

## Geological evolution of the Azraq basin, eastern Jordan: An overview

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### ABSTRACT

The Azraq basin is some 100 Km east of Amman, the capital of Jordan. Hydrologically, it occupies ~12700Km<sup>2</sup>, mostly in Jordan, but it also extends to southern Syrian and NW Saudi Arabia. The Azraq area seems to have developed as a basin during the Paleozoic testified by the total thickness of both Ram and Khreim Groups in the Azraq subsurface being slightly less than twice those in the southern outcrops. In this case, the Azraq basin is similar to the Wadi Sirhan basin. From the Carboniferous, Late Paleozoic, to the top Ajlun Group, Mid Cretaceous, no basinal development took place in the Azraq area. Dramatic changes seem to have taken place in the Azraq basin during the deposition of the Belqa Group. Northwest-trending faults became active since the Coniacian? such as the Fuluk Fault and Rajil Fault. A subsiding graben, called Hamza Graben, was the scene for a thick, fast sedimentation of more than 2000m during the Coniacian-Campanian represented by the Rajil, Hamza and Hazim Formation which are dominated by carbonates. This is explained by synsedimentary deposition in a subsiding basin. The basin continued up till the Eocene albeit being at a slower rate during the rest of the Belqa Group. By the end of the Eocene, the Neo-Tethys Ocean had migrated from the eastern Mediterranean and the Azraq area, as well as almost all Jordan, and the area became terrestrial, and subjected to erosion. The Azraq basin continued as a depression where lake deposits formed from the Miocene onwards. The large recharging area of the Azraq depression seems to have ensured enough water for the marches and springs of the Azraq oasis even in the driest climates in the past, which made the oasis a refugia for hominins and animals throughout the Pleistocene time.

**Keywords:** Azraq basin, evolution, paleoclimate, hominins

### INTRODUCTION

The Azraq Basin is situated some 100 km east of Amman. It drains an area slightly more than 12700 km<sup>2</sup> in Jordan, southern Syria and northern Saudi Arabia (Fig. 1). It is an endorheic or closed basin located in the Jordanian Plateau where all the drainage is collected at Qa 'Al-Azraq at 500m above mean sea level (amsl), a flat sabkha or salt flat which is dry but seasonally

flooded with rain water. In the near past, several springs were present at and around this Ga' such as 'Ayn Qasiyya,'Ayn Sawda, and the Lion's Spring, in addition to groundwater recharging the permanent marches at the centre of the Ga'. Consequently, this area became an oasis within a vast desert area at the cross roads with Iraq, Syria and Saudi Arabia. Two permanent settlements were established; Azraq Druze in the north and Azraq Shishan in the south. During the 1980s, the oasis became dry because of the overpumping of fresh, groundwater to the major cities of Jordan especially to the capital Amman (El-Naqa, 2010). The Royal Society for the Conservation of Nature (RSCN) have reclaimed and maintained the newly formed, much smaller (2 Km<sup>2</sup>), southern wetland at Azraq Shishan (France, 2010).

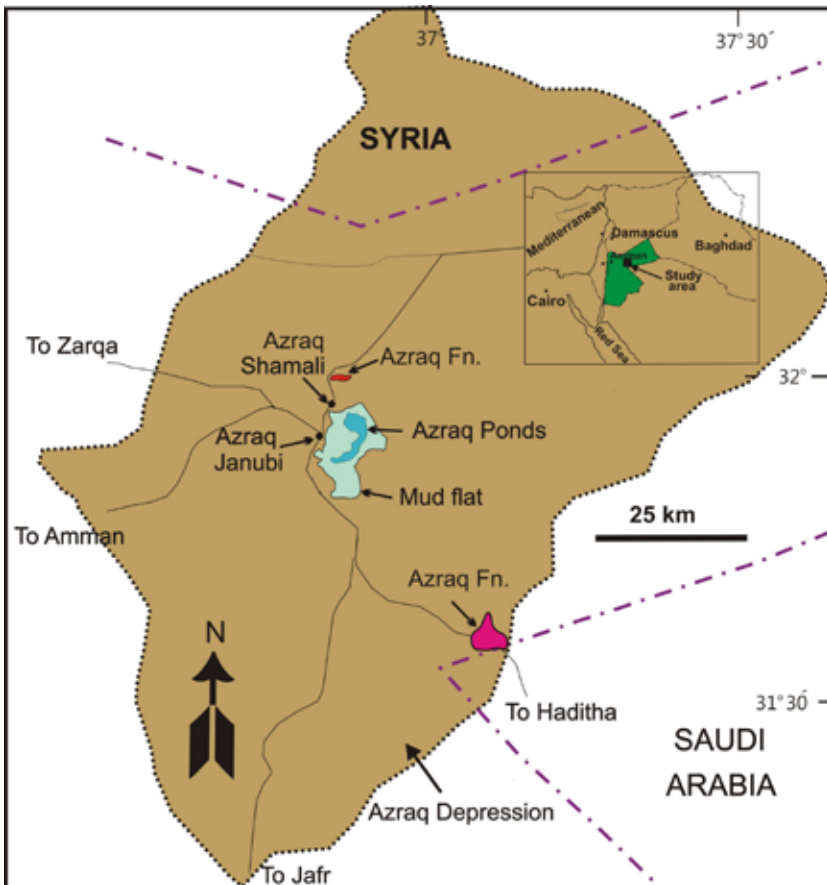


Figure 1: Location map of the Azraq basin

The Azraq oasis and the paleolakes formed within the Azraq basin during the warm, wet periods of the Pleistocene (the last 2 million years or so) were, most probably, an important route for the migration of hominins and animals, eastwards to SE Asia and northwards to Europe (e.g. Abed et al., 2008; Cordova et al., 2012; Ames et al., 2013). The Azraq paleolakes and other paleolakes in Jordan, were an important link with the similar water bodies along Wadi Sirhan and further east and southeast in northern Arabia. Thus, it is not unusual to find a rich hominin remains in the Azraq basin, indicating its importance in the archeological, paleoclimate and paleoenvironmental research (e.g. Ahmad and Davies, 2017).

On the other hand, the Azraq basin is mostly covered by Quaternary to recent sediment, especially within the Azraq Ga', as well as by basaltic rocks of the Tertiary-Holocene times. This is different from the fully exposed older geological units along the Rift valley in the west and the wadis tributing it such as Wadi Mujib (e.g. Bender, 1974; Abed 2017). Thanks to the oil wells drilled in the basin, especially the Hamza oil field where rock units down to the Precambrian were penetrated and studied (Core Lab, 1987; Andrews, 1991).

The aim of this paper is to provide an overview of the geological evolution of the Azraq basin, especially oasis and its surroundings such as Hamza oil field and Dahikiyeh, from the Precambrian to Recent with some emphasis on the paleohydrology/paleoclimate during the Pleistocene-Holocene times in relation with hominin presence.

## 2. CLIMATE

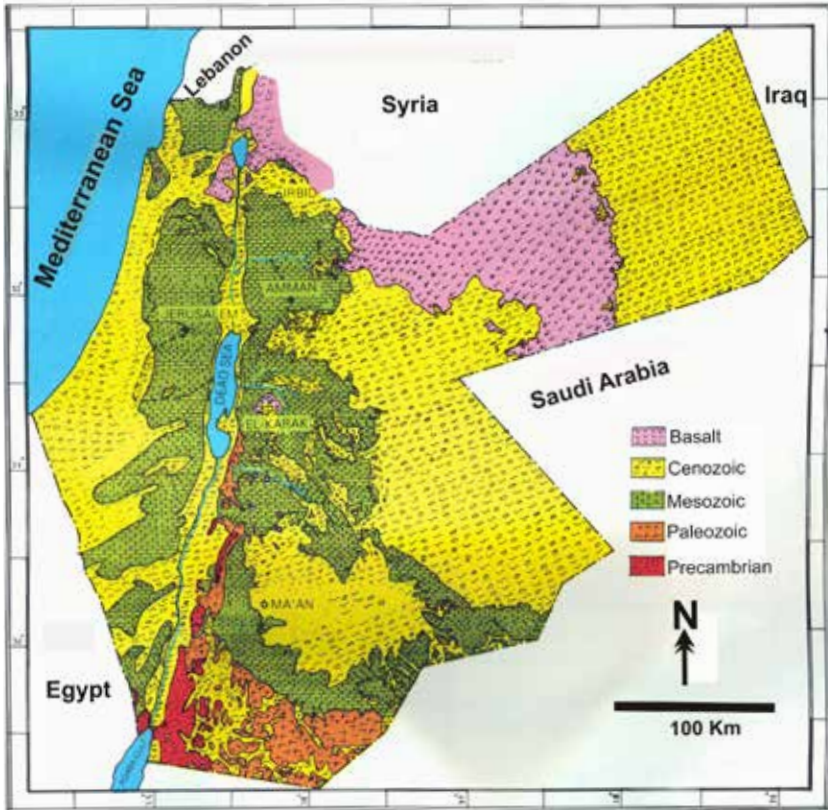
Both areas are located within the eastern desert of Jordan. Average annual rainfall, as short duration storms, is 150 mm in the northern part of the basin decreases to 60 mm in the south. The weather is recognized by two defined seasons; hot, dry, dusty and comparatively strong northwesterly wind in summer (May-October), and cold, semi dry, windy in winter (November-April) (Ayed, 1986).

The Azraq oasis was thriving in this eastern desert until late 1980s when it dried out because of over pumping of the shallow groundwater aquifer. Since then, migrating birds had changed routes.

Most of the vegetations in the area are desert shrubs (salt tolerant plants), grasses along wadis and few palms and other type of trees near the Azraq ponds. Farms are developed near the two Azraq towns and east of the mudflat irrigated by shallow wells of acceptable salinity (Fig. 1).

## 3. PRECAMBRIAN BASEMENT

Cropping out Precambrian rocks in Jordan span the period 800-540 million years (Ma). They form northernmost exposure of the Arabian Shield which covers western Arabia.



**Figure 2:** General geological map of Jordan showing the Precambrian basement in SW Jordan (red) and covered by the Phanerozoic sedimentary sequence.

In Jordan, the Precambrian basement is subdivided into an older complex called the Aqaba Complex (800-600Ma) made essentially of granitoids exposed around Aqaba and further east and north. The other subdivision is the younger Araba Complex (600-540 Ma) with abundant volcanic rocks, metasedimentary rocks mainly conglomerates, and minor granitoids (McCourt and Ibrahim, 1989). The Precambrian rocks suffered an extensive erosional phase at the Ram unconformity; that is before the deposition of the overlying Paleozoic sandstones. Consequently, the surface of the basement at the Ram unconformity consists of varying types of rocks such as the metamorphic rocks, granitoids, volcanics, conglomerates and sandstones, depending on the depth of erosion.

The exposed surface of the Precambrian basement in the south dips around 5° to the SE, E, NE and N directions, disappears and becomes deeper into the subsurface below the Phanerozoic sedimentary cover away from the outcrops

(Fig. 2). Within the Azraq basin, no deep borehole penetrated the basement except the Safra well-1 (SA-1), nearby Qasr Al-Kharraneh, few 10s of kilometers west of Azraq oasis, total depth is 2582.0 and of granite basement (Andrews, 1991). The Safra-1 well is situated at the western borders of the basin. It is an old well drilled in 1957 in upfaulted block (Safra fault) or an anticlinal structure according to Bender (1974). Consequently, its total depth to the basement is much shallower than the boreholes nearer to the centre of the basin such as Hamza oil field where the total depth of Hamza-4. For example, reached 3984.0 without reaching the basement. Thus, the depth to the basement in the Hamza Graben is in excess of 5.5 km becoming shallower away from the graben.

## 4. PALEOZOIC SEQUENCE

### 4.1 The exposed Paleozoic of Jordan

The Paleozoic sequence crops out nicely in south Jordan and along the eastern shoulders of Wadi Araba up to the southeastern tip of the Dead Sea (Fig. 2). Contrary to this, all the Paleozoic rocks are deeply buried in the Azraq basin, and the following description is taken from the deep boreholes drilled during the chase for oil and gas, especially in the Hamza oil field drilled by the Natural Resources Authority (NRA). Geologists have subdivided the exposed Paleozoic sequence of Jordan into groups and formations shown in Table 1 (e.g. Bender, 1974; Powell, 1989a). The exposed Paleozoic rocks represent the lower Paleozoic only; i.e. The Cambrian, Ordovician and lower Silurian Periods, from 541-441 Ma, and a small section of the upper Permian. In other words, the lower 100 Ma out of 290 Ma making the whole Paleozoic Era, are present in Jordan. This point is discussed below.

The exposed rocks are briefly described in the following two paragraphs. It should be mentioned, first, that the whole sequence is divided into two groups: Lower (older) called the Ram Group and upper (younger) called the Khreim Group.

#### 4.1.1 Ram Group

The lower half of the Paleozoic rocks in Jordan consists of sandstone types varying in colour, mineralogy, sedimentary structures, hardness and the like. Collectively, the whole sequence is called Ram Group because these sandstones are the back bone of the Ram area. These sandstones are ~ 1000 m thick and are divided into four rock units (formations); from older to younger: Saleb, Umm Ishrin, Disi and Umm Sahm Formations (Table 1) and Fig. 3.

**Saleb Formation** is lower Cambrian in age, overlies the Precambrian basement, consists of yellowish, arkosic sandstone (quartz plus minor feldspar), and 60 m thick in Ram area and exceeds 200 m in the Dead Sea basin. It is of braided rivers origin.

**Umm Ishrin Formation** is of late Cambrian, overlies Saleb Formation, consists of quartz sandstone, and is about 300 m thick. It is characterized by its reddish brown colour due to hematite cements, long vertical joints and consequently columns, and long vertical cliffs in excess of 300 m. Umm Ishrin is certainly the single-most beauty element in Ram and Petra. It is of braided rivers origin.

**Disi Formation** is of early Ordovician, overlies Umm Ishrin formation, and consists of around 300 m thick white quartz sandstone. Pure silica (SiO<sub>2</sub>) can reach 99%, mainly as quartz. This is the glass sand of Jordan. Weathering produces dome-shaped attractive features. Trace fossils such as *Cruziana* are abundant in the few meters thick marine shale horizon in its upper part, otherwise, it is of braided rivers origin.

العمر	التكوين	مجموعة								
Age	Formation	Group								
سيلوري Silurian	أصبحت ضمن السعودية	خريم KHREIM								
	الخشة Khushsha									
	لاندوفري Llandovrian									
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المُدوّرة	رأطية	Ratia								
طبيقات	الترا	Batra								
طبقات	Ammar glacials	Mudawwana								
أوردوڤيشي Ordovician	اشغليي Ashgillian	رم Ram								
	كارادوسي Caradocian									
	لاندليي Llandelian									
	لانڤرنليي Llanvirnian									
	أرينيجي Arenigian									
أوردوڤيشي Ordovician	أم سحم Umm Sahn	رم Ram								
	تريمادوسي Tremadocian									
كمبري Cambrian	أم عشرين Umm Ishrin	رم Ram								
	أبو حشيبية Abu Hhusheiba									
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	البرج		طيان	Tayyan						
حثة	نمبرة	Numeira								
	حثة	Hanneh								
سلب Saleb										
ما قبل الكمبري Precambrian	صخور القاعدة Basement rocks	رم Ram								

Table 1: Nomenclature of the Paleozoic rock units in south Jordan and Wadi Araba Dead Sea.

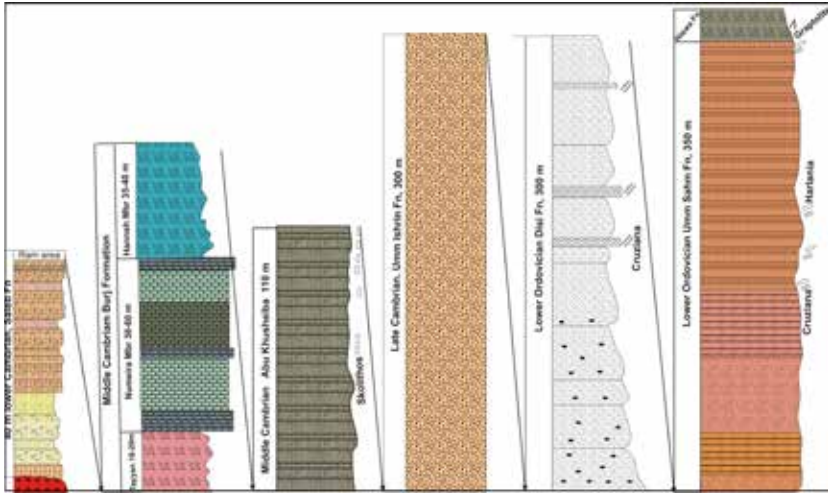


Figure 3: Lithology of the formations making the Ram Group

**Umm Sahm Formation** is the uppermost formation in this sandstone group. It is a 350 m thick, early Ordovician, reddish and indurated, cliff-making quartz sandstone and of transitional marine environment with the indicative fossils and trace fossils.

This is the story in the Ram area. However, two more rock units are added in central and north Wadi Araba and the Dead Sea basin, namely the marine **Burj formation** which consists mainly of carbonates and abundant fossils and their traces, and **Abu Khusheiba Formation** which is made of marine, white, fine quartz sandstone and vertical burrows, *Skolithos* indicating a tidal marine environment. Both formations are present between Saleb and Umm Ishrin formations (Table 1).

#### 4.1.2 Khreim Group

The Khreim Group overlies the Ram Group and consists mainly of shale, but the sandstone rocks are still important. The group is almost completely of marine deposition with fossils such as Graptolites, Brachiopods, *Conularia* and trace fossils such as; *Skolithos* and *Cruziana*. It is subdivided into four formations; they are from older to younger: Hiswa, Dubaydib, Mudawwara and Khushsha. The total thickness of the group is in excess of 550 m. See Table 1 and Fig. 4 where the formations and their ages are shown.

The **Hiswa Formation** consists of 80 m thick offshore marine shale becoming more sandy and shallower upwards, it is of middle Ordovician age. The **Dubaydib Formation** is around 130 m in thickness of alternating

sandstone and greenish shale with *Skolithos* burrows especially in the sandstone. It is of middle Ordovician. **Mudawwara Formation** is around 220 m thick similar in lithology with the underlying Dubaydib Formation, except for its middle part (**Batra Member**) where an 80 m thick, offshore marine shale with Graptolite is present. **The Khushsha Formation** is the uppermost unit of the Khreim with a lithology similar to upper part of the Mudawwara Formation.

## 4.2 Paleozoic in the Azraq basin subsurface

No Paleozoic rock is cropping out in the Azraq basin. They are deeply buried in the subsurface. Thus, these rocks are studied from the boreholes drilled in the basin, especially within the Hamza oil field in the eastern part of the basin. In general, the exposed Paleozoic succession in the south, described above, is also present in the subsurface of the Azraq basin. However, two main points should be mentioned. First, the thickness of the formations increases in a northeastern direction compared with the outcrops in the south. Second, there is a systematic omission of Paleozoic strata in a westward direction. Both points are discussed below.

The total thickness of the exposed sequence in the south is ~1550 m, including all the cropping out formations from the base of Saleb Formation of the Ram Group to the top of the Khushsha Formation of the Khreim Group. This is lower than the total thickness of the same sequence in the Azraq basin, but this depends on the position within the basin where this is not the case. One of the major reasons for the changes in total thickness of the Paleozoic is the systematic omission or erosion of formation during the Hercynian Orogeny which took place during the Middle Carboniferous, discussed below.

### 4.2.1 Hercynian Orogeny

A major tectonic event seems to have occurred, most probably, during the Middle Carboniferous throughout Belad Ash Sham and its surroundings (**Gvirtzman and Weissbrod, 1984**). A major geanticline was formed in the area where its maximum uplift and curvature was near Gaza and northern Sinai. The Paleozoic strata older than the event (Carboniferous), i.e. Cambrian, Ordovician, Silurian and Devonian became accordingly emerged and dip away from the apex of the geanticline. Thus, the more distance from the apex to the east and southeast, the lower the strata became. Consequently, erosion and removal of the preexisting formation was less severe towards the east and south east. For this reason, more Paleozoic material was preserved in Tabouk and Aleppo compared with Jordan.



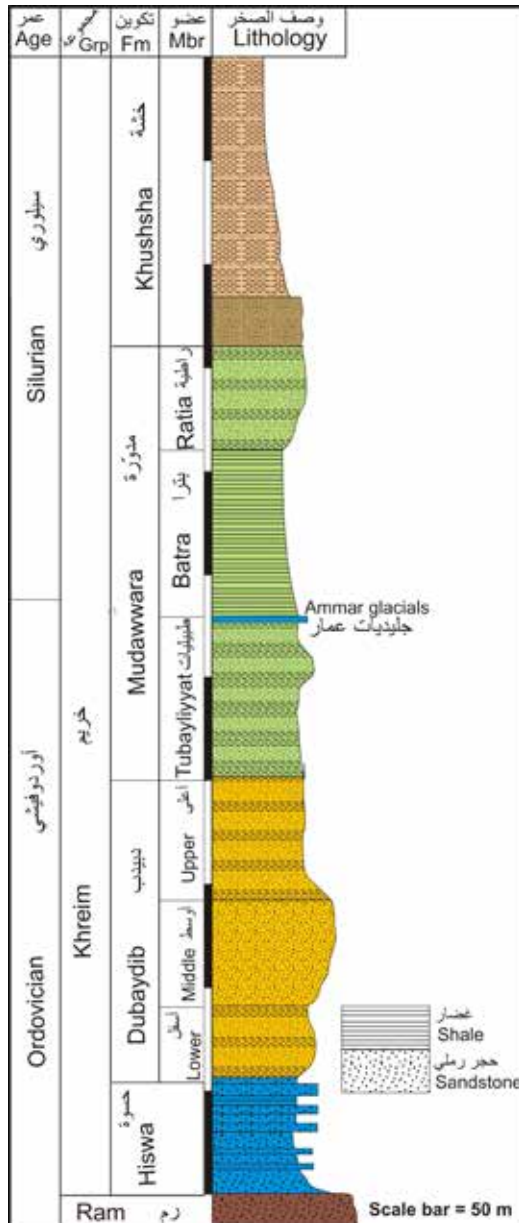
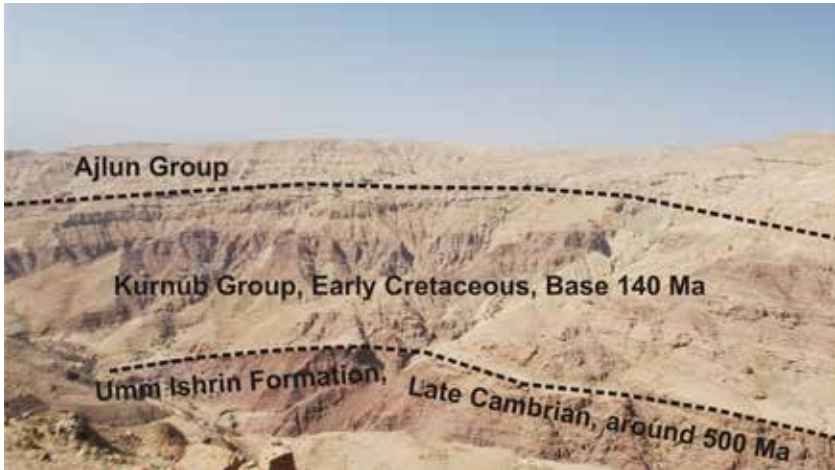


Figure 4: Columnar section for the formations making the Khreim Group In the outcrops.



**Figure 5:** Field photo from Wadi Karak showing the unconformity between Umm Ishrin Formation overlain by the Early Cretaceous Kurnub Group.

In Jordan, erosion and omission of the Paleozoic formations is greatest in the west throughout the outcrops along Wadi Araba-Dead Sea coast. For example, the outcrops at Wadi Al-Karak till Wadi Al-Mujib preserve only the Cambrian formations: Saleb, Burj and Umm Ishrin, while the rest of the Ram Group and all the Khreim Group were removed by erosion (Fig. 5).

Nothing like such outcrops can be seen to the east throughout the Jordanian plateau, and the deep oil wells are used to show the extent of the Hercynian Orogeny on Paleozoic formations. More than 100 boreholes (Fig. 6), mostly by the NRA during the 1980s - early 1990s, were employed by Andrews (1991) and his colleagues to study this phenomenon in the subsurface of Jordan. Their effort produced Fig. 7 which shows the distribution of the Paleozoic formation throughout Jordan. It clearly shows, despite being an approximation, that the more and more formations have escaped erosion exists in an eastward direction. On the map Fig. 7, the area where the name of the formation is written indicates its presence in part, in the subsurface under that area and further east, but it is not present (eroded) west of that.

For example, in the western parts of the Azraq basin, Safra well (SA-1), the Khreim Group is completely removed, in addition to the upper parts of Ram Group (Umm Sahm and most of Umm Ishrin where only 40 m exist) (Fig. 6). The total thickness of the Paleozoic in this well is 280m only. In the eastern parts of the basin, such as the Dahikiyeh area and east of the Fuluk fault, removed material includes the upper Mudawwara Formation (Batra and Ratia Members) as well as all overlying strata.

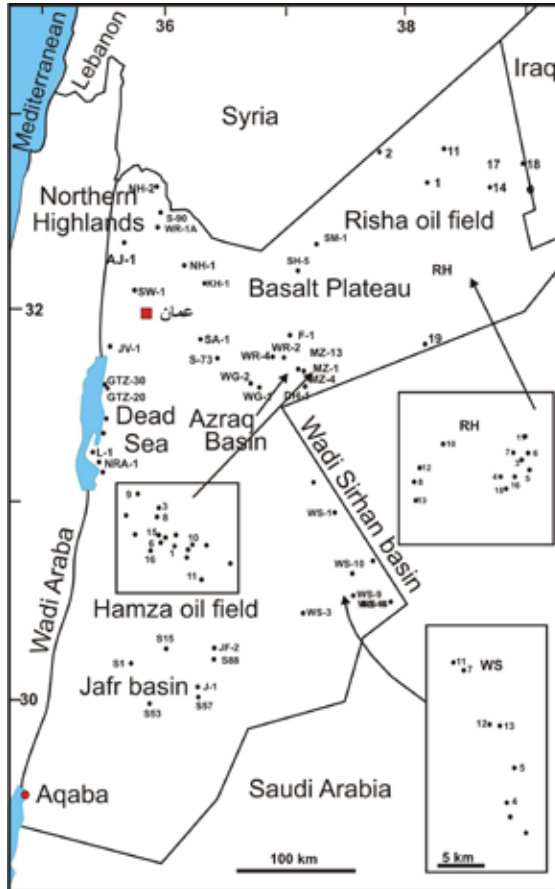
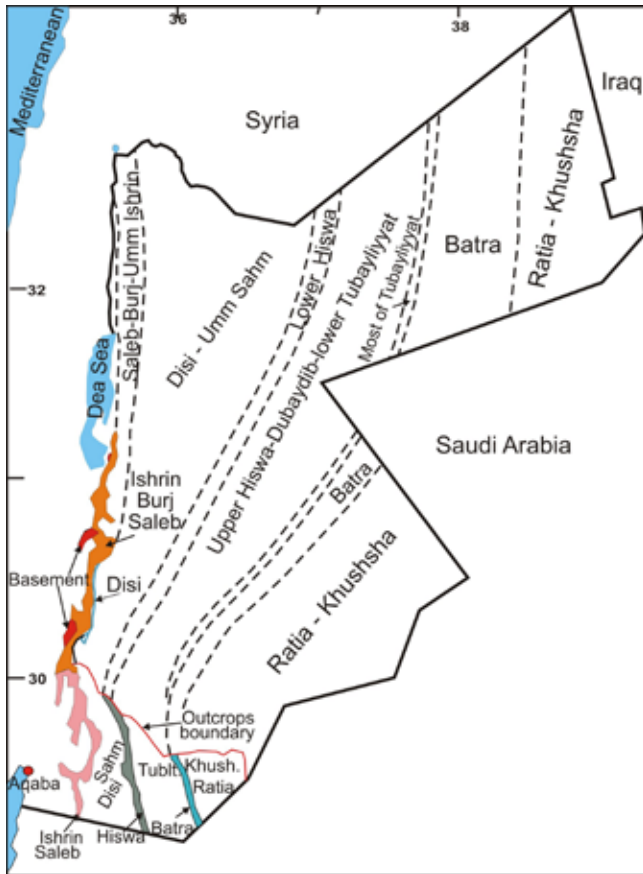


Figure 6: Shows the location of the oil wells drilled in Jordan

#### 4.2.2 Formations details

Starting with the **Ram Group**, and despite more than 25 wells were drilled in the Azraq basin, two wells only penetrated the whole succession down to the **Saleb Formation**. They are Safra well (SA-1) and Wadi Ghadaf-2 well (WG-2). Well WG-2 did not reach the Precambrian basement and the Saleb Formation was not fully penetrated. However, the penetrated thickness was 115.0 and 70+ m in SA-1 and WG-2 respectively (Andrews, 1991). It consists of arkosic sandstones with some pebbly horizons deposited in a continental environment by braided rivers similar to what has been mentioned in the outcrops, possibly with less pebbles due to being distal compared with the southern outcrops.



**Figure 7:** Distribution of the Paleozoic formations in the in the subsurface and the outcrops (south of the red line) (Modified after Andrews, 1991).

**Andrews (1991)**, in his isopach map for the Saleb Formation, indicated that the total thickness of the Saleb Formation in the Azraq basin should be more than 750m. This is based on the finding of such thickness in boreholes in nearby basin, e.g. Wadi Sirhan well-3 (WS-3) =750m, Sweileh-1 (SW-1)=931.0m, Northern Highlands-1 (NH-1)=531.0m, Hammar well-1 (HM-1)=1100m and GTZ-3D Dead Sea coast=401.5+. Some of these boreholes were studied by **Amireh and Abed (2000)** and **Amireh et al., (2008)** in cores and cuttings to develop criteria to distinguish the Saleb Formation from the underlying Umm Ghadah Formation (UGF). The latter formation is of Ediacaran age (Late Precambrian). Petrographically, UGF is distinguished from the Saleb by having abundant rhyolite lithic fragments compared with more feldspar in Saleb Formation. It was easily proved that the lower

parts of most of these well consist of UGF while the upper part is Saleb. For example, in WS-1 the lower 327m belongs to UGF, HM-1 the lower 475m belongs to UGF. Consequently, the 750m thickness of Saleb Formation in the Azraq basin, according to **Andrews (1991)**, cannot be accepted. However, the thickness of Saleb in SA-1 is twice as much as in the southern outcrops, but it is only half the thickness in the Dead Sea basin (**Powell, 1989a**).

The **Burj Formation** is of lower middle Cambrian age; it overlies the Saleb Formation of the lower Cambrian. The Burj Formation is fully marine where it was deposited in shallow marine environments with abundant fossils and trace fossils that can be seen in the wadis along the southern Dead Sea (**Amireh et al., 1994**). It was not deposited in southern Jordan, but starts from central wadi Araba in the outcrop and Jafr basin in the subsurface and continues northwards. The thickness of the Burj is almost uniform throughout the surface and the subsurface and varies within a small range from 100- 135m (SA-1, 135 m; WG-2, 118.3m; **Andrews, 1991**). Likewise, the **Umm Ishrin Formation** has a subsurface thickness in the Azraq basin (226m in WG-2) comparable with the southern outcrops (230-320 m) without great changes. The 40 m+ in SA-1 is due to truncation by the Hercynian Orogeny as discussed above. The lithology and depositional environments are essentially the same as those of the southern outcrops. **Disi and Umm Sahn Formations** are not easily separable in the subsurface. In the southern outcrops, both formations consist of quartz sandstones with varying degrees of cementation and induration as discussed above with a total thickness of both formation ranging 460-635 m (**Powell, 1989a; Andrews, 1991**). Total thickness of the two formations increases in a northeastern direction relative to the southern outcrops. The thickness almost doubled in the Azraq basin. This is indicated by the presence 1270m thickness in WG-2, the only borehole that penetrated the whole sequence. Similarly, WS-1 in Wadi Sirhan to the south the thickness reported is 1191m and 1204m in the Jafr basin JF-1. More fine materials are reported in the subsurface compared with the southern outcrops. However, the depositional environments are essentially similar. This is the end of the Ram Group.

The **Khreim Group** begins with the offshore marine shale of the **lower Hiswa Formation** with Graptolite. In the southern outcrops the thickness is 30 m becoming 100.0+ m in WG-2, 146.0 m in DH-1. No more wells penetrated this formation in the Azraq basin. The upper part in WG-2 was truncated at the Hercynian Orogeny keeping 100 m of the formation, while in DH-1 the formation is fully preserved because it is more to the east. The presence of the planktonic graptolites indicates an offshore marine environment rich in organic matter.

The overlying sedimentary interval includes **most of Hiswa + all Dubaydib formation + some parts of lower Tubeiliyat.**; that is essentially Dubaydib Formation of the middle Ordovician, but with some Late Ordovician. It was

named by **Andrews (1991)** in the subsurface Umm Tarifa Formation. This unit was penetrated by many wells in Wadi Sirhan and Risha area, but not in the Azraq basin. In the Azraq basin, it is eroded in SA-1 and WG-2, both being to the west. It is penetrated in two well in the Hamza oil field, MZ-4= 118.0+ m and MZ-13=69.0+ m. In both wells the upper part is eroded. In the Dahikiyeh well DH-1 further east, its thickness = 494.0+ m, the upper contact is eroded.

Two wells in Wadi Rajil, WR-2= 90.0+ m and WR-4=47.0+ m, both wells are truncated by the Hercynian Orogeny. For the location of the mentioned wells, see Fig. 6 above. To give an idea about the depositional thickness before erosion, this unit is 560m in JF- 1 to the southwest and 1114m in RH-3 (Risha area to the northeast). The Azraq basin is midway between the two basins, and the thickness in the Azraq basin might have been around 800 m before erosion. However, the preserved thickness after the Hercynian erosion in the Azraq basin increases eastwards towards the Dahikiyeh area from 47.0 m to 494 m. The age of this unit is Llandeilo-Caradoc-Ashgill (Middle to Late Ordovician). Lithologically, the complete well in the Risha and Sirhan basin shows that this formation consists of a lower silty unit, an interbedded unit of siltstone and sandstone, and an upper silty unit. Trace fossils are similar to the southern outcrops. The rest of the Khreim Group from the upper Tubeiliyat to the top Khushsha are all eroded in the Azraq basin and well not be discussed further. However, they can be studied in the Risha basin northeast of the Azraq basin to those who wanted to do so, see **Andrews (1991)**.

To conclude, the total thickness of the Ram Group in the southern outcrops is ~ 1000m becoming ~1750m in the Azraq subsurface. The preserved lower Khreim Group in the Azraq subsurface is ~640m compared with ~400m of the equivalent sequence in the southern outcrops. Consequently, there is an increase in the thickness of the Paleozoic rocks in the Azraq subsurface, which would indicate the presence of a basin during the Paleozoic similar to the Wadi Sirhan area.

## 5. TRIASSIC SEQUENCE

### 5.1 General

The Triassic Period is the 1st period in the Mesozoic Era following the Paleozoic Era. It extends from 250-203 Ma; that is 47 million years. In Jordan, the Triassic rocks crop out along the northeastern coasts of the Dead Sea, starting from Wadi Mujib northwards till north of Wadi Hisban (e.g. **Cox, 1923, 1925; Wagner, 1934**). Two separate outcrops are present in Wadi Al-Bahhath, to the west of Na'ur, and a 3rd isolated exposure of, the Late Triassic, is present at the Zarqa River, west of King Talal Dam or north of Al- Subeihi town. No Triassic rocks are exposed in any part of Jordan except those mentioned above in western Jordan (**Abed, 2017; Bender, 1974; Bandel and Khouri, 1981; Powell, 1989b**).

The Exposed Triassic rocks mentioned above are called collectively the **Zarqa Ma'in Group**. The Triassic sequence along the Dead Sea coasts was subjected to erosion at the Early Cretaceous Kurnub Group unconformity. Thus, there is no complete Triassic succession within the outcrops along the NE Dead Sea. Erosion and removal of the Zarqa Ma'in Group increases southwards until the whole group disappears completely at Wadi Mujib. No Triassic rocks are present south of Wadi Mujib including all of central and southern Jordan (e.g. Makhoulf, 1987; Powell, 1989b; Andrews, 1992a). The absence of the Triassic rocks in most Jordan (central and south) is not all erosional, but it is depositional. There is an agreement among the workers in the geology of the area that the paleoshore lines of the Triassic was along Wadi Mujib; meaning that the Neo-Tethys Ocean shore line was at the Mujib during the Triassic and the rest of Jordan was emerged where Triassic sediments were not deposited (e.g. Bender, 1974). So, Triassic rocks were not originally deposited in central and south Jordan, but were deposited north of the shore line where marine environment was present (Fig. 8). The deposited sequence north of Mujib was later subjected to erosion and removal at the Early Cretaceous Kurnub unconformity.

### 5.2 Subsurface Triassic in the Azraq basin

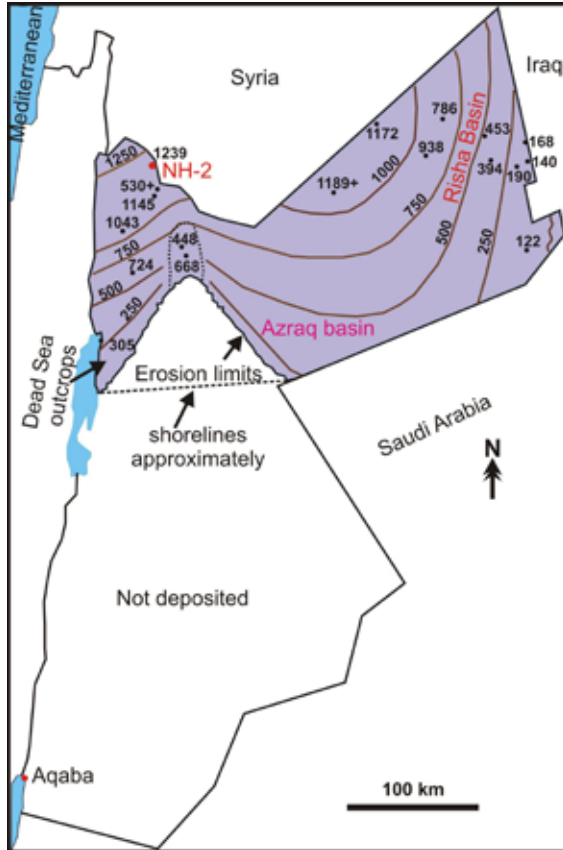
From the foregoing, it is clear that the Triassic rocks were deposited in north Jordan, north of the Triassic shore line extending, approximately, from the Mujib to the Azraq basin. These rocks were partially or completely removed in north Jordan during the Early Cretaceous (Fig. 8).

It is said previously that the exposed Triassic rocks are collectively grouped as Zarqa Ma'in, but Andrews (1992a) gave it a new name called the **Ramtha Group**. He also gave new names for the subsurface formations. In this article the former name is kept throughout.

Fig. 8 shows that the Triassic deposits are thickest in the Northern Highland well NH-2 near Ramtha city, where 1239m compared with a total thickness of around 300 m in the Dead Sea outcrops. These deposits were penetrated in more than 36 wells indicating, as shown in the isopach map, that the total thickness of the Zarqa Ma'in Group is thinning towards the ESE.

In the Azraq basin, Triassic rocks were penetrated in many wells, especially in the Hamza oil field, many are closely spaced. However, 7 wells only penetrated the whole Triassic sequence. These are:

DH-1	269.0m	Dahikiyeh
F-1	443.0m	Fuluk Fault area
MZ-4	295.0m	Hamza, 14m dolerite
MZ-13	265.5m	Hamza
WH-1	310.0m	Wadi Hazim
WR-2	339.0m	Wadi Rajel
WR-4	285.5m	Wadi Rajel



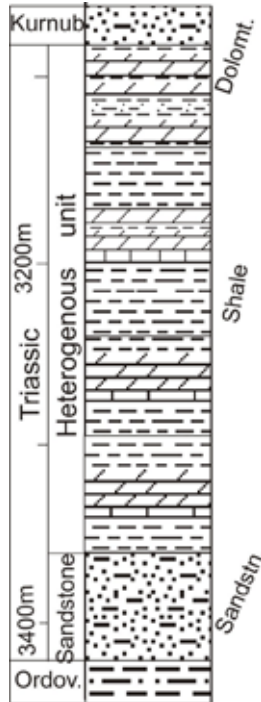
**Figure 8:** Isopach map of the Triassic rocks in Jordan both surface and subsurface (Modified after Andrews, 1992a).

The total thickness of the whole Triassic sequence in the Azraq basin ranges between 265-443m. This is far below the thickness in NH-2. Thus, it was not possible to differentiate the sequence into formations. It can be divided into two facies (Fig. 9).

- A sandstone facies at the base of the sequence: colorless to pale-grey made of coarse to fine-grained sandstone. Some thin streaks of dark grey silty shale are scattered in the sandstone. Some glauconite is also seen,
- An interbedded dolomite-shale-sandstone unit overlies the previous facies up to the top of the sequence. Dolomite beds can reach 7 m in thickness. A typical facies is the dolomitized bioclast grainstone. Shale beds are grey to black Limestone is rare.



The age of the sequence in DH-1, MZ-4 and WR-2 is Carnian (Late Triassic), while in WR-4 it is Mid-Late Triassic (Core Lab, 1987). These facies seem to have been deposited in a slightly restricted, shallow marine shelf (intertidal-subtidal). The bioclasts, oolite and coated grains indicate a high energy regime while the shale might indicate a calm subtidal environment.



**Figure 9:** Triassic sequence in well WR-2 (Wadi Rajel) in the subsurface of the Azraq basin (After Andrews 1992)

It should be emphasized that the Triassic rocks in the Azraq basin are overlain by the Early Cretaceous Kurnub Group sandstone. Also, No Permian rocks are present in the Azraq basin. They were not deposited there.

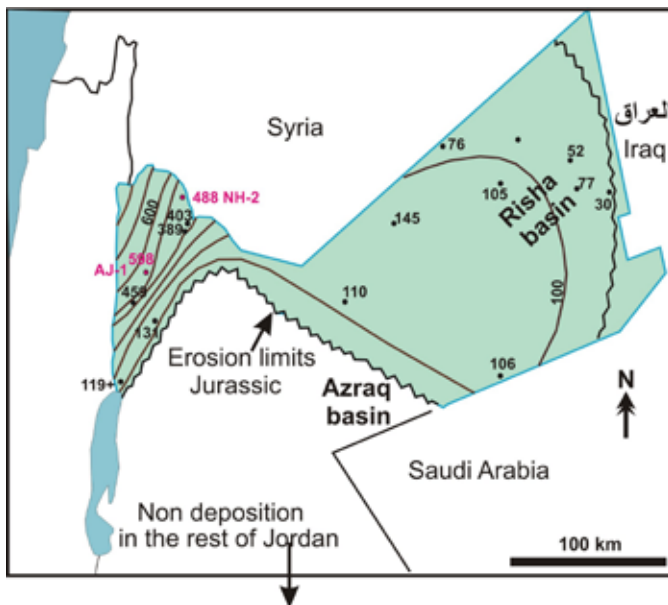
## 6. THE JURASSIC PERIOD

The Jurassic represents the 2<sup>nd</sup> period of the Mesozoic Era which extends 203-140 MA; a duration of 63 million years. It is widely distributing in the surrounding countries and it is a major source rock for oil in the Arabian Gulf and Iraq. In Jordan, however, it is restricted to northern Jordan from its shore line passing roughly from Amman eastwards and southwestwards. The outcrops are present near Mahis, Baqa', west of As-Salt, A'rda, and Zarqa

River (Bender, 1974; Abed, 1987; Powell, 1989b). They are designated **Azab Group** and also in the subsurface. Total thickness in the outcrops is 400 m, while in the subsurface in Ajlun well (AJ-1) it is 598 m and NH-2 = 488m. Thus, the Jurassic basin centre is to the northwest of Jordan because it is much thicker in the adjacent countries. It thins towards the east and southeast to few 10s of metres (Fig. 10). It consists of alternating horizons of carbonates and siliciclastics with abundant fossils and trace fossils as well as primary sedimentary structures indicative of the shallow marine depositional environments. Unfortunately, the Jurassic Period has no rocks deposited in the Azraq basin, simply because the Azraq basin was above sea level at that time; i.e. within the land and not the sea as shown in Fig. 10. The Triassic rocks in the Azraq basin are overlain by the Early Cretaceous Kurnub sandstones with no Jurassic rocks intervening.

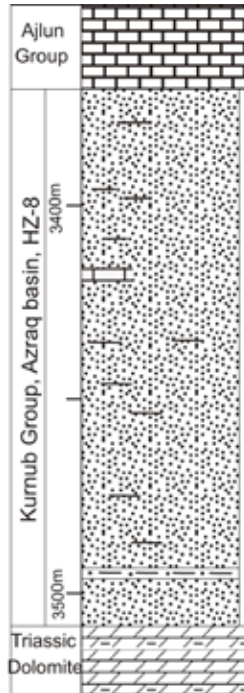
## 7. KURNUB GROUP, EARLY CRETACEOUS

The Kurnub Group is of Early Cretaceous age (~140-98 Ma); a duration of around 40 million years. Kurnub is an Arabic word for the Kurnub structure in eastern Nagab (Negev) in Palestine and was introduced to the geology of Jordan by Quennell (1951). The group consists essentially of friable, fluvial quartz sandstones throughout Jordan, except for some shallow marine



**Figure 10:** Isopach map for thickness distribution of the Jurassic rocks in Jordan (Modified after Andrews, 1992a)

interbeds in northwestern Jordan. It crops out in many parts of Jordan, in particular, the deep wadis crossing the mountain range to the Rift valley in the west. It is characterized by its massive, white sandstone at the base and varicolored sandstone in the upper part. The Kurnub Group thickness varies up to 350m to the NW of Amman. It thins to the east and SE becoming absent in the extreme SE (e.g. Bender, 1974; Amireh, 1999; Amireh and Abed, 1999; Powell, 1989b). This is all from the exposed deposits.



**Figure 11:** Columnar section in the Kurnub Group in HZ-8, Hamza oil field in the Azraq basin, dominantly sandstones.

### 7.1 Subsurface of the Azraq basin

In the Azraq basin, the sandy facies has previously been partly interpreted as to the Azab Group Jurassic), but it is reinterpreted as a Kurnub succession with rare reworked Jurassic microfossil (Core Lab, 1987; Andrews, 1992); e.g. Hamza-well-8. The Kurnub sandstone consists of white and light grey, friable, porous, fine- to coarse-grained sandstone interbedded with grey-green siltstone and shale and thin streaks of limestone (Fig. 11). It overlies the Triassic sequence and is overlain by the limestones of the Ajlun Group of the mid Cretaceous.

The Kurnub Group in the Azraq basin was penetrated in around 20 boreholes, where the thickness is much less than in western Jordan and has a range

120-180m compared up to 350m (Fig. 12). It thins further east in the Risha basin to 25-60m. Few microfossils were found in these boreholes indicating an Albian-Aptian age of the Early Cretaceous (Core Lab, 1987). The Kurnub sandstones were deposited by braided rivers grading upwards into meandering rivers. Sparse palynomorph microfauna suggest a basin wedge, intertidal-supratidal environments with a more marine influence in Wadi Hazim well WH-1 (Core Lab, 1987; Andrews, 1992a).

## 8. THE AJLUN GROUP, MID CRETACEOUS

### 8.1 General

The age of the Ajlun Group in the exposed rocks in Jordan is mid Cretaceous involving two stages: Cenomanian-Turonian; 100.5-89.8 Ma, a duration of ~11million years. The Mid Cretaceous was one the warmest periods in Earth's geological history where all the ice on Earth was melted and returned to the



**Figure 12** Distribution of thicknesses (isopach map) of the Kurnub Group throughout Jordan with the thicknesses in some borehole such as the Azraq basin (after Powell and Moh'd, 2011)

ocean as liquid water, the resultant was a global eustatic sea level rise 200-250m higher than today. Sea water transgressed and covered the continental margins with shallow epicontinental seas. Consequently, most of the eastern Mediterranean was submerged including almost all the Jordanian land. Thus, Jordan was covered with a warm, shallow continental shelf sea water where limestone and marl were the principle deposits with abundant fauna such Mollusca (Cephalopods, Gastropods, Bivalves), Echinoderms, Foraminifera, ostracods, and others (e.g. Wetzel and Morton, 1959; Bender, 1974; Powell, 1989b; Powell and Moh'd, 2011).

In Jordan, the exposed rocks of the Ajlun Group are in excess of 600m of marl and limestone. They are subdivided into five formations. They are from older to younger: Na'ur, Fuheis, Hummar Shueib, and Wadi Es Sir (Masri, 1963). See Fig. 13 and Table 2 for more details.

In general, the thickness of the group decreases southwards, sandstones increase and carbonates decrease until the group becomes made of sandstones and siliciclastics in Batn El Ghoul area some 70 km south of Ma'an. The group seems to have been deposited in a rimmed marine platform (Powell and Moh'd, 2011).

Wadi Es Sir Formation, called also A7, forms the lower part of the shallow Wadi Es Sir-Amman aquifer (A7-B2). It might have been a reservoir in the Hamza oil field, and it is a major source for building stones marl horizons, especially the Fuheis Formation marl, is used for the cement industry.

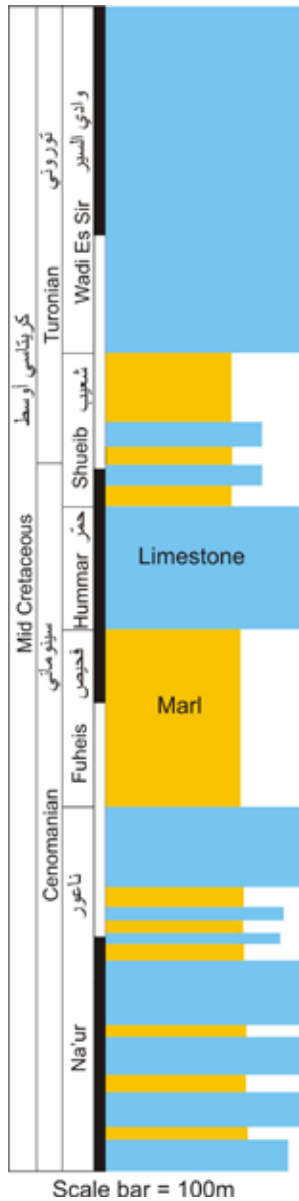
## 8.2 Ajlun Group in the Azraq basin

The Ajlun Group was deposited throughout Jordan except the extreme south and southeast as shown in Fig. 14. Many well were drilled in the Azraq basin in search for hydrocarbons, where the following brief description of the Ajlun Group in the subsurface is taken from.

The Ajlun Group in the Azraq subsurface is essentially similar to the outcrops in northern Jordan. The group in both areas consists of alternating horizons of limestone and marl/shale with abundant fossils as said above. The age of the group in Azraq is the same as in the outcrop; i.e. Cenomanian-Turonian of the Mid-Cretaceous, but, there are differences (Fig. 15).

a) The boundaries between the lower four formations are not as clear as in the outcrops in north Jordan. So, the lower sequence was divided into five informal units for the sake of correlation between wells. The Wadi Es Sir Formation is distinct.

b) The lower sequence ends by a sandstone horizon, not present in each and every well, but it is 12-24 m thick of fine-medium, glauconitic, argillaceous calcareous sandstone.



**Figure 13:** Generalized columnar section of the Ajlun Group from its exposed rocks showing the formations and their thicknesses in north Jordan.

c) At least one thick anhydrite horizon, up to 7 m thick, is present at the base of Wadi Es Sir Formation. other beds are also present. Which is not present in the outcrops.

d) Glauconitic dolomite is not uncommon in Wadi Es Sir Formation which is not the case in outcrops.

e) Furthermore, the equivalent of the Hummar and Shueib Formations have some horizons rich in organic matter, thought to be the source for the local oil in some wells.

f) Wadi Es Formation is capped by another sandstone horizon called Rajil Sandstone which is not the case in the outcrops in north and central Jordan where the same formation is overlain by chalk. The presence of this sandstone horizon is taken to indicate an unconformity between the Ajlun Group and the Belqa Group with some omitted material from the latter group. Similarly, there is an unconformity (disconformity) between both group in the outcrops (Core Lab, 1987; Powell, 1989b; Andrews, 1992b).

Age		Group	Formation	Member
Tertiary	Eocene	Belqa	Shallaleh	
			Umm Rijam Chert Limestone	
	Paleocene		Muwaqqar Chalk Marl (MCM)	
Maastrichtian	Al Hisa Phosphorite (AHP)		Qatrana Phosphorite	
			Bahiyya Coquina	
Campanian	Amman Silicified Limestone		Sultani Phosphorite	
Santonian		Ghudran	Dhiban Chalk	
Coniacian	Tafila			
	Mujib Chalk			
Late Cretaceous	Turonian	Ajlun	Wadi Es Sir	
	Cenomanian		Shueib	
			Hummar	
Fuheis				
Na'ur				
Early Cretaceous	Aptian-Albian		Kurnub (Hathira) Sandstone Group	

Table 2: Nomenclature of the Ajlun and Belqa Groups (El-Hiari, 1986; Powell, 1989b)

The thickness of the Ajlun Group is not constant in all wells. The thickness of lower part of the sequence up to the base of Wadi Es Sir has a range between 225-329m, it seems to increase westward. Wadi Es Sir Formation thickness varies between 85-290m, with a typical thickness in most wells 240-250m. Total thickness can slightly be more than 600m, which is comparable with the north Jordan outcrops.

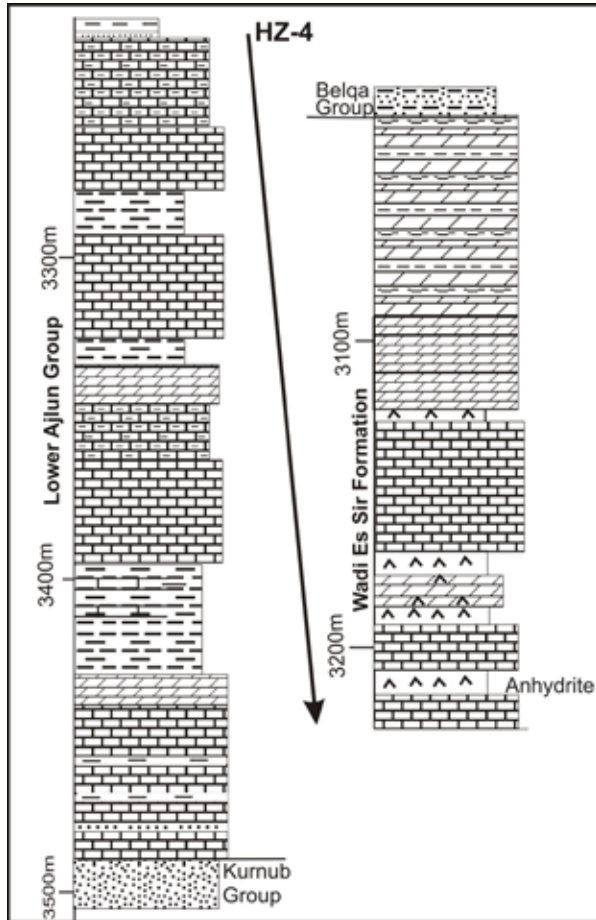
The depositional environments are comparable with the outcrops of being a rimmed platform with depositional environments varying from deep subtidal (open shelf) especially in the marl horizons, to intertidal-supratidal. The Anhydrite beds in Wadi Es Sir Formation is interpreted as a sabkha environment in the Azraq subsurface. A similar sabkha environment was described by Abed and El-Hiari (1986) extending from Wadi Mujib and



**Figure 14:** Isopach map showing the distribution of thicknesses for the Ajlun Group throughout Jordan in the surface and subsurface (After Powell and Moh'd, 2011)



further south, but it is gypsum not anhydrite. It is Turonian in age, that is possibly why it was considered as part of Wadi Es Sir Formation in the Azraq basin, because all Turonian rocks are added to the Wadi Es Sir Formation.



**Figure 15:** Hamza- 4 well log showing the lithology of the Azraq Group. Left, lower Ajlun Group up t the base of Wadi Es Sir Formation; right, Wadi Es Sir Formation (From Andrews, 1992b).

## 9. BELQA GROUP, LATE CRETACEOUS-PALEOGENE

### 9.1 Exposed formations

The Belqa Group is the last marine group which was deposited throughout Jordan from the Neo-Tethys Ocean. By its end at around the Late Eocene, the ocean migrated from the eastern Mediterranean and never back again. Since

then, Jordan became the scene for erosion and sporadic deposition in the low-lying areas such as the Rift valley and the Azraq basin.

The formations constituting the Belqa Group crop out in more than 60% of the country. These formations are from older to younger: Ghudran, Amman, Al-Hisa, Muwaqqar, Rijam and Shallaleh (Table 2 and Fig. 16). These formations consist of exotic (not common) rocks such as phosphate, bedded chert, porcellanite, and oil shale. Such rocks are believed to have been deposited from cold, upwelling currents flowing westwards along the southern shelves of the Neo-Tethys Ocean (e.g. Abed, 2013). The total thickness of the exposed Belqa Group is ~ 550m, but it varies considerably because of the highs and lows at the ocean floor during the time of deposition, because of the compression associated with the subduction then collision between the Arabian Plate and the Eurasian Plate (e.g. Powell and Moh'd, 2012; Abed, 2013; Abed et al., 2012, 2016). For example, the Muwaqqar Formation is in excess of 300m in the Yarmouk basin while it is around 100m in central Jordan (e.g. Yassini, 1979; Abed et al., 2005). Al-Hisa Formation (phosphate-bearing) is 65m and ~10m thick in Central Jordan and Al-Kora basin west of Irbid respectively (Abed and Sadaqah, 1998; Abed et al., 2016).

The Belqa Group is the source for economic deposits which are playing an important role in the development in Jordan. Most important among them are the phosphates, the oil shale, building stones, and pure carbonates.

### 9.2.1 Structural overview

The major factor affecting sedimentation the in Hamza oilfield and its vicinity is tectonics. Two faults were synsedimentary active during the Late cretaceous, Coniacian-Maastrichtian: the Fuluk Fault in the NE and Wadi Rajil Fault is the SW. They created the Hamza Graben (Fig. 17) where around 3000m of sediments were deposited. According to Core Lab (1987) interpretation, three structural units were formed in and outside the graben (Fig. 17):

- The Hamza Oilfield within the graben where the thickest sediment accumulation in the Late Cretaceous.
- Hamza High within the graben but shallower than the Hamza Oilfield. This is evident from the shallow water faunas, secondary dolomites and evaporites and, in some cases, thinning of section.
- Dahikiyeh-Wadi Al-Ghadaf Platform to the west and southwest of the graben and possibly extending southwestwards to Suwaqa Fault.

All these faults are trending NW and most probably they form part of the Wadi Sirhan Fault Zone.

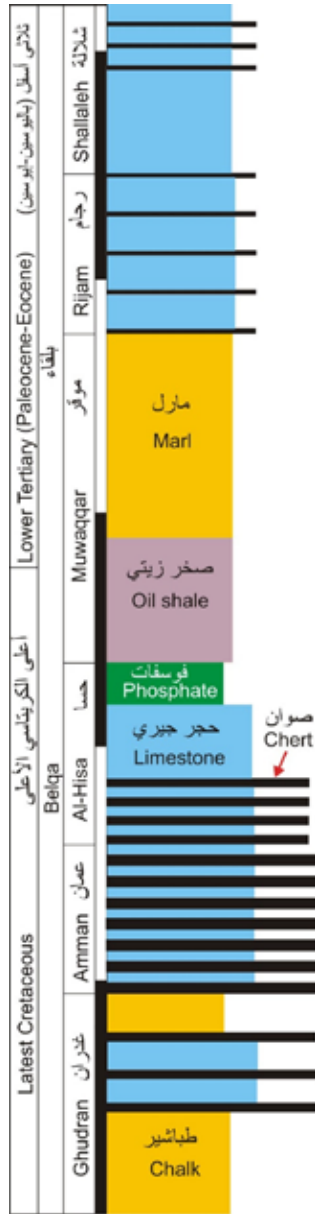
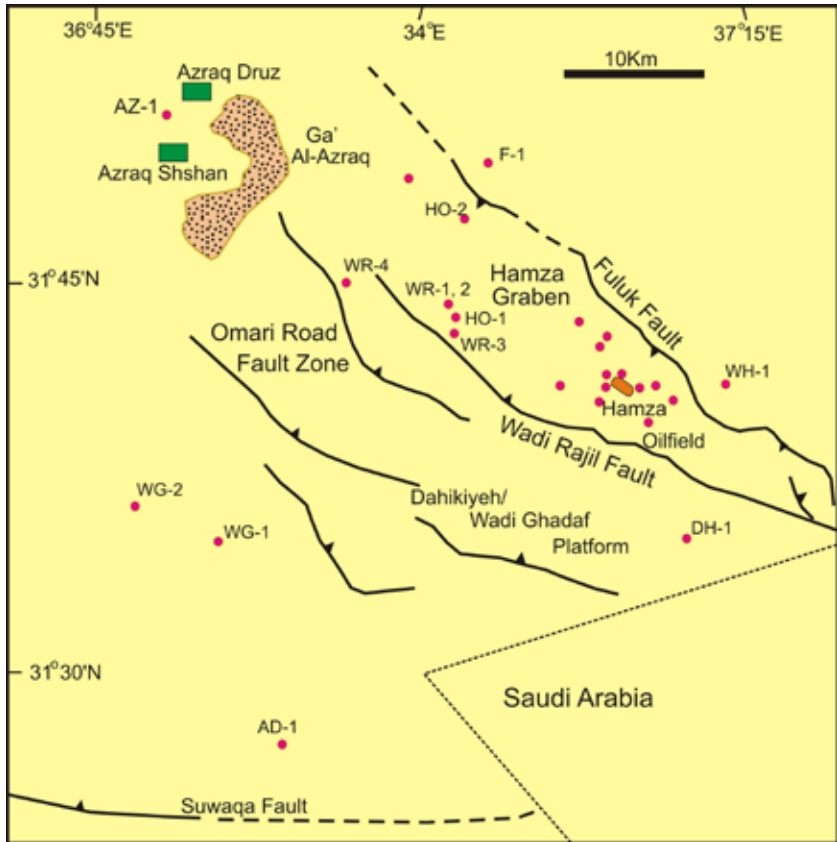


Figure 16: General composite columnar section for the Belqa Group in the outcrops



Figuer 17: General structural map of the Hamza area (Core Labe, 1987)

### 9.2.2 Belqa Group subsurface Stratigraphy

The lowermost part of the Belqa Group is supposed to start with the relatively thick chalk horizons of the Ghudran Formation, as it is the case in the outcrops. No chalk is present overlying the Ajlun Group and underlying the chert of the Amman Formation throughout the Hamza area. Instead three different facies are introduced here, all below the chert of the Amman formation. They are from older to younger.

**Rajil Formation** is the oldest formation, it overlies the limestone of the Wadi Es Sir Formation of the Ajlun Group and is well below the Amman Formation. In the Hamza Oilfield, it consists of a lower sandstone unit, mainly made of sandstone with minor interbedded claystone, chalky and dolomitic limestones. Thickness of the unit in HZ-2 is 158m. The upper unit, claystone-

limestone unit, consists of silty claystone, pyritic shale, chalky limestone and pyritic dolomitic limestone. Nodules of chert and lenses of anhydrite are present towards the unit base. Total thickness in HZ-2 is 260m. Maximum thickness of the Rajil Formation is 551m found in HZ-3 in the Hamza Oilfield. The sandstone content decreases northwards in the well HO-2, within the graben, (Fig. 17) has only 49m sandstone. Sandstone also decreases westward towards WR-4 where substantial sandstone is still present.

Total thickness of Rajil Formation is 419-566m in the Hamza Oilfield, becomes thinner in the Hamza High, and much thinner in the platform as in Dahikiyeh DH-1 181-299m. No fossils are found in the formation except the fresh-water algae *Characeae*, thus, the depositional environment is terrestrial, probably in deltas (Core Lab, 1987). Because Wadi Rajil Formation is well below the Amman formation, its age is most probably Coniacian? Santonian? up to Campanian? (See Andrews, 1992b). The Wadi Rajil Formation is not reported anywhere in Jordan except in the Hamza area.

**Hamza Formation** is present only in the graben and the platform, but not reported in the outcrops elsewhere in Jordan. It overlies Rajil Formation and consists mainly of dolomite, minor chalky limestone, sandy and sandstone towards its base, and abundant nodules of chert. Near the top of the formation, a zone 65-110m thick contains layers with residual oil and asphalt. It is thickest in the graben to 467-840m, with the greatest thickness northwards near the Fuluk Fault in HZ-4, 2, thins in the platform to 249-294m and absent NE of the Fuluk F-1. The high thickness of the Hamza Formation can be explained by the continuous subsidence during its time of deposition. No fossils are found within this formation, possibly due to dolomitization. The age is put as Santonian-Campanian.

**Hazim Formation** (after Wadi Al-Hazim) is also restricted to this part of the Azraq basin and is not reported anywhere in Jordan in the outcrops. The Hazim Formation Mainly of limestone variously argillaceous, marly, chalky, dolomitic, fossiliferous, pyritic and glauconitic. Anhydrite beds are present throughout, being up to 4m towards the top of the formation. HZ-14 has a 30m thick halite horizon. The uppermost 50m are highly variable with interbedded limestone, dolomite, marl and anhydrite. Its top ends where indurated limestone with chert begins (the Amman Formation).

The Hazim thickness is highest in the graben 413-608m nearby the Fuluk Fault, while in the platform it is thins to 155-255m. It is Absent NE of the Fuluk F-1. On the bases of not so much useful Ostracoda (*Bairdia sp.* and *Cytherella sp.*) and foraminifera (*Elphidium*), the Hazim Formation was given an Early Maastrichtian age (Al-Harithi et al., 1987). The above-mentioned fossils as well as presence of halite, anhydrite and anhydritic dolomite point out to a shallow, calm, marine lagoonal depositional environment.

The three discussed formations, Rajil, Hamza and Hazim, may be correlated in the outcrops by the disconformity above Wadi Es Sir Formation and the

Ghudran Formation. The remaining formations of the Belqa Group in the Azraq subsurface, Amman through Shallaleh (Table 2 and Fig. 13), retain their names and will be discussed briefly below.

**Amman and Al-Hisa Formations** are grouped together because of the difficulty to recognize the boundary between them in the surface and subsurface alike (e.g. Powell, 1989b; Abed and Sadaqah, 1998). The lower part, Amman formation, consists of predominant chert and minor chalk limestone. Anhydrite is also present in the lower part. Higher up, very high radioactivity was interpreted as due to the presence of phosphates/phosphatic chert in a horizon 1-15m thick. This is the principle zone where bitumen and asphalt are reported in the Hamza Oilfield such as HZ-13 with asphalt filling the fractures and cavities in a brecciated dolomite. Al-Hisa Formation consists of phosphatic and bituminous limestone with the chert being below (Fig. 19).

Due to inconsistency of defining the Amman/Al-Hisa in the subsurface, the reported thickness varied greatly. Core Lab (1987) added all strata belonging to the Campanian to Amman Formation and the resultant thickness was 1313m. This is too high compared with outcrops. On lithology and geophysical logging, Andrews (1992b) redefined the two formation despite their age in the wells on the basis of lithology and geophysics. Accordingly, the maximum thickness in Hamza Oilfield is 138.5m in HZ-11.

In the up thrown side of the Fuluk Fault, Al-Hisa is called Usaykhim Formation with sandy phosphatic facies with a maximum of 87m in Hazim well WH-1.

The age of both formations in the Azraq subsurface is most probably Maastrichtian (Dilley, 1985). Consequently, the age and thickness of both formations are comparable with the outcrops.

The **Muwaqqar Formation** is well-known in the outcrops, throughout Jordan, by being made of soft marl and oil shale. Andrews (1992b) used the same out crops terminology for the subsurface and made the Muwaqqar Formation equal to Ghareb, Taqiye and Sara Formations, frequently used in the NRA reports. The Muwaqqar in the Hamza Oilfield, as in HZ-2, consists of argillaceous, phosphatic, locally fossiliferous and partly marly limestones with rare chert nodules overlain by soft marl interbedded with partly fossiliferous, argillaceous or chalky limestones (Andrews, 1992b) (Fig. 19).

Accordingly, the total thickness of the formation in the Hamza Oilfield is 128.0 (AZ-1)-288.0 (HZ-4). This thickness is comparable to outcrops and there is no need for extensive subsidence envisaged by those who defined the Muwaqqar Formation according to age (Maastrichtian-Paleogene), where the total thickness reached 975 m, and explained that by continuous subsidence (Core Lab, 1987). Depositional environments are similar to the outcrops.

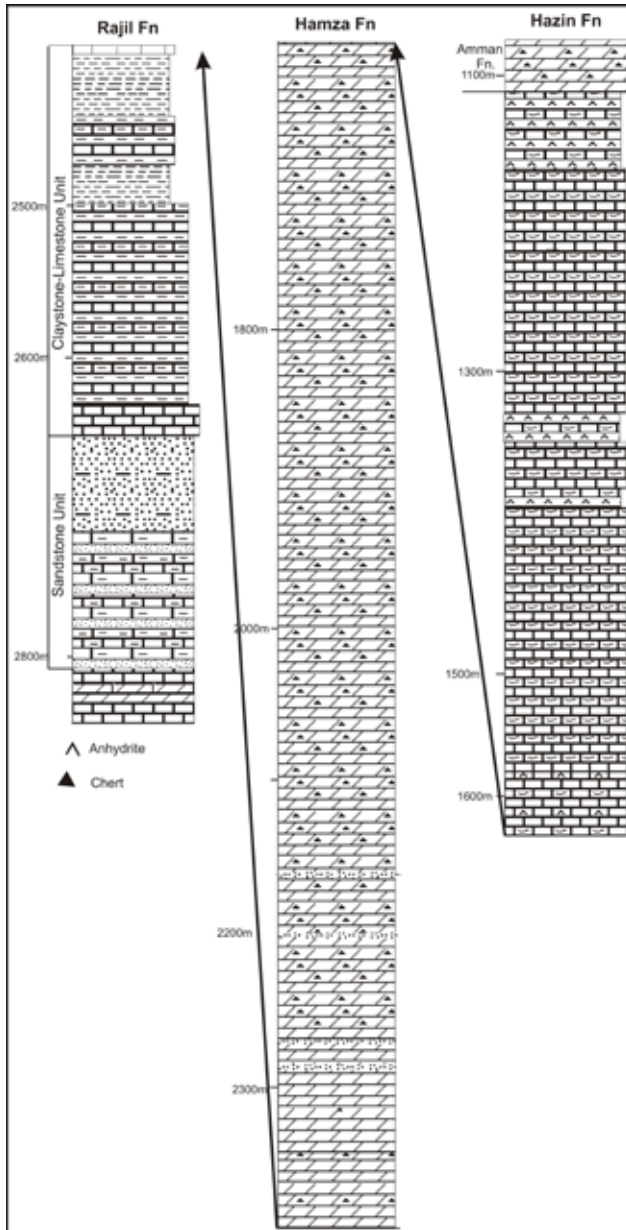


Figure 18: Columnar sections for the Rajil, Hamza and Hazin Formation at the base of the Belqa Group (Modified from Andrews, 1992b)

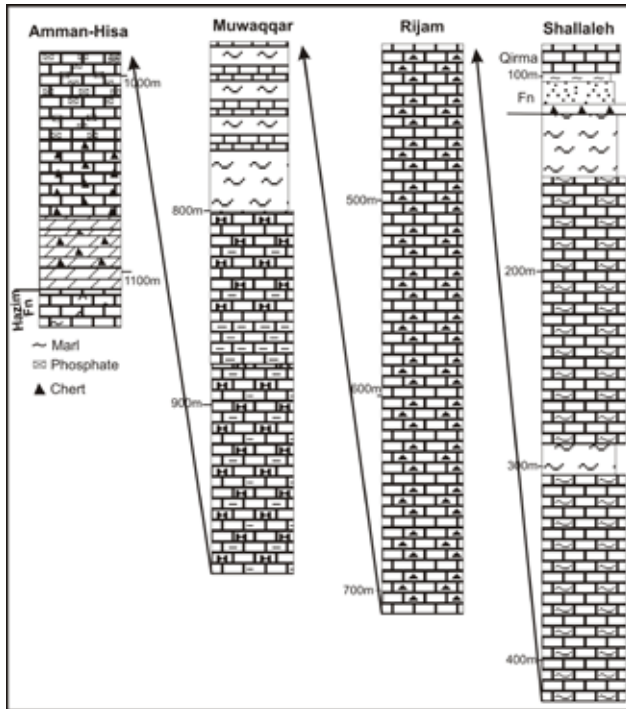


Figure 19: Well HZ-2 log showing the lithology of the Amman through Shallaleh Formations in the Azraq subsurface.

**Rijam Formation** crops out in many parts of the Azraq basin with a similar definition of the other outcrops in Jordan. It consists of bedded chert and limestone to marly limestone with some phosphate. There seems to be no differences in lithology between the outcrops and the Azraq subsurface. The thickness of Rijam Formation in the outcrop near Irbid is 220m, decreasing southwards. In the Azraq subsurface, it has a maximum of 311m in HZ-1 and early to middle Eocene age. Otherwise, it is similar to the outcrops.

**Shallaleh Formation** crops out mostly in eastern and northern Jordan as it is the case in the Azraq basin. The formation crops out at Faydat Al-Dahikiyeh area where it consists of 60-70m of marl and 30 m of limestone with chert concretions and marl. The marl contains bitumen, glauconite and phosphate (Bender, 1974). A sandstone horizon is present at its top in this area. In the subsurface of Hamza Oilfield, represented by well HZ-2, the formation consists of marly limestone and marl with chert concretions (Fig. 19). The thickness of the outcrops in the Azraq basin is around 55m where the base is not seen. However, in the Hamza Graben, the thickness increases towards the Fuluk Fault from 160m to 428m in well HZ-16. It is



given an age of early- to middle Eocene in the Azraq area (Core Lab, 1987). It was deposited in mid to outer shelf marine environment.

## 10. POST NEO-TETHYS DEPOSITS

The Neo-Tethys Ocean, which submerged Jordan during Late Cretaceous-Eocene, had migrated from the area during the Late Eocene or possibly the very Early Oligocene; i.e. at around 35 Ma ago. The migration was due to the compression and uplift of the area caused by subduction and later the collision of the Afro-Arabian Plate with the Eurasian Plate, through the continuous northward movement of the former plate (e.g. Abed, 2013 and the references therein). Consequently, Jordan became almost completely emerged and subjected to erosion of the previously deposited Belqa Group. Deposition was restricted to low-lying areas such as the Rift valley in the west and the Jafr, Azraq basin and the like in the east. Known deposits in the Azraq basin are described below.

### 10.1 Qirma Formation

The name is after Tell Qirma to the southeast of the Azraq towns. The formation consists, mainly, of quartz sandstone sometimes burrowed, but micritic limestone and dolomite with algal mud cracks are also reported (Ibrahim, 1996). See Fig. 20 for full description of the Formation. The thickness of the formation is 38-44m in the outcrop, but reaches 211m in the Hamza Oilfield. Its base is the unconformity with the basalt of the Wisad Group and its top is also the unconformity with the basalt of the Safawi Group.

The age of the Qirma is Miocene (Tutonian), according to the presence of the *Discerbinella montereyensis* and *Valuylineria casitasensis* described by Baker and Harza (1958) in water wells in the basin. The Miocene age is also confirmed by the absolute age dating of the underlying Wisad basalt at 13 Ma while the overlying Safawi basalt is 8 Ma. The Qirma Formation, most probably, was deposited from a brackish lake, despite some advocating marine origin.

### 10.2 Azraq Formation

The Azraq Formation crops out around the Azraq towns and continues south and east up till the Saudi borders. It consists of soft, gently sloping sediments which does allow the exposure of the whole thickness of the formation. Furthermore, varying lithologies were described from different parts of the basin. For example, the rocks present in the Umari area are, sandstone, conglomerates, limestone with abundant fossils (Figs. 21, 22), Fig. 23 shows the columnar section in Umari area. In other localities, limestone, gypsum beds, gypcrete, gypsiferous marl and rare halite are present.

At the oasis, boreholes were drilled for bentonite exploration by the NRA to a depth of 80m. The following description is taken from Alali and Abu Salah (1993) and Ibrahim (1996).

- Gypsiferous clays and clay layers (a few meters thick in the upper parts of some boreholes).

- Gray, white dolomite and dolomitic limestone (less than 2 m thick) (in few boreholes).
- Brown to green, yellowish brown, gray to light gray clay layers (14 to 30 m thick), occasionally silty, gypsiferous, calcareous and diatomaceous.
- Gray to dark green diatomaceous clay, soft and massive (4.5-31 m thick) (in two levels).
- Gypsum layers as intercalations with gypsiferous clays and clay layers (a few meters thick in the upper parts of some boreholes).
- Loose sand, silt and gravel intercalations.
- Whitish gray to white sandstone beds, calcareous-cemented, intercalated within clay layers.
- Basalt flows and tuft layers occur within clay layers (found in three boreholes in Al Bayda area).

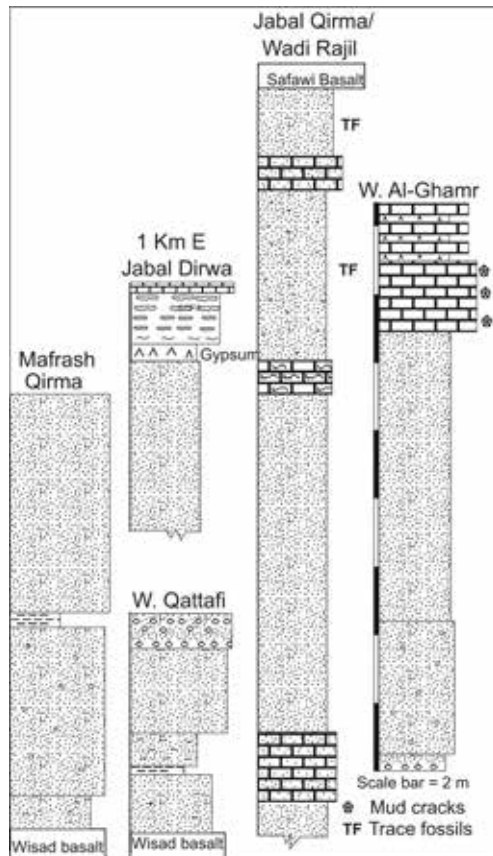
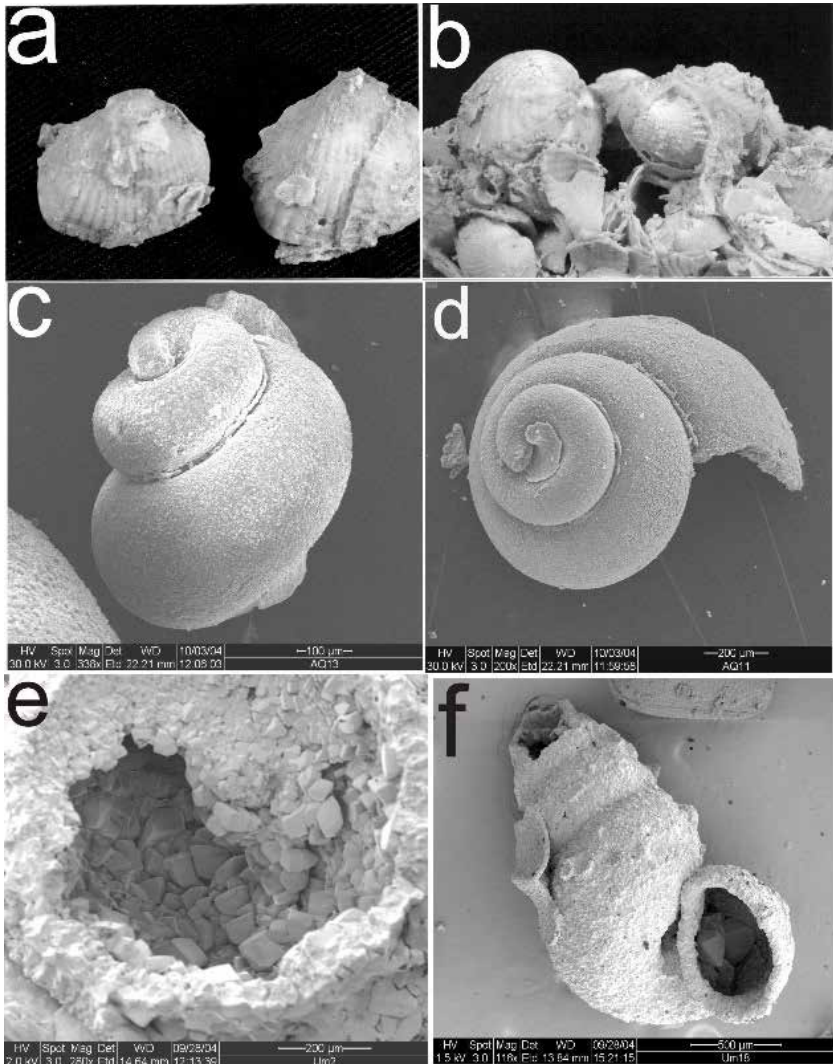
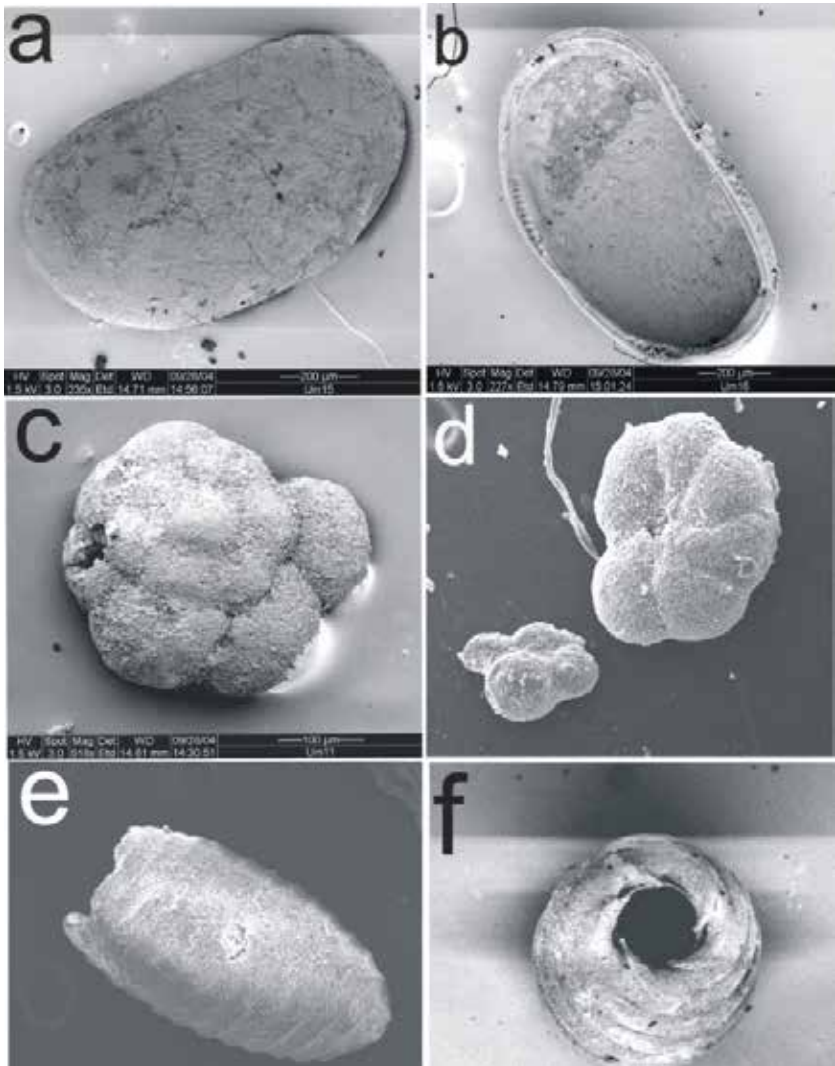


Figure 20: Sections in Qirma Formation (Ibrahim, 1996)



**Figure 21:** Mulluscan fossils from the Umari area. a. *Cardium* shell from Azraq. b. *Cardium* shell from Al Umari. c. *Bythinia* sp. d. *Gyraulus* sp. e. Highly diagenetic gastropod shell. f. *Hydrobia* sp. (Abed et al., 2008)



**Figure 22:** Ostracods and Charophyte fossils. a. *Cyprideis torosa* gr., smooth and sieve like, exterior right valve. b. *Cyprideis torosa* gr. exterior left valve. c. *Ammonia beccarii tepida* ventral view. d. *Ammonia beccarii tepida* dorsal view. e. Charophyte gyrogonite of *Croftiella cf. escheri*. f. Charophyte top view (Abed et al., 2008).

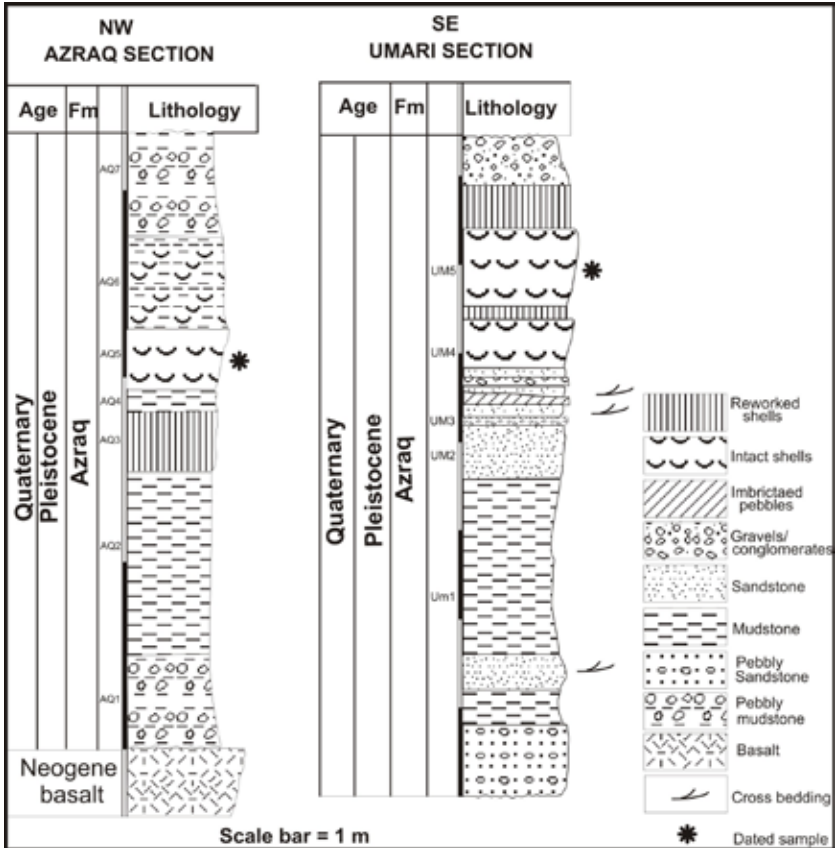


Figure 23: Two columnar sections showing the lithology of the Azraq and Umari sites where fossils were found (Abed et al., 2008).

Total thickness in the outcrops is around 15m, while in the boreholes in the centre of Qa' Al-Azraq it is 80m (Ibrahim, 1996). The age of the formation is certainly Pleistocene, not Pliocene, as indicated by others (e.g. Ibrahim, 1996 and the references there in). The Pleistocene age is based on U-Th age dating of the Umari section at 331 Ka by Abed et al., 2008), and OSL dating for a sandstone horizon further north at 656 Ka by Turner and Makhoulf (2005).

The Azraq Formation was deposited in a lake/lakes occupying the Azraq depression partly or wholly depending on the paleoclimate. The abundance of clays and diatoms at the centre of the basin, (Ga' Al-Azraq), may indicate the permanent presence of relatively deep and fresh water. During times of dry paleoclimate, the lake shrinks and gypsum, and possibly halite, can form at certain parts of the lake. During Marine Isotope Stage 9 (MIS9), at

331 Ka, which was a wet and warm period of the Pleistocene, the lake/lakes was/were occupying the basin from the Umari in the east till Azraq Druze in the north (Fig. 24) (Abed et al., 2008).

More recent deposits of the Late Pleistocene to the Holocene are also present. They are younger than the Azraq Formation and include: the Dashaha silt dunes up to 10m high at the periphery of the Ga', the abundant gravels at the mouths of the major wadis recharging the Ga', and the desert pavement.

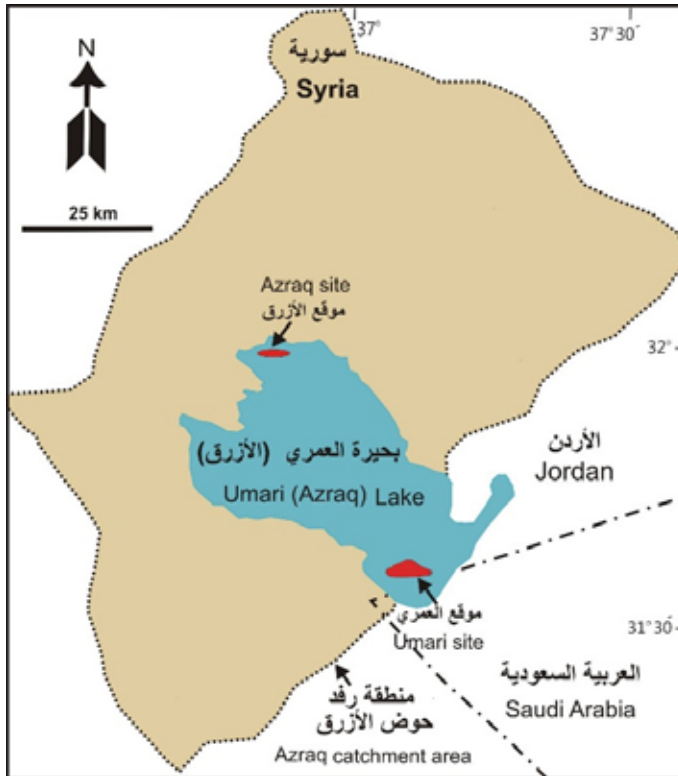


Figure 24: The extent of the Azraq paleolake at 330 Ka BP. The shoreline of the paleolake is drawn at the 540 m contour above sea level (Abed et al., 2008)



Figure 25: Basalt overlying Shallaleh Fn in W. Uwayned west of Azraq

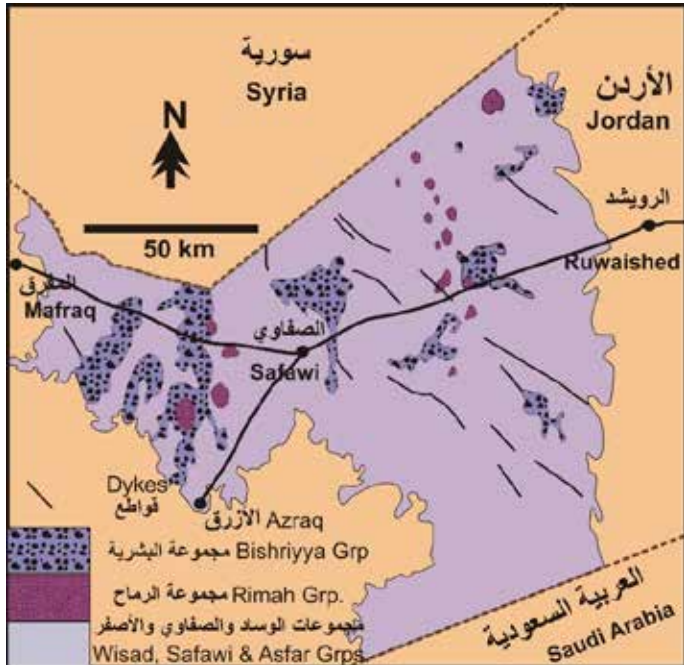


Figure 26: Map showing Harrat Esh Sham in Jordan with the basalt groups

## 11. VOLCANIC ROCKS

Remarkable volcanic activities took place during the Cenozoic. Since the Early Miocene, 25 Ma ago, up till 100Ka in the Azraq area, Jordan and its surroundings witnessed abundant volcanic eruptions in the form of fissure eruptions along faults or as cone eruptions. This event, both tectonic and volcanic, took place during the release of stress in the Afro-Arabian Plate after colliding with the Eurasian Plate at about 25 Ma, which led to the formation of the Syrian-East African Rift system including the Red Sea (e.g. Abed, 2017).

A huge basaltic plateau or field, 45000 km<sup>2</sup> was formed in Southern Syria, Palestine, NE Jordan (11000 km<sup>2</sup>) and Saudi Arabia. Collectively, this basaltic field is known as Harrat Esh Sham Supergroup. Harrat Esh Sham consists mainly of the black basalt (Fig. 25) erupted along faults and fissures parallel to the Res Sea; i.e. in a NW-SE direction. The other type of material are the cinder cones where pyroclastic material were produced as volcanic bombs and ashes such as in Jabal Aritain, Tell Hassan and Tell Rimah.

In Jordan, cropping out Harrat Esh Sham is divided into 5 major groups. They are from older to younger: Wisad, Safawi, Asfar, Rimah, and Bishriyya (Fig. 26). Older eruptions are also present in the subsurface. The maximum thickness in Jordan near Jabal Druze in southern Syria is 400 m. Paleosol is reported between the groups. This is a major topic that needs to be discussed separately.

## 12. EVOLUTION OF THE AZRAQ BASIN

The Azraq area, especially the Hamza oilfield area, seems to have been a basin during the Paleozoic. The Ram Group thickness in the subsurface is slightly less than twice the thickness of the southern outcrops. This is also true for the preserved parts of the Khreim Group. This might be due to the position of the Azraq basin as a continuation of Wadi Sirhan basin, where the NW-trending Sirhan Fault Zone crosses Sirhan basin. Although the Sirhan Fault Zone is a Tertiary feature, it might have been a reactivate Najd Faults, which have the same trend. Its Activity was later subdued until it was active again during the Tertiary as discussed below (e.g. Abed, 1985; Amireh and Abed, 2008, Powell et al., 2014).

Since the Carboniferous up till the end of the Ajlun Group, no basinal development had taken place in the Azraq area. The relatively thin, marine Triassic deposits in the Azraq basin do not indicate basin formation. The Triassic basin is in fact in northwestern Jordan. The Jurassic was not deposited there and the Kurnub Group of the Early Cretaceous is terrestrial sandstone. The total thickness of the Ajlun Group, despite being marine, as well as the thickness of each formation in the group, are essentially similar to those in the outcrop. Consequently, there are no sign of a basin developed at the time of deposition during the Mid Cretaceous (Cenomanian-Turonian).



Dramatic changes seem to have taken place in the Azraq basin during the deposition of the Belqa Group. Northwest-trending fault became active since the Coniacian? such as the Fuluk Fault and Rajil Fault (Fig. 17). A subsiding graben, called Hamza Graben, formed in between the two fault and a relatively thick sequence of sediments was deposited. It includes the Rajil, Hamza and Hazim Formation, Coniacian-Campanian, with a total maximum thickness of 2000 m of sandstone at the base becoming carbonates with some chert and evaporates up section as discussed above (Andrews, 1992b). There is nothing like that in the outcrops, except for 100m of equivalent Ghudran Formation in central Jordan. The overlying formations in the Belqa Group, Amman through Shallaleh Formation, have a comparable thicknesses and lithology with the outcrops in northern Jordan, albeit being slightly higher in thickness and reach a total thickness ~1200m; thus making the total thickness of the Belqa Group in the Hamza oilfield up to 3200m (Fig. 27).

The thick sedimentation in the Hamza Oilfield can be explained by syndimentary deposition associated with active subsidence along, especially, the Fuluk Fault. The Fuluk Fault and other faults involved in creating the Hamza Graben, are trending NW, and can be considered as a rejuvenation of the Precambrian Najd Faults oriented in the same direction (Abed, 1985; Amireh and Abed, 2008; Powell et al., 2014). The NW- trending faults in Jordan are younger than the formation of the Hamza Graben, most probably they are Miocene in age; e.g. the Karak-Fayha Fault zone (Bareri et al., 1979). In the opinion of the present author, the Wadi Sirhan Fault zone, which has the same trend and involves the same area, is also Miocene in age. This is because no volcanic activity occurred along the Sirhan Fault Zone before the Miocene, documented by the age of the basalt erupted along these fault; i.e. 26-Recent (e.g. Al Kwatli, et al., 2014; Ibrahim et al., 1998). So, the formation of the Fuluk Fault and the Hamza Graben may be considered as an earlier rejuvenation event along the Sirhan Fault Zone.

Since the Late Eocene-Oligocene, the interior eastern Mediterranean underwent a process of uplift, in advance of the formation of the Dead Sea Transform (DST). This uplift process led to the migration of the Neo-Tethys Ocean westwards and northward (e.g. Bender, 1974; Abed, 2013). Consequently, almost all the interior eastern Mediterranean, including almost all of Jordan, became terrestrial. Thus, no marine strata have been deposited within the Azraq area after the Eocene. However, lacustrine deposits formed from lakes such the Miocene Qirma Formation, the Middle Pleistocene Azraq-Umari lake/lakes and the Azraq Pleistocene-Recent lake (Ibrahim, 1996; Abed et al., 2008).

Since its emergence at around the end of the Eocene, the Azraq Basin has existed as a depression. Non-marine strata deposited during this time interval is about 150 m thick at the centre of the basin and consists of sandstone, marl, mud rocks with diatomites and limestone (Core Lab, 1987; Ahmad and Davies, 2017). Towards the periphery of the basin, the younger parts of these

terrestrial sediments crop out and are designated as the Azraq Formation. Although the Azraq Formation is dominated by sandstones, it has a variable lithology difficult to correlate because of the lack of well-established dates (Ibrahim, 1996; Rabba'a, 1998).

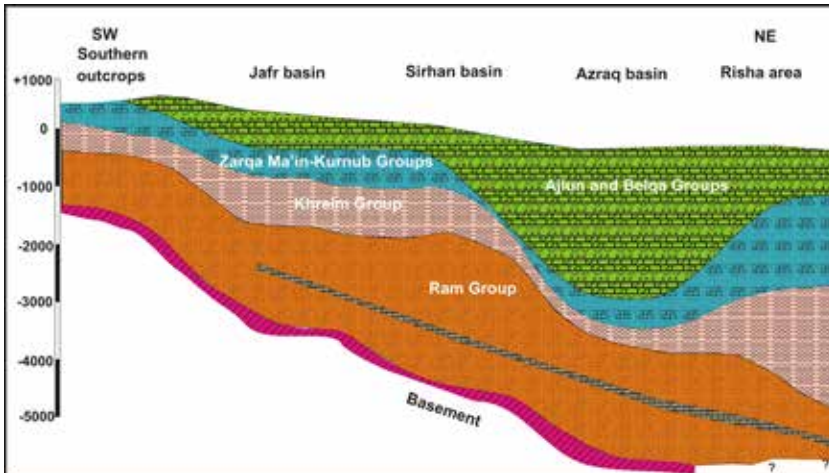


Figure 27: A SW-NE cross section from southern Jordan to the Risha area showing approximately the Azraq basin deposits and other basins.

## 12. HOMININ REFUGIA IN THE AZRAQ BASIN

The Azraq basin, especially Ga' Al-Azraq or the oasis, was occupied by a cyclic wet and dry climate sediments, dominated by wet periods (Ahmad and Davies, 2017), throughout the Pleistocene. (Ames et al., 2013). Thus, the Azraq basin worked as bridge in the migration routes for hominins and animals between Africa, Arabia and SE Asia on one hand, and Asia and Europe on the other hand. The large area of the Azraq basin,  $\sim 12700 \text{ km}^2$ , ensures enough precipitation and then groundwater for the Azraq marches and springs to survive for thousands of years. The presence of several springs in the oasis, as well as the emergence of groundwater to the surface, make the Ga' small area a pocket in an otherwise a harsh environment (Cordova et al., 2012).

Abundant research work on the archaeology of the Azraq basin is present since the early 20th century. All major Paleolithic, Epipaleolithic and Neolithic archaeological sites are well represented in the Azraq basin, especially in and around the oasis. Consequently, hominin population, paleoenvironments and paleoclimates at the time, within the Azraq basin, are now better understood, sometimes at a detailed scale (e.g. Cordova et al., 2012; Ames et al., 2013 and the literature therein).

In general words, it can be concluded from the published archaeological works that the Azraq oasis has had an almost continuous presence of water as ponds, even in the driest paleoclimatic conditions where the elevated areas are dry. This conclusion is supported by the large recharge area constituting the Azraq basin (Cordova et al., 2012; Ames et al., 2013; Ahmad and Davies, 2017 amongst others). These ponds were serving as a refugia for hominins and animals during these harsh climates. During wet climates hominins would disperse and use the higher lands and the many wadi courses tributating the Ga'. For example, the Middle Paleolithic seems to have been a harsh, dry environment where the hominins moved to the ponds in the oasis. This dry period corresponds with the glacial Marine Isotope Stage (MIS) 6, around 250-130Ka. Paleoclimate became wetter and warmer during the MIS 5a and 5c in the Azraq basin and hominins remains are found in higher areas like Wadi Enoqiyya (Hours, 1989; Shea, 2008; Cordova et al., 2009). This may indicate that hominin population was less vulnerable to contractions and extinctions in the Azraq area compared with other parts of the eastern Mediterranean (Ames et al., 2013). This is in agreement with the findings of Abed et al., (2008) that warm periods in the Pleistocene climate were wetter than the cold, glacial periods.

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