and other major wadies, caused instability of the wadi flanks and resulted in flexuring, small-scale faulting and landslides along the escarpments (Abdelhamid, 1995)

4.3.4. VOLCANIC ACTIVITY

Further to the north in the Golan Heights, several basalt flows are interfingering the equivalent lacustrine sediments (Gesher formation) prior to the main phase volcanism represented by plateau basalts (Cover Basalt 5.1 Ma). Yarmouk Basalt (0.7 Ma) constitutes the topmost part of Golan Heights whereas Raqqad Basalt is 0.4-0.1 Ma (Basem, 2000) during the first volcanic stage (from about 51-3.5 Ma according to Mor 1993, and Heiman *et al*., 1996), the Cover Basalts spread over the entire area covering the existing relief. During the volcanic stage (2.9-17 Ma), basalts erupted and flowed both in Rift and around it. Yarmouk Basalt which constitutes the younger flows of this stage originated in southern Syria, and flowed through the Yarmouk gorge to the Rift Valley area. In the following volcanic phase (from about 0.4 to 0.1 Ma) the Raqqad Basalt flowed through the Raqqad and Yarmouk gorges to the Rift Valley. As the rifting in the northern part of the Jordan Valley is concerned, the structural stratigraphic evolution of the Zemah area is reproduced here based on model suggested by Marcus and Slager, 1985).

The late Tertiary-Quaternary continental basalt exposed in Northeast of the JNH is part of the North Arabian Volcanic Province. This basalt in the area is considered as one super-group Named Harrat Ash sham Basaltic Super-Group. The basalt comes from deferent

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sources such as volcanic centers, fissures, feeder dykes and flows from outside the area such as Jabal Druze volcanic center. These features are important aspects for introducing an evolution model for continental basaltic succession (Mohr, 1983)

The evolutionary pathway of Harrat Ash Sham Basaltic super group correlates with the evolutionary model of the intraplate flood basalt recommended by Mohr (1983). The same author explained the major process of the volcanic events in this area as the reason of the regional uplift and regression of the Tethys Ocean; tensional faulting; sets of fissure feeders which were later represented by dykes system.

The main faults and volcanic ridges within the Harrat Ash Shamm volcanic field strike northwest; this is known as the Red Sea trend (Sebai *et al*., 1991). Detailed fieldwork combined with analysis of Landsat images by Weinberger at al., 2000) indicate that at least seven prominent fissure eruptions bisect the Harrat Ash Shaam super Group. The results also indicate that the activity along WNW trending fissures eruptions, as early as 23 Ma, concurrent with the opening of the NW trending Red Sea Rift. Later spatial and temporal activity during the middle Miocene to Pleistocene took place along the same WNW trending weak zone, although the stress field has changed over these periods (Weinberger *et al*., 2001). Furthermore, the duration and pattern of volcanism determined from K-Ar dating are within the range of the Red Sea volcanism. These similarities imply a common origin for Harrat Ash Sham and the Red Sea systems (Shimon *et al*., 2001). The same author suggests that volcanic fields were formed above upper-mantle upwelling that extended northward to the Aleppo region in northwestern Syria and Karacalidag volcanic field in southern Turkey.

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CONCLUSION

In conclusion, the study shed light on the structural style of the JNH area, which is complex. It defined the JNH area as a block that has been disrupted by various deformations. These deformations are zones of fault systems that traverse zones of fold belts.

The area has been subjected to the motion of the Arabian Plate since Cambrian times. Thus, the Dead Sea Transform (DST) is the main tectonic element which affected the recent geology of the area. The DST is believed to have a direct control on the structural setting and the recent geology of the study area.

From a regional perspective, the JNH area comprises a distinctive geological setting in the eastern margins of the Mediterranean Sea where it is surrounded by significant tectonic elements; Rutba Uplift to the east, the Golan Heights to the northwest, and Jordan Uplift to the west. Tectonically, they all share the origin and style of the JNH (Figure 4-18)

The DST

The DST motion shaped the structural framework of the JNH. Folding elements which were delineated in the JNH area strongly suggest the effects of compression and tension stresses which ca directly is assigned to the DST motion. A good indication of this is the existence of broad folding belts such as Amman Hallabat structure and Wadi Shueib Structure. All the folded features found in north and central Jordan reveal a major horizontal stress source from SE to NW and a second major N-S component. This fits with Burdon (1959). The stress is controlled by movement of the Arabian plate. The compressed structures are tightly folded, close to the rift, while the intensity of deformations decreases eastwards. In addition, N-S and E-W faulting trends are associated with the rift, resulting from a regime of transpressional stresses that led to a deformation process in the region throughout geologic time

GOLAN HEIGHTS

Golan Heights comprises the northeastern corner of the JNH. A dominant NE-SW fault branch of the DST (along the Yarmouk River), separates it from the JNH. A correlation between its structure and JNH (the northern part of the JNH) revealed similar structural style (e.g. NFZ and KFZ fault systems after Shulman and Ben-Avraham, 2004).

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THE SOUTHERN SYRIAN DESERT

The southern Syrian Desert occupies the northern borders of JNH with Syria. The structural style of the Southern Syrian Desert is highly related to the one that dominates the JNH area in terms of trend, type, and origin.

SIRHAN BASIN

Sirhan Basin or Druze depression is considered to be one of the basins that extend from the Nefud in Saudi Arabia to the Euphrates River in Syria, which structurally represents arms of relative subsidence formed between Rutba-Hail Uplift, Jordan Uplift, and Aleppo Uplift.

The subsurface and surface interpretation emphasizes it as a tectonic subsidence element caused by E-W and NE-SE tension stress. Ramtha Sirhan Fault System is the dominant structural element that controls the Sirhan Basin.

THE JORDAN UPLIFT

Jordan Uplift comprises the eastern margins of the DST where Ajlun Dome comprises its center with Cretaceous rocks. Initiation of the growth of the folds across the Jordan Uplift can be traced to the Late Cretaceous or early Palaeogene

RUTBA UPLIFT

Rutba Uplift comprises the largest uplift to the northeast and east of the Sirhan Depression where Triassic rocks are brought up to the surface at its central part.

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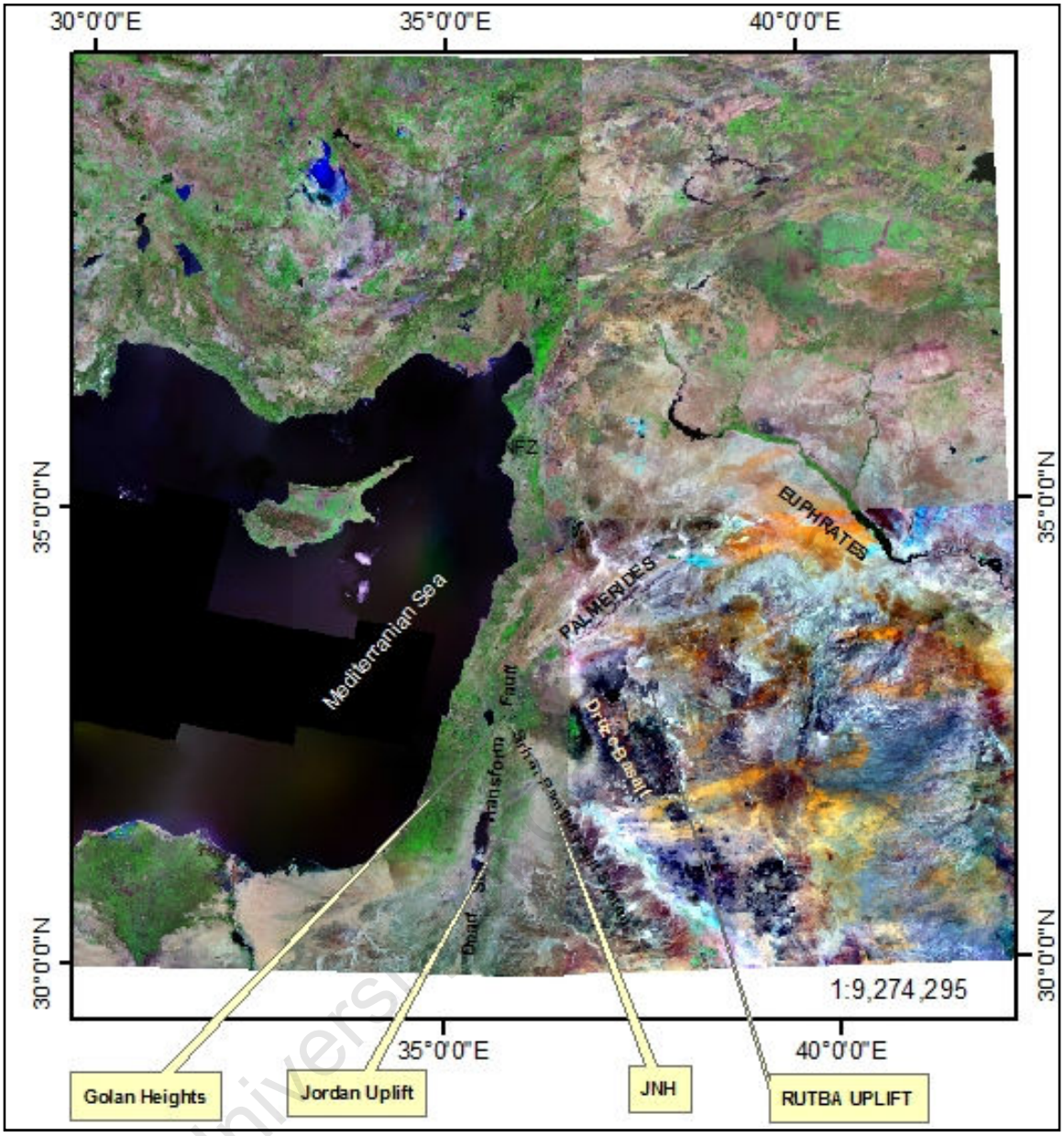

Figure 4-18: A mosaic from four LANDSAt TM images showing the regional tectonic setting of the JNH. These images were downloaded from NASA Mr, Sid website; enhanced and geo-referenced.

Subsurface studies indicate that this uplift was an early Paleozoic depocenter

The structural style of the JNH is formed by complex structural zones of faulting and folding with major NW-SE, NE-SW, NNE-SSW, N-S, and E-W. The combination of faulting and folding has led to the formation of series of horst, grabens, uplift, and domal structural elements. Interpretation revealed strong dips toward the north, northeast, and east

Ramtha-Sirhan Fault System is the dominant structural element in the area as well as Zarqa Fault System, Fuluq Fault System, Amman-Hallabat Structure, Wadi Shueib Structure, Ajlun Dome, the major NE-SW trends, Sirhan Basin, Irbid Ramtha Basin, and the DST.

Analysis of the depth contour maps shows significant thickening of the Mesozoic sedimentary cover toward the north, northeast, east, and southeast, and noticeable thinning toward the west and southwest where Cretaceous horizons almost reach the surface. Triassic and Paleozoic sequences show remarkable thickening toward the east and southeast, unlike the Jurassic which is pinched out in this direction.

Basement shows shallow depth toward the northwest, west, and southwest, as opposed to the northeast, east, and southeast.

The JNH area can be subdivided into four major terrain zones. These zones indicate the relationship between the topography and the structural style of the JNH; high elevated areas with steep slopes, high elevated areas with intermediate slopes, low elevated areas with steep slopes, and low elevated areas with intermediate slopes. The relationship between the structural style of the JNH and its terrain appears clearly where the dominant faults overlay the main wadi courses forming basins and depressions, while major folds comprise hills and mountains. The Ajlun Anticline, The Irbid-Ramtha Basin, The Bala'ama Zone of Synclines and Anticlines, and The Mafraq-Azraq Zone of Basins are major structural zones that reflect the topography.

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BIBLIOGRAPHY

- 1996, Report On Busra Ash Sham Well Bus-1, NRA
- Abdelhamid, Gh., 1993. Jarash, Sheet #. 3154 I.
- Abdelhamid, Gh., and Barjous, M., 1991. The Geology of NW-Jordan, To Accompany the Preliminary 1:100,000 Geologic Map. NRA, Geology Directorate, Internal Report
- Abed, A. M., 2000. Geology of Jordan, Environments and Water. Jordanian Geologists Association, Amman, 571p
- Abu Hamideh, Kh., 2000. Geophysical Studies Of Crustal Structures In Northern Jordan, PhD Dissertation, Jordan University.
- Abu Jaber, N., Kimberly, M., and Cavaroc, V., 1989. Mesozoic – Paleozoic Basin Development Within The Eastern Mediterranean Borderland, Petroleum Geology, 12, No 4, 419-436
- Al Hiyari, A., 2004. Qasr Al Hallabat, Sheet #.3254 II.
- Al Zoubi, A., and Abu Hamatteh, Z., 2009. Geological Evolution Of The Jordan Valley, J.Virtual Explorer, 32, 1441-8142
- Al-Fares, A.A., M. Bouman and P. Jeans 1998. A New Look At the Middle to Lower Cretaceous Stratigraphy ,Offshore Kuwait. Geoarabia, V. 3, No. 4, P. 543-560.
- Al-Saad, D., Sawaf, T., Gebran, A., Barazangi, M., Best, J., And Chaimov, T., 1992. Crustal Structure of Central Syria: The Intercontinental Palmyrides Mountain Belt. Tectonophysics, 207, 345-358.
- Amoco Oil Co, 1987. Block 5 Evaluation The Hydrocarbon Potential Of The Dead Sea Rift Basin
- Atallah, M., 1992. On The Structural Pattern of the Dead Sea Transform and Its Related Structures in Jordan, Abhath Al Yarmouk, Vol. 1, 127-143.
- Bajjali, W., Clark, I., and Fritz, P., 1997. The Artesian Thermal Ground Waters Of Northern Jordan, Journal Of Hydrology, 192, 355-382
- Bandel, G., 1981. New Stratigraphic And Structural Evidence For Lateral Dislocation In The Jordan Rift Valley Connected With The Description Of The Jurassic Rock Column In Jordan. N. Jb. Geol. Palaeont. Abb, 161, 271-308
- Bandel, K., Khoury, H., 1981. Lithostratigraphy of Triassic in Jordan, Facies, 4, 1-26.

University of Cape Town

- Barbieri, F, G, Capaldi, P. Gasperini, G. Marinelli, R.Santcroce, R. Scandone, M. Treuli, And J. Varec, 1980. Recent Basaltic Volcanism of Jordan and Its Implication to Geodynamic History of the Dead Sea Shear Zone. ATTI. Accad. Naz. Lincei, 47, 667 – 683.
- Barjous, M., 1993.Suwaylih, Sheet #. 3154 II
- Barjous, M., And Mikbel, S, 1990.Tectonic Evolution Of The Gulf of Aqaba _ Dead Sea Transform Fault System. Tectonophysics, 180, 49-59.
- Basha, S & Mikbel, Sh.1983. A Contribution to the Stratigraphy and Tectonic Of the Lower Ed-Dhira-East of Lisan (Jordan Rift). Dirasat, Vol XIV, No 12.
- Basha, S., 1981. Distribution of Triassic Rocks in Jordan and Levant. *Dirasat*, VIII; 1: 49-67.
- Batayneh, A. And Hassouneh, M., 1992. Interpretation of Aeromagnetic & Gravity of NW-Jordan.
- Bayer, H. J., Et Al., 1988. Sedimentary and Structural Evolution of the NW Arabian Red Sea Margin. Tecto. 135, 137-151.
- Beicip, 1981. Structural Study of Jordan, Beicip, NRA, Internal Report, Jordan.
- Beicip, 1976. Study of the Northern Highlands and West Bank.
- Bender, F., 1974. Geology of Jordan, Gebruder Bontraeger, Berlin, Stuttgart, V 7.
- Bender, F., 1975. Geology Of The Arabian Peninsula, Geological Survey Professional Paper 560-I
- Beydoun, Z, 1977, Geological Evolution of the Eastern Mediterranean.
- Beydoun, Z.R., 1991. Arabian Plate Hydrocarbon Geology and Potential - A Plate Tectonic Approach: Arabian Plate Hydrocarbon Geology and Potential - A Plate Tectonic Approach. In: (Eds), Studies in Geology, American Association of Petroleum Geologists, 33, 77.
- Blake, GS.1939. Geological Map of Palestine. Scale 1:250,000. Survey Of Palestine, Jerusalem
- Blankenhorn, M.1903. Die MinEralscatze Palestine, Mitt. Und.Nachr Des Deutch. Palestine Ver. 1902, 65-70
- Blankenhorn, M.1914. Syrian, Arabian and Mesopotamian. Handbook Reg. Geol. S. Heidelberg 5, Abt 4

University of Cape Town

- Boom, V., And Sawwan, O., 1966. Report On Geological And Petrological Studies Of The Plateau-Basalt In Ne-Jordan. Unpub. Rep. Germ. Geol. Miss. In Jordan, 42p.
- Brew, G., 2001. Tectonic Evolution Of Syria Interpreted From Integrated Geophysical And Geological Analysis, PhD Dissertation, Cornell University (F14).
- Brink, U and Z. Ben-Avraham, 1981. The Anatomy of Pull-Apart Basins: Seismic Reflection Observation for the Dead Sea Basin. Tectonics, V. 8, 1989.
- Burdon, D. J., 1959. Geology of Jordan, Benham and Company Limited, Colchester, 50-65.
- Chaimov, T. A., Barazangi, M., Al-Saad, D., Sawaf, T., and Gebran, A., 1991.Mesozoic and Cenozoic Deformation Inferred From Seismic Stratigraphy in the Palmyrides Fold Belt, Syria. Gsa Bulletin, In Press.
- Chaimov, T. A., Barazangi, M., Al-Saad, D., Sawaf, T., and Gebran, A., 1990. Crustal Shortening in the Palmyrides Fold Belt, Syria and Implications for Movement along the Dead Sea Fault System. Tectonics, 9: 1369-1386.
- Coleman, R, 1993, a Brief Essaybon the Geological Evolution of the Red Sea. Pure/Sci. & Eng., V 2, No. 1, 89-117.
- David E.H., And Thomas A.J.1992. Computer Modeling Of Geologic Surfaces and Volumes. AAPG#01. American Ass. Of Petroleum Geologists, USA
- Dewy, J., Pitman, W., Ryan, W., and Benin, 1973. Plate Tectonics And Evolution Of The Alpine System, Geol.Soc.,Am., Bull., 84, 3137-3180
- Diabat, A., Atallah, M. And Salih, M, A., 2004. Paleostress Analysis O The Cretaceous Rocks In The Eastern Margin Of The Dead Sea Transform, Jordan, American Earth Sciences Elsevr, 38, 449-460.
- Dybertret, L. 1929. Etude Des Regions Volcaniques Du Houran, Du Djebel Druze Etdu Direct Et Touboul Rev. Geol. Dyn.12:275-321
- El-Isa, Z., Mechie, J., Prodehl, C., Makris, J. & Rihm, R., 1987. A Crustal Structure Study Of Jordan Derived From Seismic Refraction Data. Tectonophysics, 138: 235-253.
- Eyal, Y. , Reches, Z., Bartov, Y., And Steinitz, G.,1981, Tectonic Development Of Western Margin Of The Gulf Of Elat (Aqaba) Rift, Tectonophysics,80,39-66
- Eyal, Y. And Reches, Z., 1983. Tectonic Analysis Of The Dead Sea Rift Region Since The Late Cretaceous Based On Meso-Structures, Tectonics, Vol. 2, No. 2, 167-185.

University of Cape Town

- Filon, 1975. Petroleum Exploration in the Hashemite Kingdom of Jordan, Denvor Colorado.
- Fisher W.L., and Brown L.F., 1983. Basin Analysis and Seismic Stratigraphy. First Indian reprint
- Fruend, R., 1965. A Model of the Structural Development of Israel and Adjacent Areas since Upper Cretaceous Times, Geol. Mag, V 102, No.3, 191-205.
- Fruend, R., Garfunkel, Z., Zak, I., Goldberg, M., Weisbrod, T., and Derin, B., 1970. The Shear along the Dead Sea Rift. Phil. Trans.Roy.Soc.London A, 267, 107-130
- FUTYAN, And A. H. Jawzi, 1994. Hydrocarbon Potential of the Arabian Peninsula. Unpublished Report , NRA
- Garfunkel, Z., 1981. Internal Structure Of The Dead Sea Leaky Transform (Rift) In Relation To Kinematics., Tectonophysics., 80, 81-108
- Garfunkel, Z., *Et Al*., 1981, Active Faulting In The Dead Sea, Tecto. 80, 1-26.
- Gharaibeh, A., 2003. Umm Al Jimal, Sheet #.3254 I.
- Gharaibeh. 2005. The Geology Of Umm El Jimal Area, Map Sheet No.3254-I, Natural Resources Authority, Amman, Bulletin, 61
- Ginat, H., Enzel, Y., and Avni, Y., 1998. Translocated Of The Plio-Pleistocene Drainage Systems Along The Arava Fault Transform, Tectonophysics, 284, 151-160
- Girdler, R. W., 1990, The Dead Sea Transforms Fault System, Tecto. 180, 1-13.
- Girdler, R., 1985. Problems Concerning The Evolution Of Oceanic Lithosphere In The Northern Red Sea, Tectonophysics, 116, 109-122
- Gomez, F., Khawlie, M., Tabet, C., Darkal, A., K. Khair M., and Barazangi M., 2006. Late Cenozoic Uplift Along The Northern Dead Sea Transform In Lebanon And Syria, Earth Planet. Sci., Lett. 241, 913-931.
- Grabowski, G.J., Jr. And I.O. Norton 1995. Tectonic Controls On The Stratigraphic Architecture And Hydrocarbon Systems Of The Arabian Plate. In, M.I. Al-Husseini (Ed.), Middle Eastern Petroleum Geosciences, GEO'94 .Gulf Petrolink, Bahrain, V. 1, P. 413-430
- GSI, 1985, Seismic Survey of the Northern Highlands.
- Guba, I., and Mustafa H. 1988. Structural Central of Young Basaltic Fissure Eruptions in the Plateau Basalts Area of the Arabia Plate, NE Jordan, J. Volcan. Geoth. Res.35, 16p

University of Cape Town

- Haq and Al-Qahtani A. M. 2005. Phanerozoic Cycles of Sea-Level Change on the Arabian Platform. Geoarabia, Vol. 10, No. 2, Gulf Petrolink, Bahrain
- Hassouneh, M., 2003, Interpretation Of Potential Field By Modern Data Processing & 3D Gravity Modeling Of Dead Sea Pull – Apart Basin/ Jordan Rift Valley (JRV) , PhD Dissertation, Weisberg.
- Hatcher, R., Zietz, I., Regan, R., and Abu Ajamieh, M., 1981. Sinistral Strike-Slip Motion of the Dead Sea Rift: Confirmation from New Magnetic Data. Geology, 9, 458-462
- Hydrocarbon Habitat of the Arabian Plate: Geoarabia, V. 6, P. 407-442.
- Ibrahim, Kh. 1993. Al A Azraq Map 3353I. Geol. Dir.,NRA, Jordan
- Ionides, M.G. And Blake, G.S.1939. Report On The Water Resources Of Transjordan And Their Development. Incorporating Report on Geology, Soils, Minerals and Hydrogeological Correlations. London: Crown Agents For Colonies
- Isa, Z., 1991.Seismicity and Seismic Risk in Jordan, Al Kutba Pub., Goethe, Amman, 119/3/1991, 21-27.
- Johnson, P.R., 1998. Tectonic Map of Saudi Arabia and Adjacent Areas, USGS-Tr-98-3 (IR-948).
- Jurkun A., Zielke J., 1995a: Detailed Geological Map of Poland 1:50,000, Proceedings 10th Arc Info European User Conference, Prague.
- Jurkun A., Zielke J., 1995b: Szczegolowa map geologiczna Polski 1:50,000 - baza danych oraz wspomaganie redakcji mapy, V Konferencja Naukowo-Techniczna Systemy Informacji Przestrzennej, Warszawa.
- Kassler, P. 1973. The structural and geomorphic evolution of the Persian Gulf. In, B.H. Purser (Ed.),
- Kazmin, V.G., 2002. The Late Paleozoic to Cenozoic Intraplate Deformation in North Arabia: A Response to Plate Boundary Forces, EGU, 2, 123-138.
- Khalil, B., 1997. Irbid, Sheet #.3155 II.
- Khalil, B., and Muneizil, S., 1992. Lithostratigraphy of the Jurassic Outcrops in North Jordan (Azab Group), NAT. RES. AUTH., Geol. Dir., Map. Div., *Bulletin* 21, Amman.
- Khouri , J.,1982, Hydrogeology Of The Syrian Steppe And Adjoining Arid Areas, Quarterly Journal Of Engineering Geology & Hydrogeology; Vol. 15; No. 2; P. 135-154
- Konert, G., A. M. Al-Afifi, S. A. Al-Hajri, And H. J. Droste, 2001, Paleozoic Stratigraphy And

University of Cape Town

- Kumar R., Ainampudi S.B., and Subramania S. 2010. Integration of surface and sub-surface data optimizes hydrocarbon exploration. VI Magazine, Promoting Spatial Design for A Sustainable Tomorrow
- Lartet, L.1869. La Geologie De La Palestine Ann. Sci. Geol. Paris 1
- Lovelock, P.E.R. 1984. *A* Review of the Tectonics of the Northern Middle East Region. Geological Magazine, 121, 577-587.
- Macdonald, Sir M. And Partners. 1956. East Band Water Resources. Hydrological Survey of the Madaba-Maan Area, Vol 1-3. Central Water Authority, Jordan
- Macqueen R.W, Leckie D.A. 1992. Forland Old Basins Belts. AAPG#55. American Ass. Of Petroleum Geologists, USA
- Makhlouf, I.M., Turner, B.R. And Abed, A.M. 1990. Depositional Facies and Environments in the Lower Triassic Ma'in Formation, Dead Sea Area, Jordan. *Dirasat* B 17, 7-26. University Of Jordan, Amman
- Marathon Company, 1988. Jordan North Highlands, International New Ventures, Houston, Texas.
- Mart, Y., 1991. The Dead Sea Rift from Continental Rift to Incipient Ocean, Tecto. 197, 155-179.
- Masri, A., 1988. Al Mudawwara and Halat Amar Sheets, 3248 III And 3248 IV. 1:50000 Geological Map Series, NRA, Amman, Bull. 13
- Mccllough, R., and Marshall, J., 1988. Block 5 Evaluations, Report No 88106.
- Mccourt, W. J., And Ibrahim, K., 1990. The Geology, Geochemistry, and Tectonic Setting of the Granitic and Associated Rocks in the Aqaba and Araba Complexes of SW Jordan. Nat. Res. Auth., Geol. Dir., Map. Div., Bulletin 10, Amman
- Mikbel, Sh. And Atallah, M., 1983, Tectonics of Jordan, Contribution to the Structures of North Jordan, Jordanian Geological Conference, 446-459.
- Mikbel, Sh. And Zacher, S., 1981. The Wadi Shueib Structure in Jordan, Geol. Jahrb, C68, 1-68.
- Mikbel, Sh., 1985, New Lights On The Major Structural Framework And Rift Tectonics Of North And Central Jordan; Presented Before The First International Geomorphology Conference, Manchester.
- Mikbel, Sh., and Zacher, W., 1986. Fold Structures in Northern Jordan, N.JB. Geol. Palaont.Mh.H4, 248-256.

University of Cape Town

- Mitchell, R., 1959, Notes On The Geology Of Western Irak And Northern Saudi Arabia, Geologische Rundschan, Vol 46, Issue 2, 476-493.
- Moumani, K., 2002. The Geology of Jabal Al Batra (Jibal Thlaja) Area, Map Sheet No. 3149-IV, 1:50,000 National Mapping Project, NAT. RES. AUTH., Geol. Dir., Geol. Map. DIV., Bulleti*n* 52, 106p, Amman
- Murris, J., 1980. Middle East; Stratigraphic Evolution And Oil Habitat, American Association Petroleum Geologist, Bulletin 64, 597-618
- Nabulsi, S., 2000, Structural Aspects For Hydrocarbon Exploration In Northern Highlands, Jordan, R/NH/1/2000
- Nabulsi, S., 2002. Sirhan Block SE Jordan, NRA, Jordan
- Niemi, T.M., and Ben-Avraham, Z., 1994. Evidence for Jericho Earthquake from Slumped Sediments of the Jordan River Delta in the Dead Sea, Geology, 22, 395-398.
- Nuweihed, S., 1981. Seismic Reflection Survey, Mafraq-Ramtha , Geophysical Service Inc, Cairo
- Occidental International Exploration & Production Company, 1991, Hydrocarbon Potential in Jordan.
- Panikarov, V.P. (Editor-In-Chief), 1967. The Geology Of Syria: Explanatory Notes On The Geological Map Of Syria, Scale 1:1,000,000. Ministry Of Industry, Damascus, Syria.
- Powel, J.H.1989a.Stratigraphy and Sedimetology of the Phanerozoic Rocks in Central and South Jordan. Part A: Ram and Khrayim Groups. Bull.11, Geoloo.Dir., NRA, Jordan
- Powel, J.H.1989b.Stratigraphy and Sedimetology of the Phanerozoic Rocks in Central and South Jordan. Part B: Kurnub, Ajlun and Belqa Groups. Bull.11, Geoloo.Dir., NRA, Jordan
- Powell, J., 1989. Stratigraphy and Sedimentation of the Phanerozoic Rocks in Central and South Jordan. Bull. 11: Part A: Ram And Khrayim Groups, Part B: Kurnub, Ajlun, And Belqa Groups, NRA, Geology Directorate, Mapping Division, Amman.
- Purser, B.H. and E. Seibold 1973. The principal environmental factors influencing Holocene
- Qudaira, M., 2001. AZ Zarqa, Sheet #.3254 III.
- Quenelle, A., 1956. Geological Map of Jordan (East Of the Rift Valley), 1:250,000, Hashemite Kingdom Of Jordan, Dept. Of Lands And Surveys

University of Cape Town

- Quenelle, A., 1958. The Structural And Geomorphic Evolution Of The Dead Sea Rift Quart J. Geol. Soc. London, 114, 1-24
- Quenelle, A.M., 1984. The Western Arabia Rift System, GEOLOGICAL SOCIETY, LONDON, V. 17; P. 775-788
- Quenelle, A.M.1951. The Geology and Mineral Resources of Former Transjordan. Colonial Geology And Mineral Resources,2,85-115
- Qureshi, I., Mula, H., 1971. Two-Dimensional Mass Distributions from Gravity Anomalies: A Computer Method, Department Of Geology, the University of Khartoum, Sudan.
- Rabi, H., 1987. Final Geological Report Of Well NH-1, NRA, Jordan
- Rabi, H., 1987.Final Geological Report Of Well NH-2, NRA, Jordan
- Rabi, H., 1992. Final Geological Report Of Well Ajlun (AJ-1), NRA, Jordan
- Reches, Z., And Hoexter, D., 1981. Holocene Seismic and Tectonic Activity in the Dead Sea Area, Tectonophysics, 80, 235-254.
- Ron, H., and Eyal, Y., 1985. Intraplate Deformation, Block Rotation And Structures Along The Deed Sea Transform, Northern Israel, Tectonics, 4, 85-105.
- Sawaf, T., Al-Saad, D., Gebran, A., Barazangi, M., Best, J., and Chaimov, T., 1993. Stratigraphy and Structure of Eastern Syria across the Euphrates Depression, Tectonophysics, 220, 267-281.
- Sedimentation and digenesis in the Persian Gulf. In B.H. Purser (Ed.), the Persian Gulf. Springer-
- Selley, R.C., 1978. Ancient Sedimentary Environments. Second Edition, Chapman And Hall, London
- Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury And M.D. Simmons. 2001. Arabian Plate Sequence Stratigraphy. Geoarabia, Special Publication 2, Bahrain. 371 Pp.
- Shulman, H., and Ben-Avraham, Z., 2004. The Structure Of The Golan Heights And Its Tectonic Linkage To The Dead Sea Transform And The Palmyrides Folding, ISR. J. Earth SCI.; 53: 225–237
- Smadi, A., 1997. Al Mafraq, Sheet #. 3254 IV.
- Stampfli, G. M., And G. D. Borel (2002), A Plate Tectonic Model For The Paleozoic And Mesozoic Constrained By Dynamic Plate Boundaries And Restored Synthetic Oceanic Isochrones, *Earth. Planet. Sc. Lett*., *196*, 17-33.

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- Stampfli, G. M., Hochard C., Moix P., and Wilhem C. 2001, 2002, 2008. Global Reconstruction and Database Project. UNIL University Of Lausanne, IGP, Anthropole, CH 1015 Lausanne, Switzerland
- Steen, G., 1987. Stratigraphic Influences On Tectonic Style, Amman Area, Amoco
- Suboh, A., 2003. Al- Ramtha, Sheet #. 3255 III.
- Sawariah, A., And Masarweh, R., 1997. Geothermal Water In Mukheiba And North Shuna Areas, NRA, Internal Report
- Swartz, D. H. And Arden, D. D (1960). Geologic History of Red Sea Area, American Association of Petroleum Geologists. Bulletin, V. 44, N. 10, P. 1621-1637.
- Swartz, D.H. and Arden D.D. 1960. Geologic history of Red Sea area. Am Asso. Petrol. Geol. Bull., history of Red Sea area: Am. Assoc. Petrol. Geol. Bull., v. 44
- Tarawneh, K., Shimon I., Rabba, I., Harlavan, Y., Peltz, S., Ibrahim, K., Weinberger, R., and Steinitz, G., 2000. Dating Of the Harrat Ash Shaam Basalts/NE Jordan (Phase 1). NRA-GSI Report, 65p.
- Tarawneh, Kh., 1996, Alhamidiyya (Al Hamidya), Sheet #. 3254 III.
- Tarawneh, Kh., 2000. Umm El Quttein, Sheet No. 3354 Iv.
- Tavakoli S. 2008. Construction of a solid 3D model of geology in Sardinia using GIS methods. Department Of Technology and Built Environment. Master thesis.
- Tearpock D.J. and Bischke R.E. 2002. Applied Subsurface Geological Mapping with Structural Methods (e book). 2nd ed. Prentice Hall
- Ten Brink, U, Ben-Avraham, Z., Bell, R., Hassouneh, M., Coleman, G. Andersen, D., Tibor, G., and Coakley, B., 1993. Structure of the Dead Sea Pull-Apart Basin from Gravity Analyses. Journal of Geophysical Research, 98, 21,877-21,894.
- Trollinger, 1986, Petroleum Exploration in the H.K of Jordan, Trollinger Marsh Resources, Inc.
- Van Den Boom G., And Sawwan, O.1966. Report On Geological And Petrological Studies Of The Plateau Basalts In NE Jordan. Germ. Geol. Mission Jordan, 42p
- Van Der Plujm B. A. And Marstak S. 1997. Earth Structure, an Introduction to Structural Geology and Tectonics. WCB/Mc Graw-Hill
- Von Raumer J. F., and Stampfli, G. M. Bussy Francçois G. 2002.-Derived Microcontinents — The Constituents Of The Variscan And Alpine Collisional Orogens Ang.,

University of Cape Town

- Waldemar G., Tomasz B., Aldona J., Jacek K., Jacek Z**.** 1996.Computer aided production of The 1:50,000 Detailed Geological Map of Poland
- Walley, C. 1988. A Braided Strike-Slip Model for the Northern Continuation of the Dead Sea Fault and Its Implications for Levantine Tectonics. Tectonophysics, 145, 63-72.
- Walley, C. 1998. Some Outstanding Issues in the Geology of Lebanon and Their Importance in the Tectonic Evolution of the Levantine Region. Tectonophysics, 298, 37-62.
- Wdowinski, S., and E. Zilberman, 1997. Systematic Analyses of the Large Scale Topography and Structure across the Dead Sea Rift, Tectonics, 16, 409-424.
- Wender, L.E., J.W. Bryant, M.F. Dickens, A.S. Neville and A.M. Al-Moqbel 1998. Paleozoic (Pre-Khuff (Hydrocarbon Geology of the Ghawar Area, Eastern Saudi Arabia. Geoarabia, V. 3, No. 2, P. 273-302
- Wetzel, R. And Morton, D.M.1958. Contribution La Geologie De La Tranjordanie. Notes Mem. Moyen-Orient, Pp. 95-191, Paris
- Wiesmann, G. And Abdullatif, A. 1963. Geology of the Yarmouk Area, North Jordan. GGM Report, 81p
- Wolfrat, R., 1967. Hydrogeology of Northern Jordan, Bundesanstalt Fur Bodenforschung, Hannover, 189-199.
- Wolfrat, R., 1967. Hydrogeology Of The Damascus Basin (Southwest Syria), Bundesanstalt Fur Bodenforschung, Hannover, 402-413
- Zhou, W., Chen, G., Li, H., Luo, H., Huang, S., 2007. GIS application in mineral resource analysis—a case study of offshore marine placer gold at Nome. Computers & Geosciences, Vol. 33. pp 773–788. doi:10.1016/j.cageo.2006.11.001.
- Ziegler M.A.2001. Late Permian to Holocene Paleofacies Evolution of the Arabian Plate and Its Hydrocarbon Occurrences. *Geoarabia*, Vol. 6, No. 3, .Gulf Petrolink, Bahrain
- Zouaghi T., Bédir M., Inoubli M. H. 2005**.** 2D Seismic Interpretation of Strike-Slip Faulting, Salt Tectonics, and Cretaceous Unconformities, Atlas Mountains, Central Tunisia. Journal of African Earth Sciences, Vol 43. Issue 4. P 464-486

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