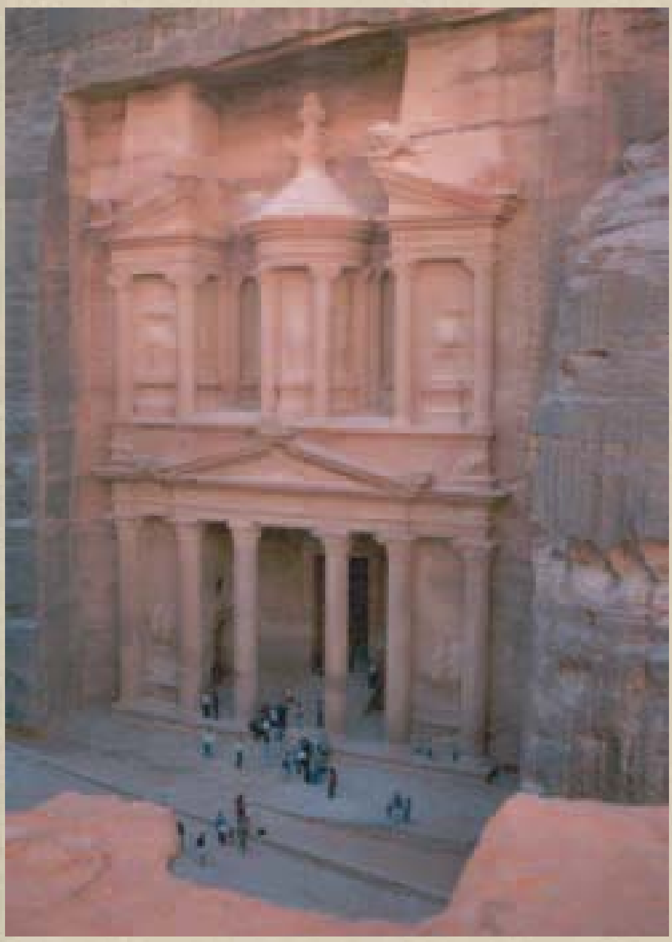
Field Trip Guide Book - P03

*Volume n° 3 - from D01 to P13*

32nd INTERNATIONAL GEOLOGICAL CONGRESS

# ACTIVE TECTONISM ALONG THE DEAD SEA TRANSFORM IN JORDAN



*Leaders: A.M. Abed, M. Atallah, A. Al-Masri*

Florence - Italy
August 20-28, 2004

**Post-Congress** **P03**

*The scientific content of this guide is under the total responsibility of the Authors*

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*Series Editors:*
**Luca Guerrieri, Irene Rischia and Leonello Serva (APAT, Roma)**

*English Desk-copy Editors:*
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# ACTIVE TECTONISM ALONG THE DEAD SEA TRANSFORM IN JORDAN

*AUTHORS:*
*A.M. Abed (University of Jordan, Amman - Jordan), M. Atallah (Yarmouk University, Irbid, Jordan), A. Al-Masri (Natural Resources Authority, Amman - Jordan)*

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**Post-Congress**

**P03**

Front Cover:
*Petra: the facade of the Khazneh,*
*carved out from the sandstone cliff wall*

*Leader: A.M. Abed, M. Atallah, A. Al-Masri*

## Programme

This is a 3-day field trip. Day one will be spent in the Jordan Valley north of the Dead Sea. Day two concentrates on the Dead Sea and Wadi Araba. On day three, participants will visit the ancient city of Petra.

### DAY 1

8.00 Leave the hotel and travel towards the Jordan Valley
9.30 – 10.30 Tall Al-Qarn pressure ridge
11.00 -11.30 Damya Bridge negative flower structure
12.00 – 13.00 Ghor El-Katar Dome (pressure ridge, the Karameh Dam)
13.00 – 14.00 Lunch in the field
14.30 – 15.00 Mindasseh, the Jordan Valley Fault which crosses the River Jordan
15.30 – 16.30 Visit Christ's historical site of baptism
17.00 – 18.30 Visit the Dead Sea, swimming, tea.
19.30 Arrive at the hotel in Amman
20.30 Dinner provided by the Jordanian Geologists Association

### DAY 2

**Travel to Aqaba via the Dead Sea**
8.00 Leave the hotel, taking your luggage with you
9.30 – 10.00 Ma'in alluvial fan displacement
10.15 – 10.30 Oil seepages, Lot's Wife monument
11.00 – 11.30 Seismites in the Lisan Formation
12.00 – 12.30 Wadi Khunaizereh, DST trace in the sub recent conglomerates
13.00 – 14.00 Tilah, several active tectonic features
14.30 – 15.30 Qasr Tilah displacement, and lunch
16.00 – 16.30 Fedan pressure ridge
17.30 – 18.00 Risha trace of the DST, fault escarpment and pressure ridge
18.30 – 19.00 Al-Muhtadi Alluvial fan tectonics
20.00 Arrive at the hotel in Aqaba
20.30 Dinner provided by the Jordan Phosphate Mines Company

### DAY 3

**Travel To Wadi Ram and Petra**
8.00 Leave the hotel, taking your luggage with you
9.00 – 10.00 Visit the famous Wadi Ram tourist site
11.30 – 16.30 Visit the ancient city of Petra including lunch
19.30 Arrive at the hotel in Amman
20.30 Reception by the Jordanian Geologists Association
END OF THE TRIP

**PREFACE**
***Ahlan wa sahlan***
in Arabic means
**Welcome to Jordan**

The Jordanian Geologists Association (JGS) has had an excellent relationship with the International Union of Geological Sciences (IUGS). In 1995, the President of the IUGS, Prof. Fyfe, gave the plenary talk of the 5th JGS conference. In 1996, the meeting of the Council of the IUGS was held in Jordan with a three-day field trip. Again the President of the IUGS, Prof. De Mudler gave the plenary talk of the 7th conference in Amman. Consequently, the chairman and the council of the JGS do feel honored to have this field trip here in Jordan and they will do their best to make it a success.

Although it is a scientific field trip, it has been mixed with some famous archeological and tourist sites that are difficult to pass by without visiting.

This is a three-day post-congress field trip. It is designed to visit some active tectonic features along the Dead Sea Transform. The duration has been fixed by the congress despite asking for four days.

The trip starts from the northern Jordan Valley, and we will spend the 1st day travelling to the Dead Sea.

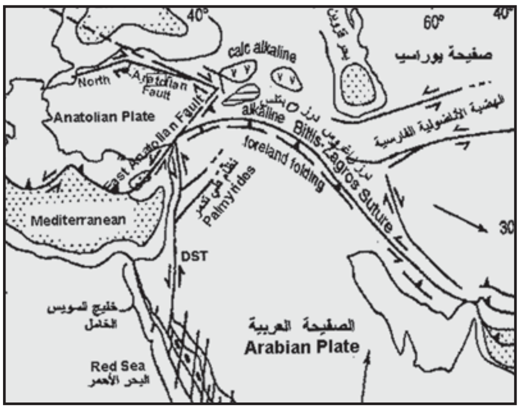


*Figure 1 - The Dead Sea Transform and its relationship with the Red Sea and the Anatolian Plate*

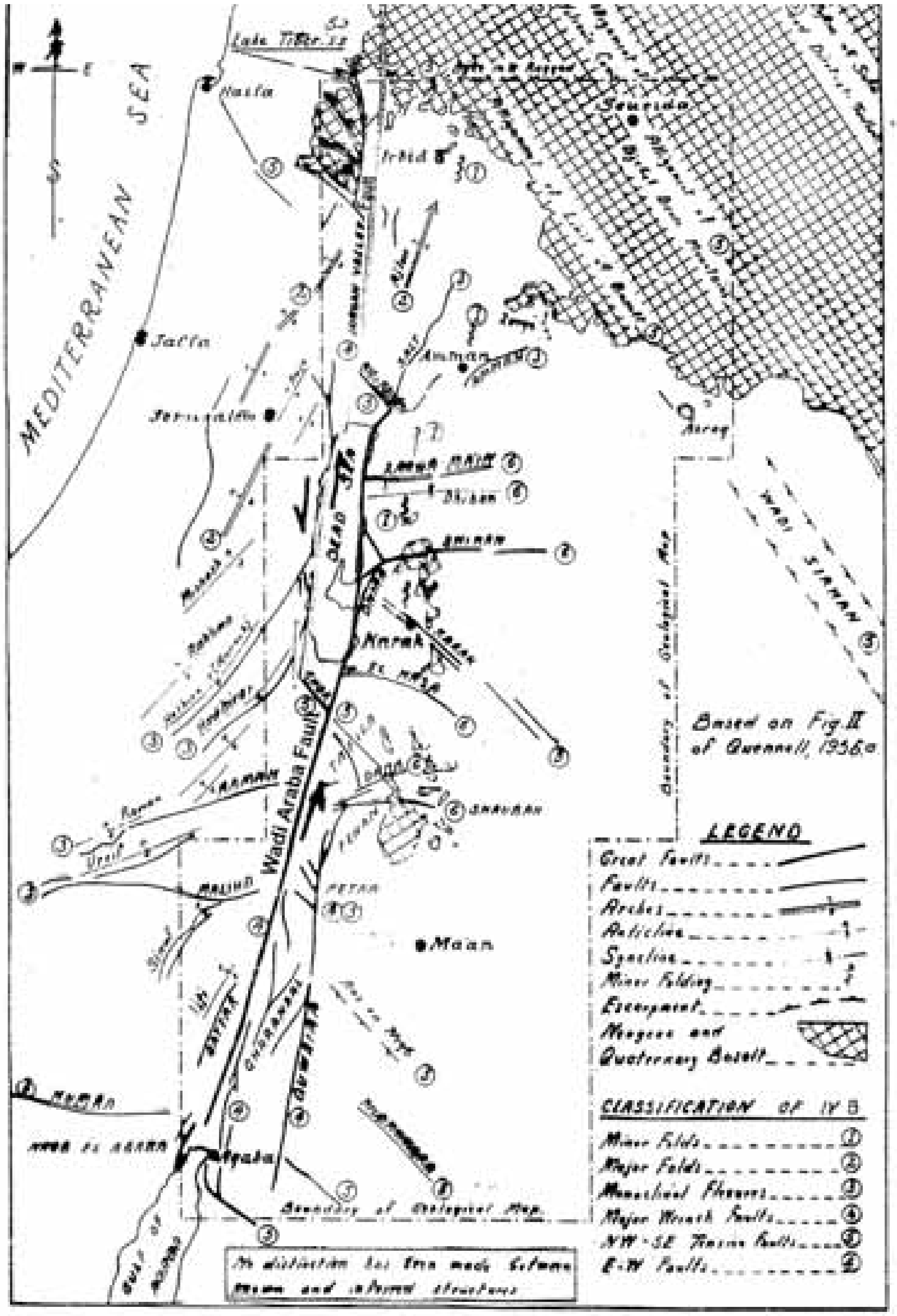


*Figure 2 - Details of the DST in Jordan: Wadi Araba Fault and Jordan Valley Fault*

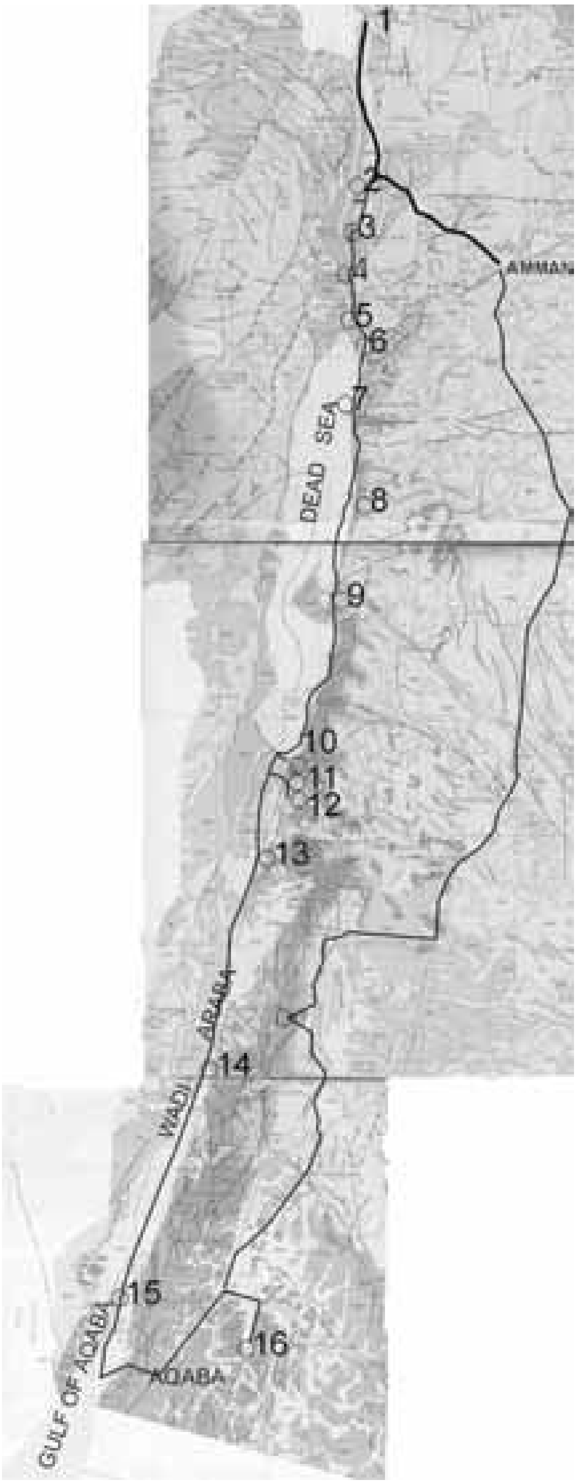


*Figure 3 - Route and Stopes*

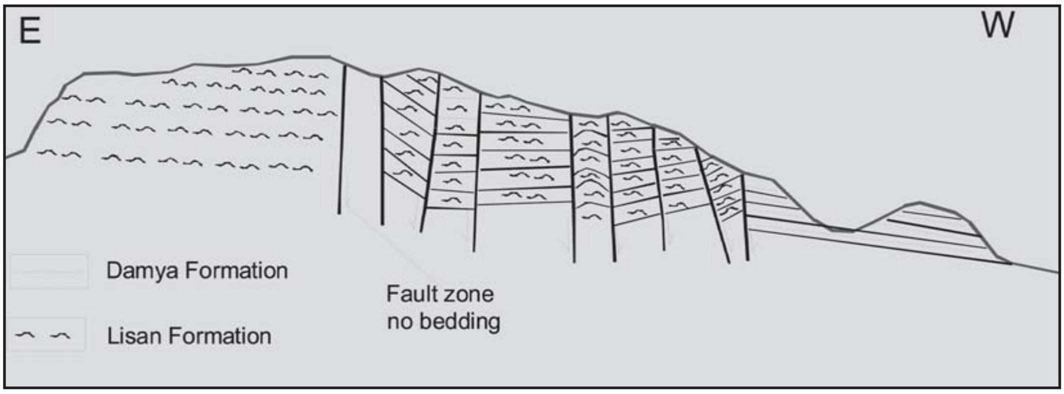


*Figure 4 - Cross section of the Jordan Valley Fault east of the Damya bridge*

There is some time to visit some famous sites, such as Christ's historical Baptism site, to swim in the Dead Sea, and see the River Jordan.

The trip continues southwards, on the 2nd day, along the Dead Sea coast, and via Wadi Araba to Aqaba. Several active morphotectonic features will be seen throughout the day. This is rather a long day, because of the long driving that has to be done (in excess of 300 km). During the last day, we will concentrate on two famous localities, that is Wadi Ram and Petra.

We hope that you will enjoy your stay in Jordan.

**The dead sea transform**

Most of the three days, the duration of this trip, will be spent along the Dead Sea Transform (DST). Following is a brief description of this fault. The DST is a plate boundary connecting a spreading regime in the south (Red Sea, Gulf of Aden), with the collision area in the north (Anatolian Plate). (Fig. 1). It is about 1100 km long, starting from the southern tip of the Gulf of Aqaba in the south, until it meets with the East Anatolian Fault in the north. The DST consists of several fault segments along its length. It is a left lateral, strike slip fault, where the Arabian Plate (including Jordan) moves in a NNE direction along it, relative to the Sinai-Palestine microplate. Average rate of movement is around 5 mm/year.

In Jordan, the DST consists of two main segments. The southern, or the **Wadi Araba Fault (WAF),** starts from the NW tip of the Gulf of Aqaba, and crosses Wadi Araba diagonally. It enters Jordan some 15 km north of Aqaba and runs along the eastern Wadi Araba, then the eastern Dead Sea Basin, until it dies away towards the NE end of the Dead Sea, a distance of about 250 km. The northern segment or the **Jordan Valley Fault (JVF)** starts from the SW corner of the Dead Sea Basin, and runs along the western side of the Dead Sea, then NNE and diagonally within the Jordan Valley. The JVF crosses the River Jordan at about 15 km north of the Dead Sea, and then NNE to pass east of Lake Tiberias. Further north, the plate boundary continues along the Yamouneh Fault in Lebanon and NW Syria (Fig. 2).

The DST is mostly obscured and cannot be seen except at certain places where there is a right or left step of the fault. Consequently, some morphotectonic features are displayed, such as pressure ridges, flower structures, sag ponds, pull apart basins, dog leg structures, and the like. Such features will be visited throughout the duration of the trip.

In the area of the upper Jordan Valley, the Dead Sea Transform is covered by highly cultivated soil, therefore a clear outcrop of the fault plane is difficult to trace on the ground. Geomorphic features, such as pressure ridges, are the only phenomena that indicate the presence of the fault. Examples of these pressure ridges are the Tall Al Arb'een and Tall Al Qarn (Tall in Arabic means "small hill"). For location of the stops see Fig. 3.

## Stop 1:

**Tall Al Qarn Pressure Ridge**

This pressure ridge is 2 km long and 1.5 km wide. The pressure ridge was formed due to the overlapping of two fault strands (Al Taj, 2000). The beds of the Ghor Al-Katar formation were folded and highly dipping to the west, and were unconformably overlain by the

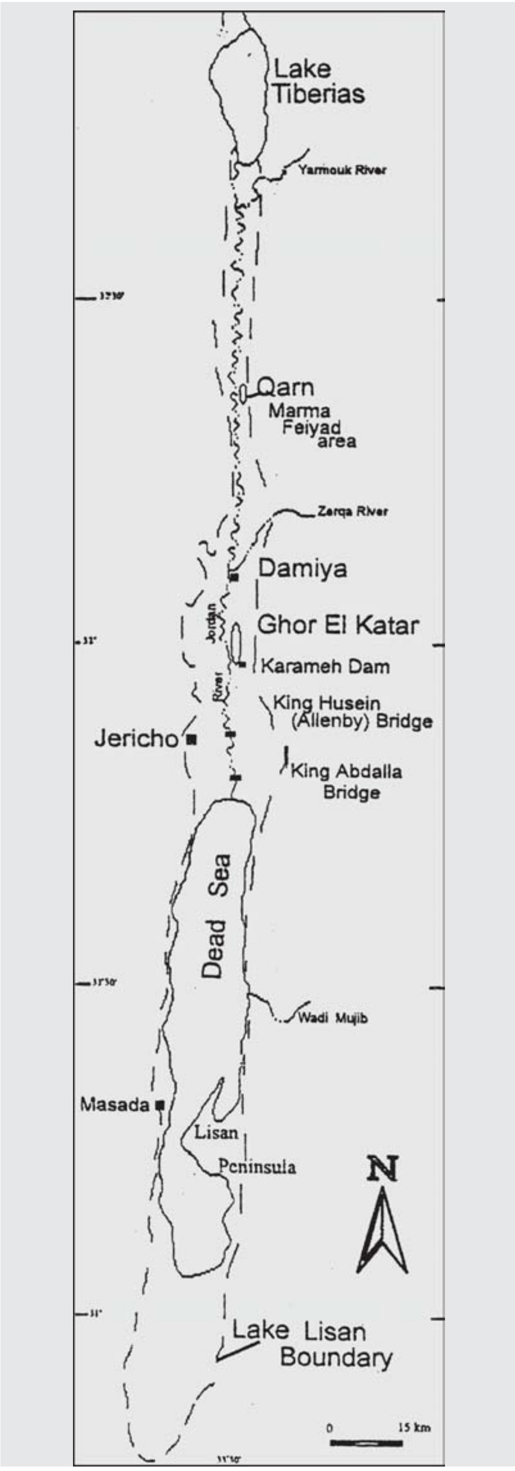


*Figure 5 - Extent of Lake Lisan*

horizontal beds of the Lisan formation. ont the eastern part of the "tall", a vertical conglomerate layer, 2 m thick and striking due north, is exposed.

## Stop 2:

**Damya Bridge Negative Flower Structure**

East of the Damya Bridge on the Jordan River, the road cut exposed the Jordan Valley fault zone. The section represents a flower structure. (Fig. 4). Evidence of transtension is represented by several normal faults and flexures. The deformed beds are the Lisan formation and the overlying Damya formation.

LISAN FORMATION

The Lisan Formation comprises 40 m thick, white, soft, laminated sediments, and was deposited by Lake Lisan (Fig. 5). The Lisan Lake extended from Lake Tiberias in the north, to the south of the Dead Sea. It is more than 200 km in length, and about 16 km in width. Consequently, the deposits of Lake Lisan are present throughout the Jordan Valley and the Dead Sea Basin. The Lisan Lake started at about 65 Ka before present, and ended at 16/15 Ka before present, a duration of about 50 000 years in the latest Pleistocene.

Although the formation is easily recognized in the field by its mm thick lamination, the mineralogical composition is laterally changing in a N-S direction. We believe these changes are controlled climatically. From Lake Tiberias in the north to the Qarn Sill, the Lisan Lake consists of fresh water sediments and the laminae are made of aragonite and diatomites. In the central Jordan Valley, most of the formation is made of aragonite, calcite and clay laminae, except the topmost white cliff, which consists of gypsum and aragonite. In the Dead Sea Basin in the extreme south, the lake water was saline, and the lamina consists of alternating aragonite and gypsum throughout its thickness. Fig. 6 a & b, shows two sections in the Lisan Formation, one in the central Jordan Valley near the Ghor El-Katar anticline, while the second is in the Lisan Peninsula. This variation in composition is due to a fresh water body in the north, intermediate in the middle, and saline in the south, and reflects abundant water resources in the north decreasing southwards, a climatic trend rather similar to the present day climate.

**Damya formation**

The Damya Lake was the last lake to be formed in the Jordan Valley, before the formation of the present



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| Element g/l | Dead Sea | Ocean Water | Times concentration | Element mg/l | Dead Sea | Ocean Water | Times concentration |
|---|---|---|---|---|---|---|---|
| Mg | 40.45 | 1.54 | 26 | Sr | 884 | 8 | 110 |
| Na | 39.33 | 10.50 | 3.7 | Li | 15.24 | 0.17 | 90 |
| Ca | 19.95 | 0.40 | 44 | Mn | 7.29 | 0.002 | 3645 |
| K | 6.50 | 0.38 | 17 | Zn | 3.70 | 0.01 | 370 |
| Cl | 212.60 | 19.00 | 11.2 | Cu | 0.146 | 0.0005 | 290 |
| Br | 6.12 | 0.065 | 94 | Ni | 2.0 | 0.002 | 1000 |
| SO4 | 0.67 | 2.90 | 0.3 | Co | 2.5 | 0.0005 | 50800 |
| HCO3 | 0.29 | 0.17 | 2 | F | 4.6 | 1.3 | 3.5 |
| | | | | Pb | 5.48 | 0.004 | 1370 |
| Salinity | 326 | 34.925 | 9.33 | Cd | 0.86 | 0.00011 | 8600 |

***Table 1 - Major and some trace elements in the Dead Sea water in 1990 compared with ocean water. These concentrations are increasing with time.***

day Dead Sea. It started at about 14 Ka and ended at 12 Ka before present, a duration of 2000 years. The Dead Sea as it is now started to exist 10.5-11 Ka before present.

The Damya Lake was a fresh water lake with its maximum depth towards the center of the Jordan Valley, in the vicinity of the Ghor El-Katar area. It is composed of reddish, soil-like mudstones and siltstones, with fresh water ostracods. Fig. 6a shows a columnar section in the Damya Formation. Its maximum thickness in the type locality is 14 m, decreasing north and south to few meters.

## Stop 3:
**Ghor El-katar Anticline**

The Ghor El-Katar Formation comprises 350 m thick, clastic sediments deposited in a fresh water lake sometime during the Early Pleistocene. This sequence is a good example of cyclic sedimentation influenced by the climatic changes. 28 cycles are present within this formation. Each cycle consists of thick conglomerates, calcarenite, calcisiltite, and finally calcilutite (Fig. 7)

The DST passes immediately east of the Ghor El-Katar anticline (Fig. 8). In this vicinity, the DST has a bend to the right thus producing a compressional stress regime in the Ghor El-Katar area. Consequently, the Ghor El-Katar strata were folded into an anticline or pressure ridge (Fig. 9). An olivine alkali basalt dyke formed along the anticline axis sometime in the Middle Pleistocene. The younger sediments, the Lisan and Damya Formations of the uppermost Pleistocene, overlie the Ghor El-Katar sequence with an angular unconformity. (Fig. 9).

During the excavations for the Karameh Dam, just east of the Ghor El-Katar anticline, the trace of the DST was located at a few points. In all the points, the soft, laminated Lisan Formation (65-15 Ka), is involved in the deformation. Tight folding, dragging, brecciation, and churning of the Lisan beds are some of the features noticed at these points. The trace of the DST beneath the Karameh Dam was exactly located, and the filters of the dam were thickened in that area in order to take a 4 m horizontal displacement once an earthquake of 7 or more Richter scale occurs. Unfortunately, all these active tectonic features are now below the dam body or the dam reservoir and cannot be seen.

## Stop 4:
**Mindasseh**

This short stop is designed to see the position where the JVF crosses the River Jordan.

## Stop 5:
**Christ's Place Of Baptism On The River Jordan**

This is a tourist-archeological stop. The stop is designed to visit this ancient site where Christ was baptized. Details will be given at the site.

## Stop 6:
**The Dead Sea**

**GENERAL**

Until 1960, the area of the Dead Sea was around

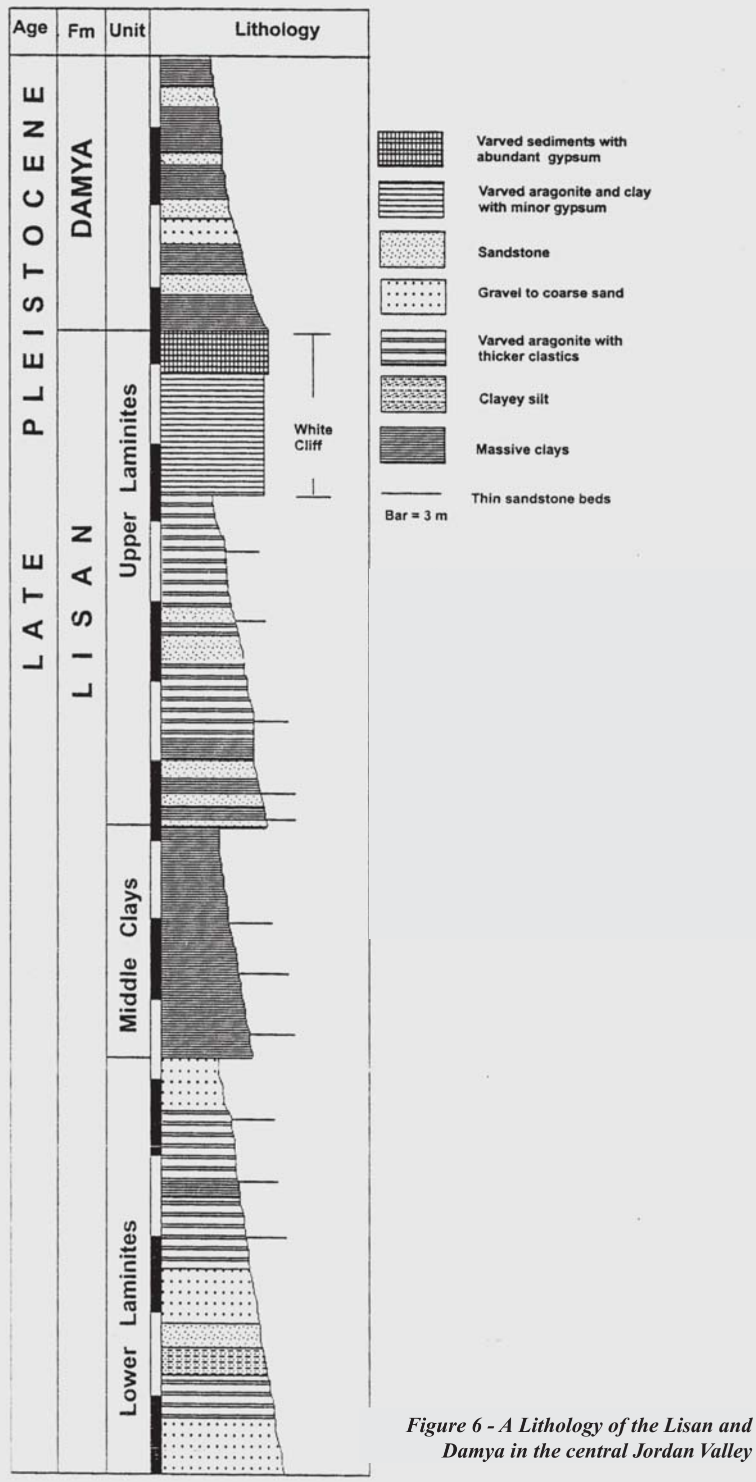



*Figure 6 - A Lithology of the Lisan and Damya in the central Jordan Valley*

75 % of its area, with a maximum depth of 400 m, and the Southern Basin with only 10 m as its maximum depth (Fig. 10). By the mid 1980s, the Southern Basin completely dried up and it is now occupied by the saltpans of the two potash companies on both sides. Dryness is due to the diversion of the whole of the upper Jordan River into Israel (in excess of 800MCM/year), and to the construction of several small dams on wadis (watercourses) in Jordan. The Dead Sea water level has been continuously descending since 1960. It was – 395 m below the Mediterranean Sea level in 1960, now it is at about – 416 m; i.e. 20 m in 40 years, or 50 cm/year. Fig. 11 shows the Dead Sea level changes.

The salinity of the Dead Sea water, in 1990, was 326 g / l, which is around 10 times the salinity of the ocean water. It is now in excess of 350 mg/l. The major and minor anions are shown in Table 1. The water column has become fully oxidized since the mid 1980s. Before that, it was stratified with the lower layer being anoxic. The age of the Dead Sea is around 10 Ka; i.e. at the onset of the present interglacial period.

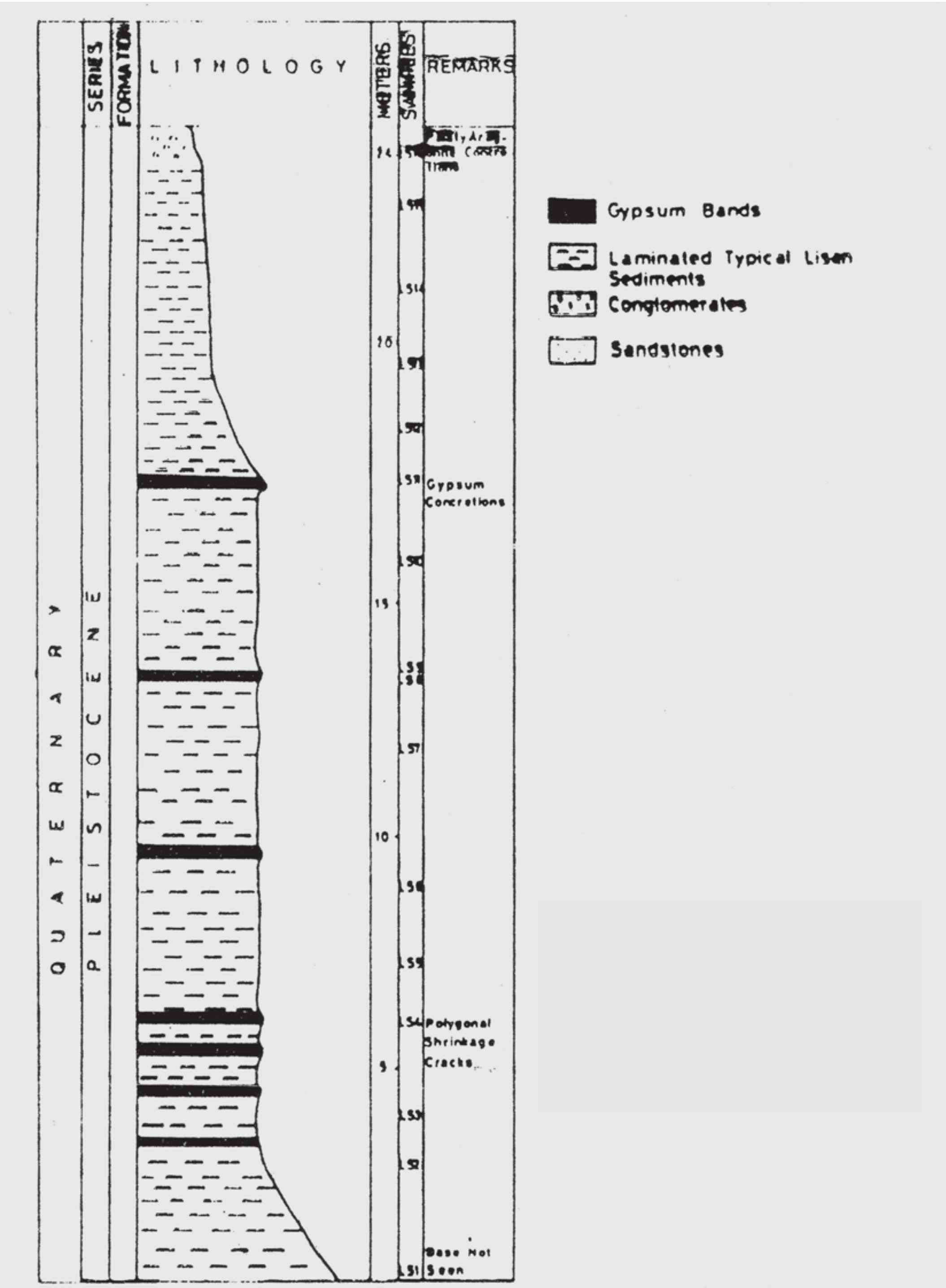
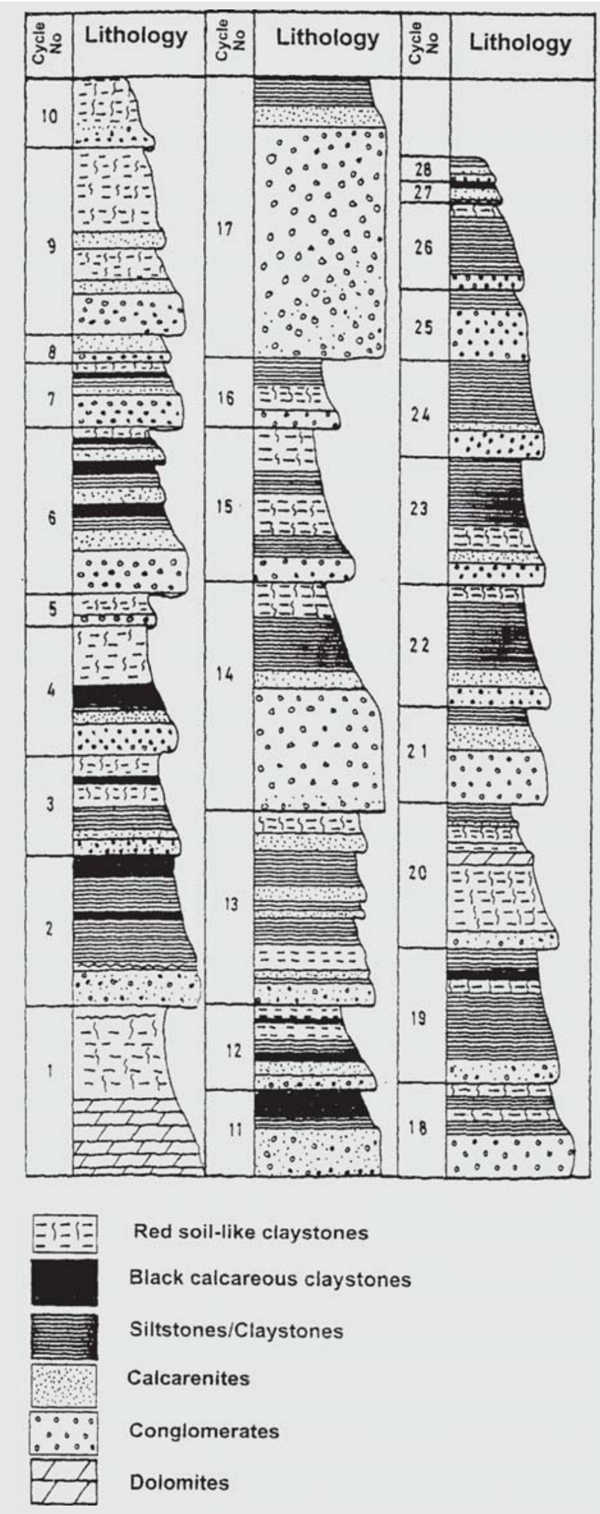



*Figure 6 b - Columnar section of the lisan formation in the lisa peninsula*




### Stratigraphy

Rocks cropping out along the eastern area of the Dead Sea can be divided into two types of formation: Pre-rift and post-rift formations. It is now in general agreement that the Dead Sea Transform, and hence the Wadi Araba-Dead Sea-Jordan Valley Rift, started at sometime in the Middle Miocene (15-17 Ma). The Tethys left the area by the Late Eocene, and no marine or terrestrial deposits are known in Jordan to represent the Oligocene. Consequently, sediments older than the Oligocene are pre-rift, while those from the Miocene are syn-rift. The post-rift sediments are post Miocene. In order not to go into all the details on the subject, Table 2 shows a summary of the stratigraphy.

### The dead sea tectonics and evolution

It is clear from the above title that the Dead Sea is bound from east and west by two faults: the WAF in the east and JVF in the west. The block east of the eastern fault, WAF, is relatively moving north, while the block west of the western fault, JVF, is relatively moving south (Fig. 12). This transtensional stress regime has produced a rhomb shaped, pull-apart basin, the Dead Sea Basin.

The southern end of the Dead Sea Basin is marked by the Khunaizereh Fault. This is a transverse fault running roughly E-W. It is a normal listric (growth) fault. The Khunaizereh Fault forms an escarpment, clearly marking the southern end of the Dead Sea Basin. No similar fault is present at the northern end of the Dead Sea. Furthermore, two more transverse faults are present within the basin. One of these faults is at the northern end of the Southern Basin, while the other is at the southern end of the Northern Basin ((Fig. 10). The Lisan Peninsula is situated between these two faults.

Since the formation of the Rift in the Miocene, its base has been subsiding, while the mountains on both sides are uplifted. The rate of subsidence is variable with time. A

*Figure 7 - Lithology of the 350 m thick, Ghor El-Katar Formation. Note the presence o 28 cycles repeated throughout the section (Abed, 1987)*

| AGE | GROUP | FORMATION | COMPOSITION & ENVIRONMENTS |
|---|---|---|---|
| Late Pleistocene | | Damya | Fresh water lake sandstone to mudstones, 14-11 Ka. |
| | | Lisan | Fresh to saline lake, laminated aragonite, calcite, gypsum, diatomite, … 70-15 Ka. |
| | | Samra | Fresh water lake carbonates and clastics, 355-70 Ka. |
| Early Pleistocene | | Ghor El-Katar | |
| | | Un -named | Coarse and fine clastics in the Dead Sea Basin. Possibly 1000 m thick (?) |
| Pliocene | | Usdom (Sedom) | Rock salt mainly, at the center of the basin, around 4000 m thick |
| **SYN-RIFT FORMATION** | | | |
| Miocene | | Dana | Conglom., calcarenites, calcisltites, calcilutites. 450 m thick in intermontane basins, and 2000 m in the Dead Sea Basin |
| **PRE-RIFT FORMATIONS** | | | |
| L. Cretaceous-Eocene | Balqa | | Marine carbonates, chert, phosphorite, epicontinental, 600 m thick |
| L. Cretaceous | Ajlun | | Marine carbonates, epicontinental, 550 m thick |
| E. Cretaceous | Kurnub | | Fluvial sandstone, 250 m thick |
| Permo Triassic | Ramtha | 10 formations | NE Dead Sea, mixed carbonates, sandstones, shale, evaporates, marine and terrestrial, 1000 m thick |
| Cambrian | Ram | Umm Ishrin | Braided, fluvial quartz sandstone, 300 m thick |
| | | Burj | Marine mixed carbonate siliclastics, 120 m thick |
| | | Saleb | Braided, fluvial arkosic, pebbly sandstone, 300 m thick |
| Precambrian | Safi | Saramouj | Alternating sandstones and conglom., 200 m thick, alluvial fans. 600 Ma |

***Table 2 - Stratigraphy of the rocks cropping out in the Dead Sea Basin, eastern side.***

long-term average may be in the order of 0.5 mm/y, and for uplift, it is in the range of 0.07 mm/, or 70 m/ 1 million year. The rate of denudation is in the range of 0.02 mm/ year, or 20 m/1 million years. (Please note that all these figures are not based on absolute dating. They are simply estimates.) The rate of subsidence plus uplift combined is far more than the rate of denudation of the mountains. Consequently, the accommodation within the rift is pretty huge.

Because of the above-mentioned subsidence, the Dead Sea Basin is acting as an active depocenter. Some 5 – 7 km of sediments have been deposited within this basin since its opening in the Miocene (Table 2). This is typical for pull-apart basins. It also explains the oil seepages, gas, and bitumen to be found within the Dead Sea Basin.

## Stop 7:

### Wadi Zarqa Ma'in

This short stop is designed to show the old alluvial fan of the Wadi Zarqa Ma'in, relative to its recent fan. The former has shifted a few 100 m to the north. Unfortunately, there are no absolute dates on both


*Figure 8 - Generalized geological map of Ghor El-Katar area and its surroundings. Width of the map is about 3.5 km (modified from Moh'd & Muneizel, 1998)*

fans to reconstruct this activity. Please also note the roughly N-S faulting of the older fan.

## Stop 8:
**Oil Seepages**

Several oil seepages were reported on both sides of the Dead Sea from the early 20th century. Also, black, lustrous bitumen blocks floating on the Dead Sea water have been known since antiquity. Natives collected and exported such material to the Ancient Egyptians.

It is now well-established that both the bitumen and the seepages are sourced from the oil shale of the Maastrichtian-Paleocene (Table 2). The oil shale horizon is situated at about 3-4 km in the margins of the Dead Sea Basin, and it is suitable for oil generation. Towards the central part of the basin, the burial depth of the source oil shale is 5-7 km, a depth suitable for producing dry gas.

Light oil seepages can be seen some 3 km south of the mouth of the Wadi Mujib. It is seeping from the Upper Cambrian Umm Ishrin formation. API is 45. A well drilled there produced heavy oil before Dead Sea water invasion. Another example is the asphalt or heavy oil seepage further south at Wadi Isal. It is impregnating the Kurnub Sandstone of the Lower Cretaceous along the Kharaza crescent shaped fault (Fig. 10).

Maturation of the source rock must have happened post Miocene, most probably in the Pleistocene; i.e. after the deposition of the thick sequence of Dana and Usdom Formations (Table 2). It is to be noted that the oil shale is not mature throughout Jordan, except in the Dead Sea Basin.

## Stop 9:
**The Seismites**

Several lamina of the Lisan marl are found contorted or folded, while the lamina below and above are more or less horizontal (Fig. 13). Axial planes of the folds are inclined towards the Dead Sea, down slope. This phenomenon is now accepted as paleo-seismites. These folds were formed while deformed laminae were still wet because of earthquakes happening in

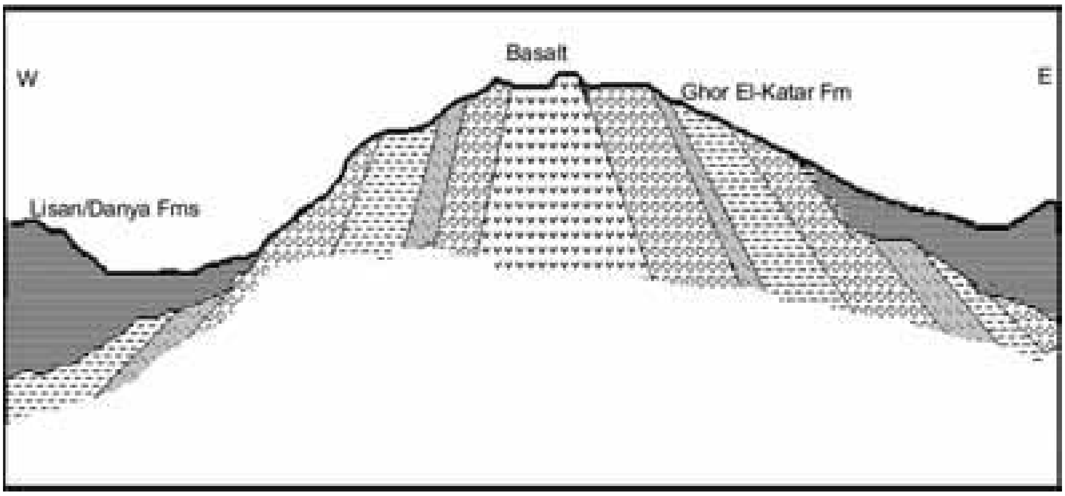



*Figure 9 - Ghor El-Katar anticline or pressure ridge in the Jordan Valley*

the Dead Sea area. They can be thought of as small scale slumping in wet sediments, triggered by the shaking of earthquakes. These seismites are repeated vertically, thus Elisa and Mustafa (1986) used them to study the earthquake frequency and recurrent periods in prehistoric times. Although not fixed, a more than 1000 years gap is found as the recurrent period for earthquakes of 6 or more on the Richter scale.

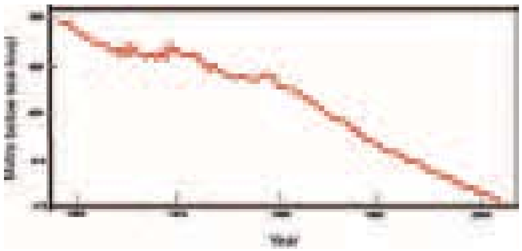


*Figure 11 - Dead Sea level from 1960 to present.*

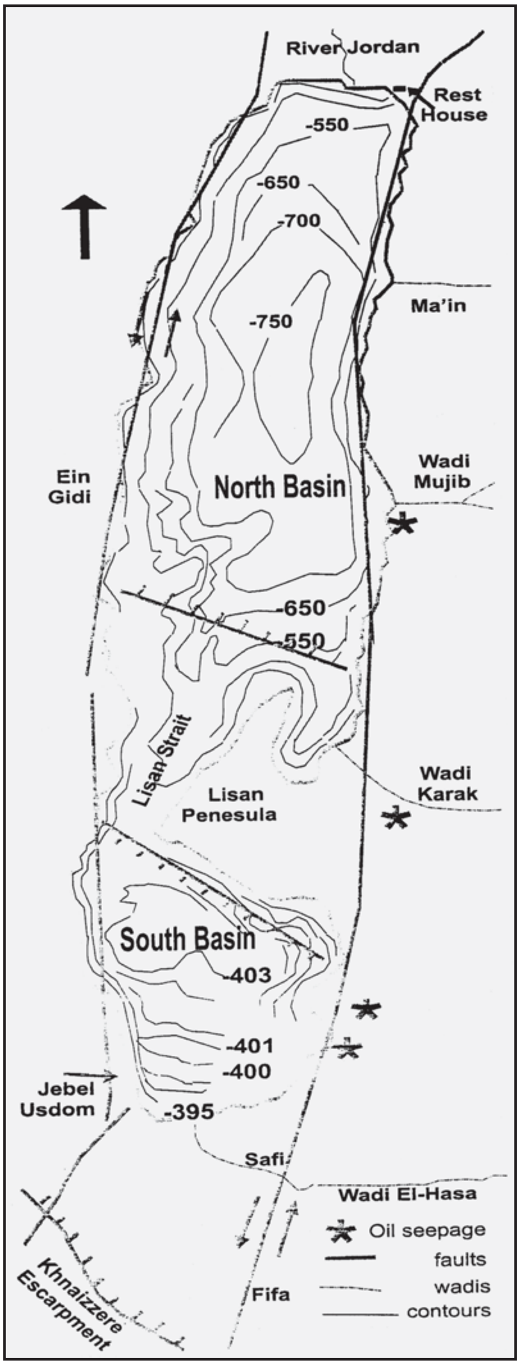



*Figure 10 - The Dead Sea floor topograpy, major faults, and oil seepages.*

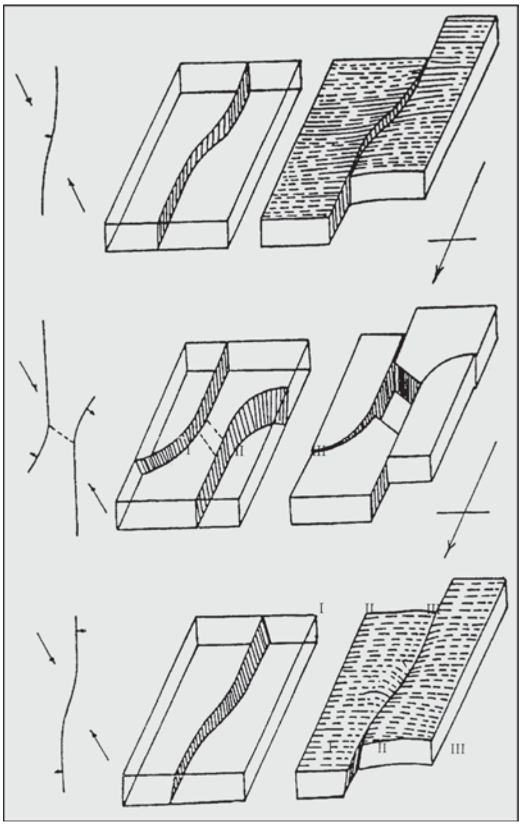


*Figure 12 - Sketch showing the formation of: Wadi Araba (bottom), Dead Sea (middle) and Jordan Valley (top)*

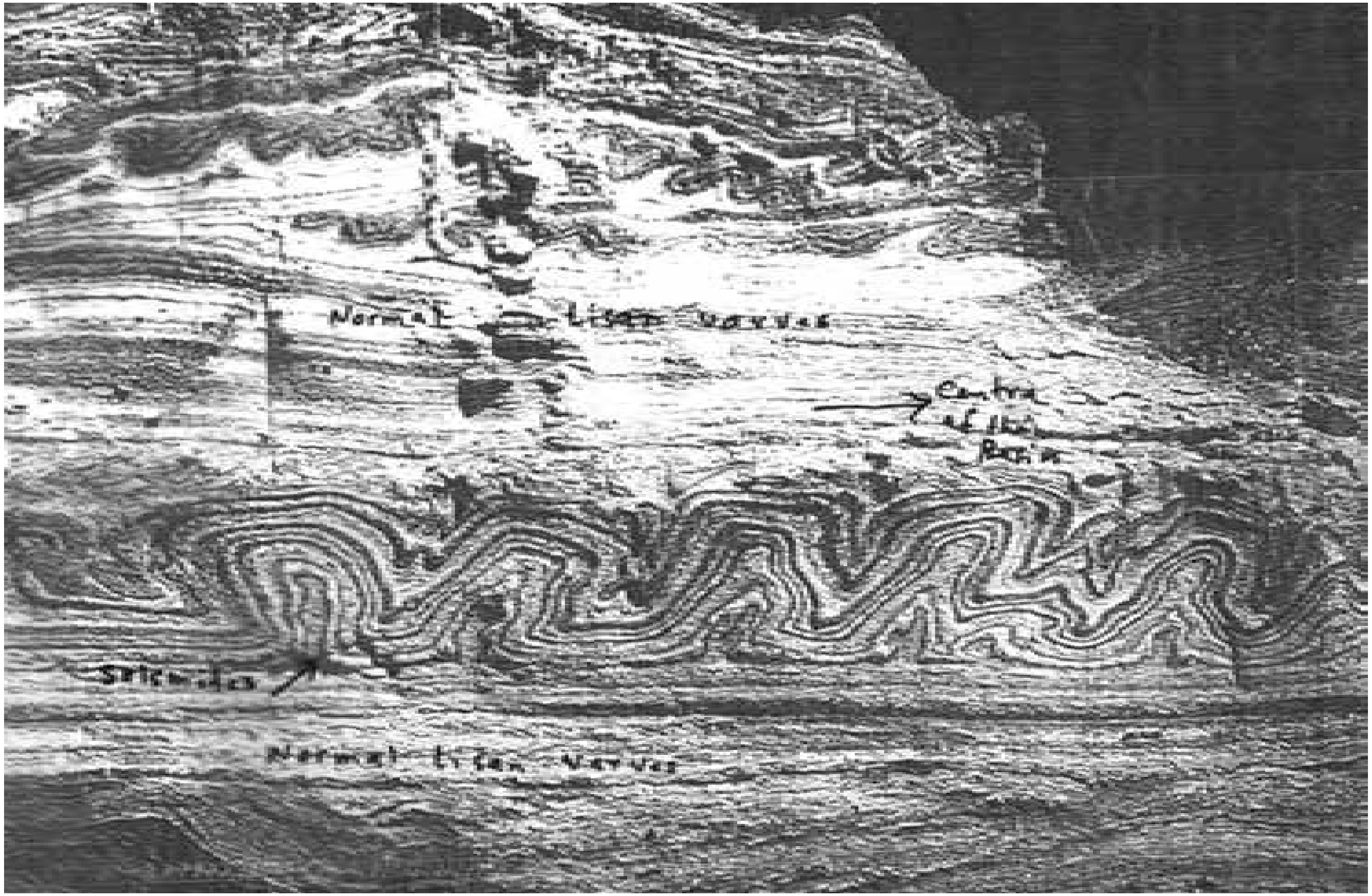



*Figure 13 - Repetitive slup structures of unconsolidated Lasan sediments caused by earthquakes and subsidence. Interformational asymmetric basinward folding is well exhibited within Nahal Perazim west of Mount Sedom*

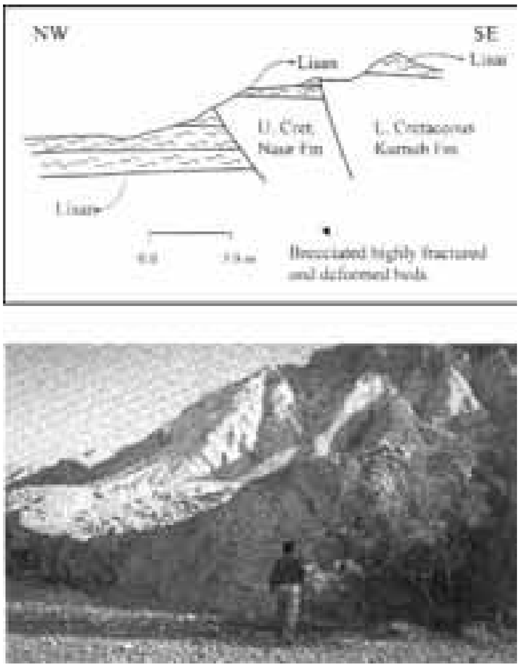



*Figure 14 - (a) On the northern bank of Wadi Khunayzira, the transform is seen as a reverse fault with Lower Cretaceous (kurnub Fm) sandstone upthrown relative to the Upper Cretaceous (Naur Fm) carbonates in the hanging wall. The Naur formation is highly fractured and the faults offset the Pleistocene Lisan Formation.*
*(b) Photograph of the structure viewed toward the north. Man standing in the foreground for scale.*

## Stop 10:
### Wadi Khunaizereh

In this area, the Northern Wadi Araba Fault (NWAF) is exposed in many locations along the course of the Wadi An Nakhbar and the Wadi Khunaizereh, and at their intersection. The outcropping rocks in this area are the post Lisan conglomerate (Tarawneh, 1992). 300 m south of the intersection of the two wadis, the fault crosses the floor of Wadi An Nakhbar, and forms a 50-70 cm wide dyke that is filled with oriented clasts in a well-cemented conglomerate. Here the WAF has an attitude of N15E, 80 SE. Several meters to the north, the WAF has the attitude of N15E, 75 SE with well-developed striations on pebble surfaces that plunge 25, S20W. A prominent Riedel shear marked by a cemented fault gouge strikes N-S, 70 W. In the western bank of Wadi Khunaizereh, the WAF exhibits normal separation; the attitude of the fault plane is N15E, 80 NE and the striations plunge 20 toward the S05W. The eastern block was down faulted. The vertical throw across this fault is 4 m, as observed from the offset of a gravel bed. The horizontal displacement is calculated to be 8 m (Atallah, et al, 2002). 300 m north of the two wadis intersection, a system of synthetic (Riedel) and antithetic (conjugate Riedel) faults form the western wall of the Wadi Khunaizereh course. The movement along one of these subsidiary faults caused the dextral offset of 2 m of a Roman aqueduct (Galli and Galadini 2001). In the northern bank of Wadi Khunaizereh, the WAF shows reverse separation: the Lower Cretaceous Kurnub sandstone is upthrown relative to the Upper Cretaceous Na'ur carbonates (Fig. 14). Lower and Upper Cretaceous rocks are highly fractured and brecciated. The neighboring and the overlying Lisan beds are in apparent buttress unconformable contact with the deformed beds.

## Stop 11:
### Tilah

In this area, the WAF crosses the alluvial fan surfaces west of the Dhahal Mountains. This fault segment was a subject of detailed geologic and topographic mapping; three trenches were excavated to study the paleoseismicity of the area. Here typical morphotectonic features were formed, indicating the active nature of the fault. Due to the aridity of the area, the fault trace is clear both on aerial photographs and in the field. North of this stop, a series of pressure ridges were formed along the fault trace. One of these pressure ridges was bulldozed for gravels, and a positive flower structure was exposed across the pit. An this point, Upper Cretaceous rocks and Lisan Pleistocene beds were pushed up and highly fractured and pulverized. This pressure ridge was logged by Niemi et al (2000) (Fig 15). Further to the south, a small sag pond was formed due to the fault step. A bulldozer trench was excavated across the sag pond (Fig. 16).

Another morphological feature, which shows active horizontal movement, is the offset of the alluvial fan surfaces, and the offset of stream courses, and the formation of dogleg. Typical cumulative displacements of 54 m, 39 m, 22.5 m, 6 m, and 3 m of stream channels and alluvial fan surfaces across the fault, were measured from detailed geologic and topographic mapping (Niemi et al, 2001). See Figs. 18, 19, and 20. 4.7 mm/yr average slip rate of the Northern Wadi Araba Fault was calculated by Niemi et al (2001), and 4 mm/yr as calculated by Klinger et al (2000). Another trench was excavated

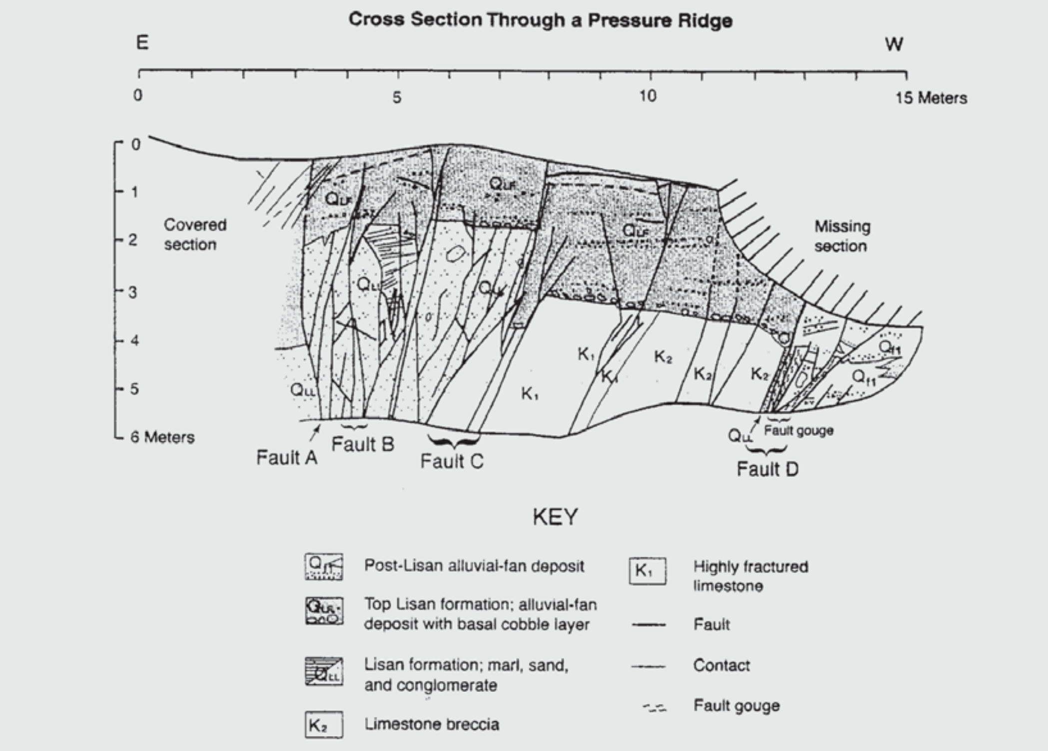



Fig. 15 Log of a pressure ridge exposed in a gravel excavation along strands of the Wadi Araba fault (See Figure 3 for location). A well-developed, positive flower structure is exposed in the outcrop. A prominent erosional unconformity that beveled the Cretaceous bedrock, fault breccia, and Upper Pleistocene Lisan formation is marked by a layer of rounded cobbles. This erosional horizon was produced by the final regression of Lake Lisan around 15 ka. The lag deposits are overlain by a 3-m-thick sequence of alluvial sheet-wash sediments of the topmost Lisan formation ($Q_{Lf}$). The deformed erosional unconformity and $Q_{Lf}$ fan deposits are in fault contact with younger post-Lisan alluvial-fan sediments ($Q_{f1}$).

across the fault scarp; a 9 m wide flower structure was excavated. Horizons of paleosoils were exposed; implying many paleoearthquakes (Fig. 17).

## Stop 12:

**Qasr Tilah**

The Qasr Tilah archeological site is located along the Northern Wadi Araba Fault. The site contains a fort, a water reservoir (birkah) with aqueducts leading to it from the adjacent Wadi Tilah, and aqueducts leading from the reservoir to agricultural fields. Although the fort itself has been mostly destroyed, the water reservoir is still well preserved. Charcoal collected from the foundation mortar and upper wall mortar of the reservoir reveal that it was built ca 641-687 A.D (Niemi, 2000), or 558-776 A.D (Klinger et al., 2000), indicating its use in the Late Byzantine to Umayyad period. The eastern wall of the reservoir is cut into the bedrock, and the rest of the structure is built using cemented and plastered limestone and sandstone blocks. The southwestern wall, which is a very well preserved and rectilinear structure striking N60$^0$E, is tilted counterclockwise, with a 30 cm offset measured at the eastern corner. The reservoir was built across the active NWAF trace, so that its western wall is cut and offset by the fault, which is represented by 0.5-1 m wide, N8 E striking fracture (Fig. 21). In a detailed topographic survey, using the total station, the offset of the western wall was measured at 2 m. The northwestern corner was cut, dragged and tilted by the fault. Some restorations of the southwestern wall, made with the same stone and building style of the reservoir, imply that the damaging event probably occurred at about the same time of the reservoir construction. Archeological excavation showeda sinistral offset of the aqueduct leading from the birkah, (water reservoir) located west of the western wall. To study the earthquake history after

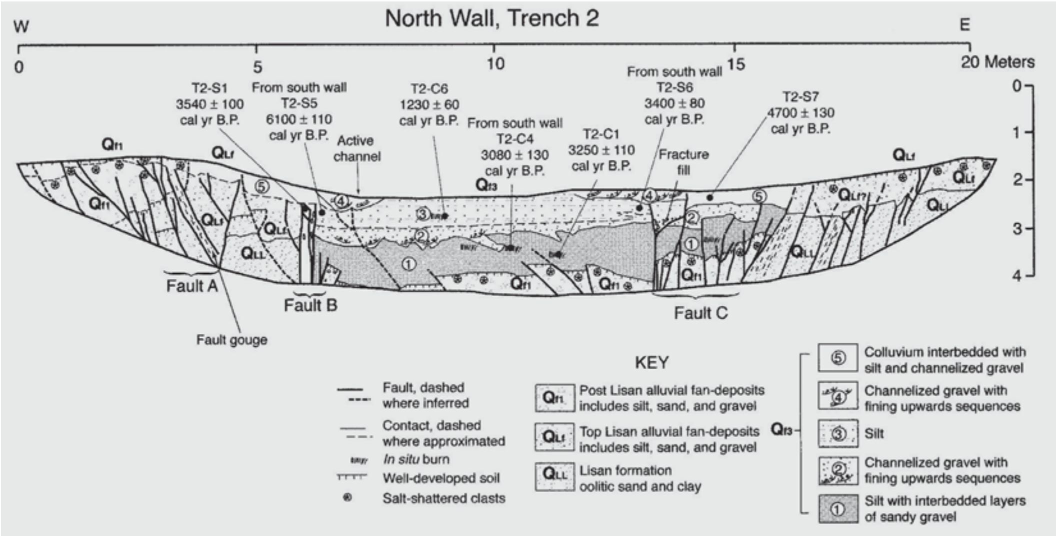



***Figure 16 - Map of northen wall of Trench 2 showing multiple fault strands that bound a pressure ridge and a shutter ridge. The central zone depression filled with alluvium ponded by the shutter ridge on the west. Faults are identified by rotated and aligned clasts, fracture fills gouge zones, and stratigraphic offset. Locations of radiocarbon samples from the south wall are shown at their approximate stratigraphic. See Table 3 for further information on radiocarbon data. See Figures 3, and 11 for location of trench.***

the construction of the reservoir and the aqueduct, two trenches were dug to study the stratigraphy of the surface sediments. At least three faulting events cut sedimentary layers full of mortar, charcoal, building blocks, and other tumble debris from the collapse of the birkah (Hayens et al, 2003). Several earthquakes are known from historical records to have occurred in the vicinity of the southern Dead Sea and Wadi Araba. These include the earthquakes of A.D. 31, 363, 660, 1068, 1212, 1293, and 1459 (Ambraseys et al, 1994).

## Stop 13:

**Humrat Fedan**

On the road to the Village of Qurayqira, the flat topography of the Wadi Araba is interrupted by a series of elongated small hills, composed of squeezes and uplifted Cretaceous sandstone and limestone. These hills are a series of Pressure ridges, formed along the trace of the WAF. This stop is one of these pressure ridges formed due to the right bending of the WAF. The rocks are highly crushed and pulverized in some places, the bedding planes are recognized with difficulty. The pressure ridge acts as a wall to contain the alluvial deposits accumulated on the eastern plain, as this structure locally divides two plains with a topographic step of about 40 m. Several springs (with high trees) occur along the WAF south of this stop, the eastern water table being just a few meters below ground surface. South of this point, several entrenched wadis show a 60 m sinistral displacement at the fault trace (Galli, 1999). Further to the south, the WAF truncated a field of sand dunes, and forms the western boundary of it, the dunes adjacent to the fault show some dragging as an effect of active displacement. North of this stop, an assemblage of morphotectonic features were formed along the WAF, indicating active displacement (Fig. 22). Further to the north, the WAF trace forms a vegetation line crossing the stream deposits and sand fields.

## Stop 14:

**Jabal Ar Risha**

The Jabal Ar Risha (Ar Risha Mountain) in central Wadi Araba (height = 250 m above sea level) represents the topographic divide between the northern Wadi Araba basin (the base level is the Dead Sea) and the southern Wadi Araba basin (the base level is the Gulf of Aqaba). Jabal Ar Risha is the largest pressure ridge formed along the WAF. At this stop, the southern Wadi Araba fault passes along the eastern flank of the Jabal Khureij, which is composed of Upper Cretaceous rocks. The fault steps to the right, forming the pressure ridge of Jabal Ar Risha. The ridge is composed of the Pleistocene gravel known as the Ri-

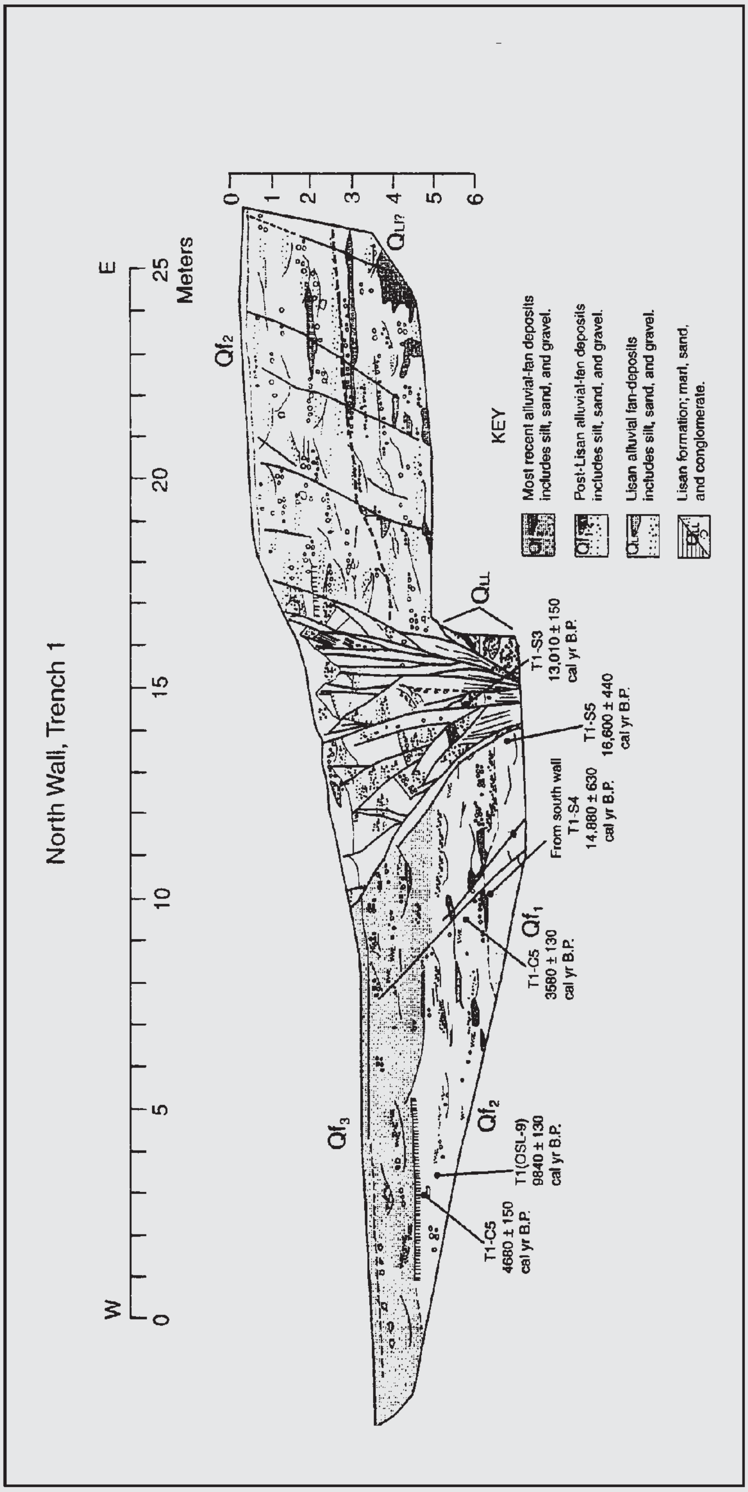



Fig. 17 **Map of northern wall of Trench 1 showing a 9-m-wide flower structure. Pulverized rock in a fault gouge indicates repeated motion along two main strands of the fault. Extensional fractures extend several meters east of the main deformation zone. Faults are identified by rotated and aligned clasts, fracture fills, fault gouge zones, and stratigraphic offsets. Locations of radiocarbon samples from the south wall are shown at their approximate stratigraphic level. See Table 3 for further information on radiocarbon data. See Figures 3 and 4 for location of trench.**

sha Formation (Ibrahim, 1993). The eastern flank of the Jabal Ar Risha is characterized by subvertical fault plane truncating gravels with a free face more than 5 m high (Galli, 1999). Slickensides on the fault plane indicate sinistral movement, with a reverse faulting component associated with uplift and folding (Galli, 1999). South of this stop, the SWAF disappears under the mud flat of Ga' As Saydiyyin, and further to the south, under the dunes and Taba Sabkha.

## Stop 15:
### Wadi Um Ratm-Wadi Al Muhtadi alluvial fans

The first appearance of the WAF in the Jordanian side of Wadi Araba is traced south of the Wadi Um Ratm fan. The WAF strikes N20E. The fault forms an eastwards facing 5 m high scarp. This scarp overlaps with two fault strands, forming the western border of a 2 km long and 350 m wide pull apart basin of the Wadi Um Ratm

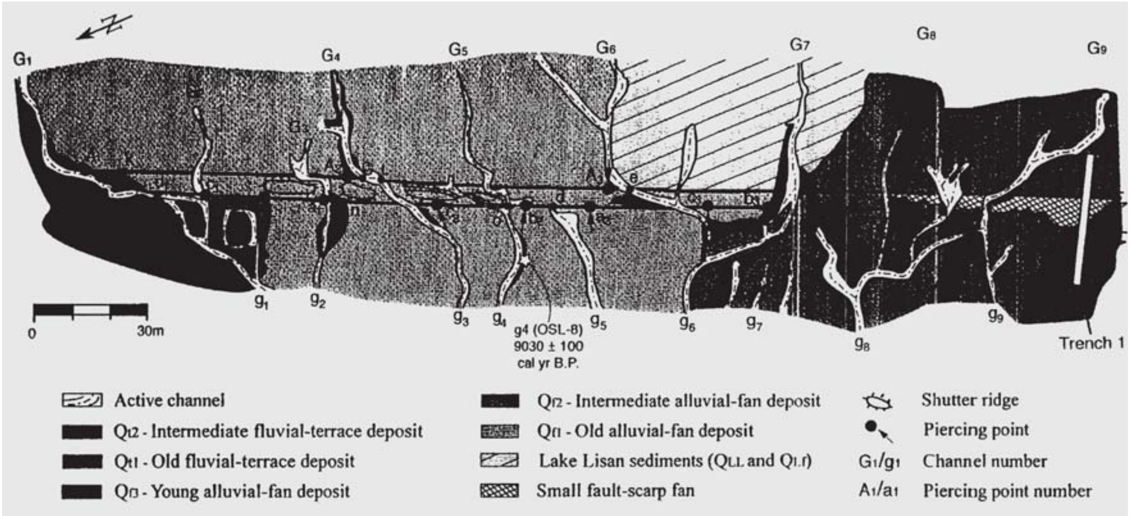



*Figure 18 - Detailed geologic map showing offset gullies developed on the $Q_{f1}$ alluvial fan surface. Piercing points used to calculate slip are marked as solid dots on the map. We use uppercase "G" for upstream gullies east of the fault and lowercase "g" for downstream channels west of the fault trace. Likewise, projected piercing points are uppercase letters east of the fault and lowercase letters west of the fault: The gullies are numbered from north to south. See Figures 3 and 4 for location of map.*

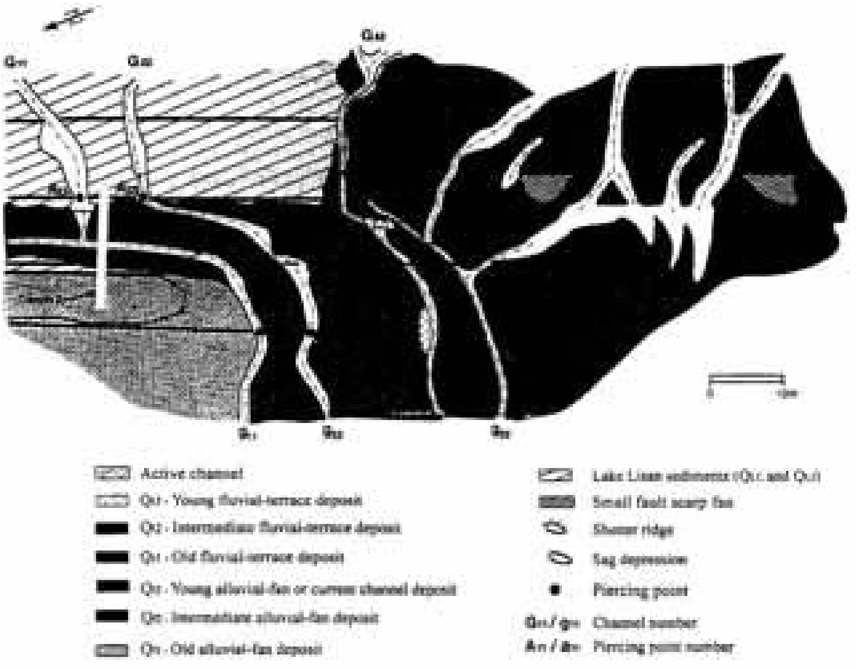



Fig. 19. Detailed geologic map showing offset gullies in the vicinity of Trench 2. Piercing points used to calculate slip are marked as solid dots on the map. We use uppercase 'G' for upstream gullies east of the fault and lowercase 'g' for downstream channels west of the fault trace. Likewise, projected piercing points are uppercase letters east of the fault and lowercase letters west of the fault. The gullies are numbered from north to south. See Figures 3 and 4 for location of map.

fan (Fig. 23). The floor of this basin is filled with fine sediments and has a smooth topographic surface. The eastern border of this pull apart basin consists of two fault scarps. Small alluvial fans were formed in front of the eastern fault scarp. The western fault of this basin continues northwards, with a small scarp facing eastwards. Sinistral displacement along the fault trace is indicated from the offset of the alluvial deposits and stream channels. A right step is formed along this fault, forming a small pressure ridge at a point between Wadi Um Ratm and Wadi Al Muhtadi fans (Fig. 23). Further to the north, the scarp of this fault faces to the west. In the Wadi Al Muhtadi fan, it steps to the

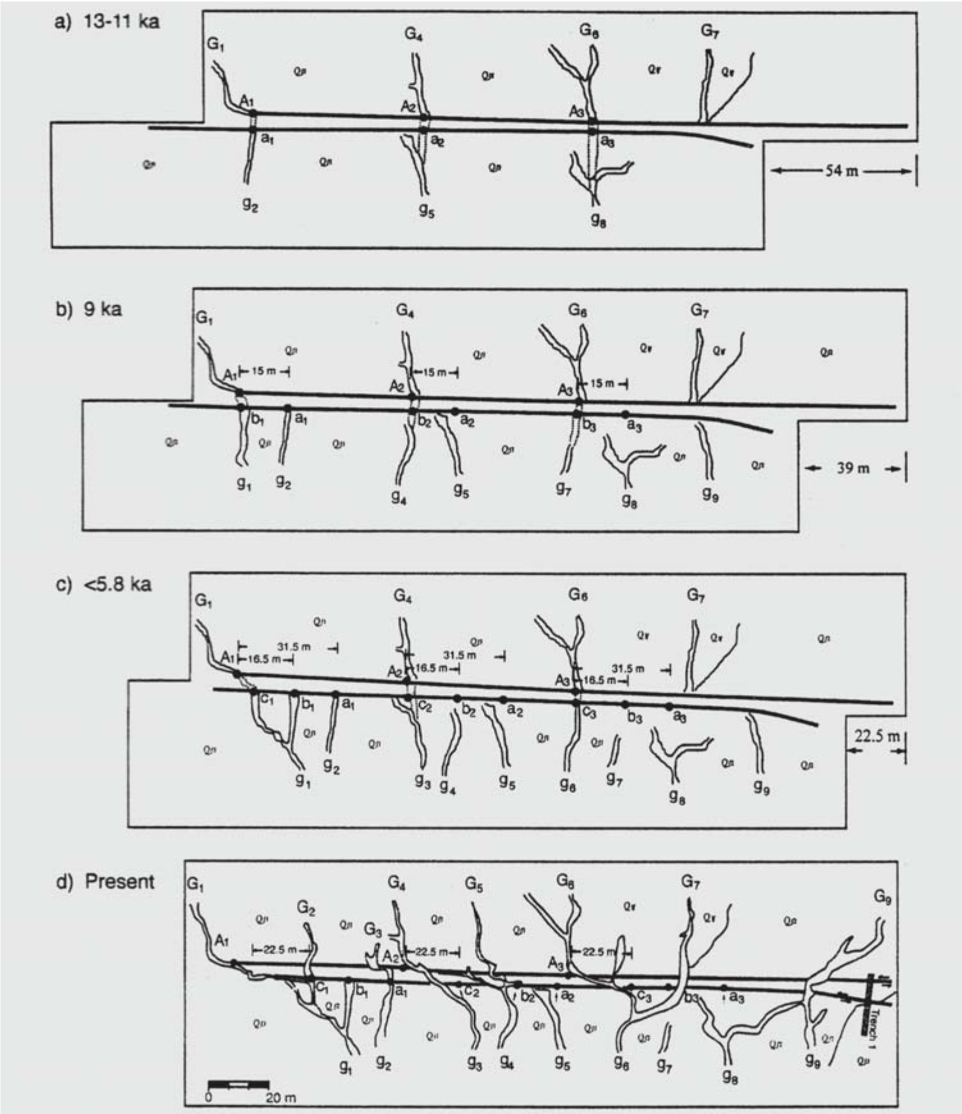



Fig. 20 Paleogeographic map illustrating the offset history of gullies developed on the Qf1 alluvial fan. We use uppercase 'G' for upstream gullies east of the fault and lowercase 'g' for downstream channels west of the fault trace. Likewise, projected piercing points are uppercase letters east of the fault and lowercase letters west of the fault. a) Three prominent gullies flow across the fault (G1-g2, G4-g5, and G6-g8) ca 13–11 ka.
b) Around 9 ka, after 15 m of cumulative slip, gullies G1, G4 and G6 abandon their downstream channels that lie west of the fault. New downstream gullies g1, g4 and g7 form.
c) Around 5.8 ka after 16.5 m of cumulative slip, gullies G1, G4, and G6 once again abandon their downstream channels and develop new straight courses (g1 at point c1, g3, and g6).
d) Map of the present configuration of gullies.

left, forming a 1.5 km long triangular pull apart basin. The northeastern border fault of this basin consists of two fault scarps trending S15E, which represent a synthetic Riedel shear. Small alluvial fans were formed in front of the eastern fault scarps. North of the Wadi Al Muhtadi pull apart basin, the western fault changes the direction of its scarp from east to west, forming a prominent fault scarp east of the road to Aqaba.

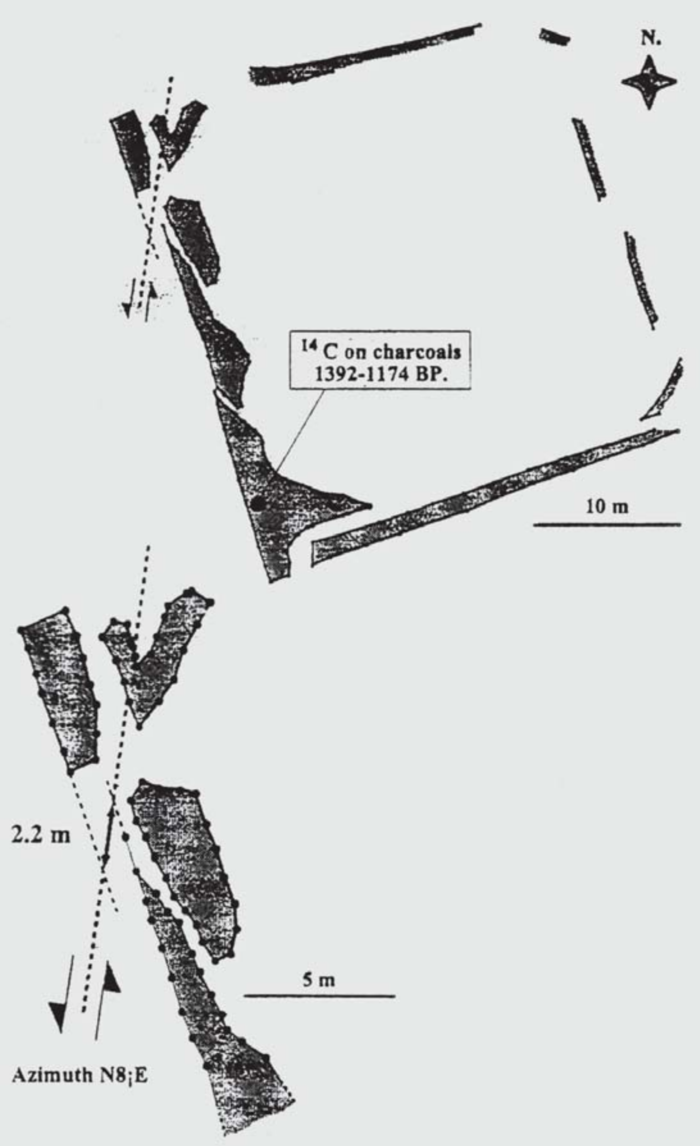



Fig. 21 Map of the water tank at the Tilah Castle from a total station survey. Lower diagram shows measurement details of the offset wall.

## Stop 16:
**Wadi Ram**

This a tourist stop to see a magnificent desert area with a Cambrian/Lower Ordovician sandstone sequence, > 400 m thick, standing almost vertically because of long vertical joints. The stratigraphy of Wadi Ram is the same as that of Petra below. More will be said in the field.

## Stop 17:
**Petra**

**Stratigraphy Of The Petra Basin**

The ancient city of Petra lies in a large open valley surrounded by rugged mountains, from the pale and solid limestone slopes at the top, through the broken and colourful sandstones, to the dark and jagged ranges falling down into the Wadi Araba. These latter are the ancient basement rocks, exposed in the western area along the Wadi Siyyagh, and are part of the Bayda porphyry unit from volcanic activity in the Late Proterozoic (c.550-540 million years ago). They are pink to red, and consist of massive rhyolite lava, with relatively large crystals of clear quartz and red feldspar. They form massive, homogeneous lava, intersected by a few dark grey dykes, on which a distinct paleotopography was formed before the sandstones were overlaid.

The Ram Group was the first to be deposited on the ancient basement rocks, beginning in the Early Cambrian, and ending in the Ordovician. The group is subdivided into four formations, based on lithology and age: Salib arkosic, Umm Ishrin, Disi and Umm Sahm sandstones. Two more formations are also added to the Ram Group in central and northern Wadi Araba (west of Petra), namely the Burj and Abu Khusheiba formations. Both are of Middle Cambrian. Fig. 24 is a geological map along our route in Petra.

The Salib arkosic sandstones were laid down in the Early Cambrian (c.540 million years ago) and their only outcrop in the Petra basin is in the western part, where they form steep, rugged cliffs. The sandstone consists of interbedded reddish and yellowish brown,

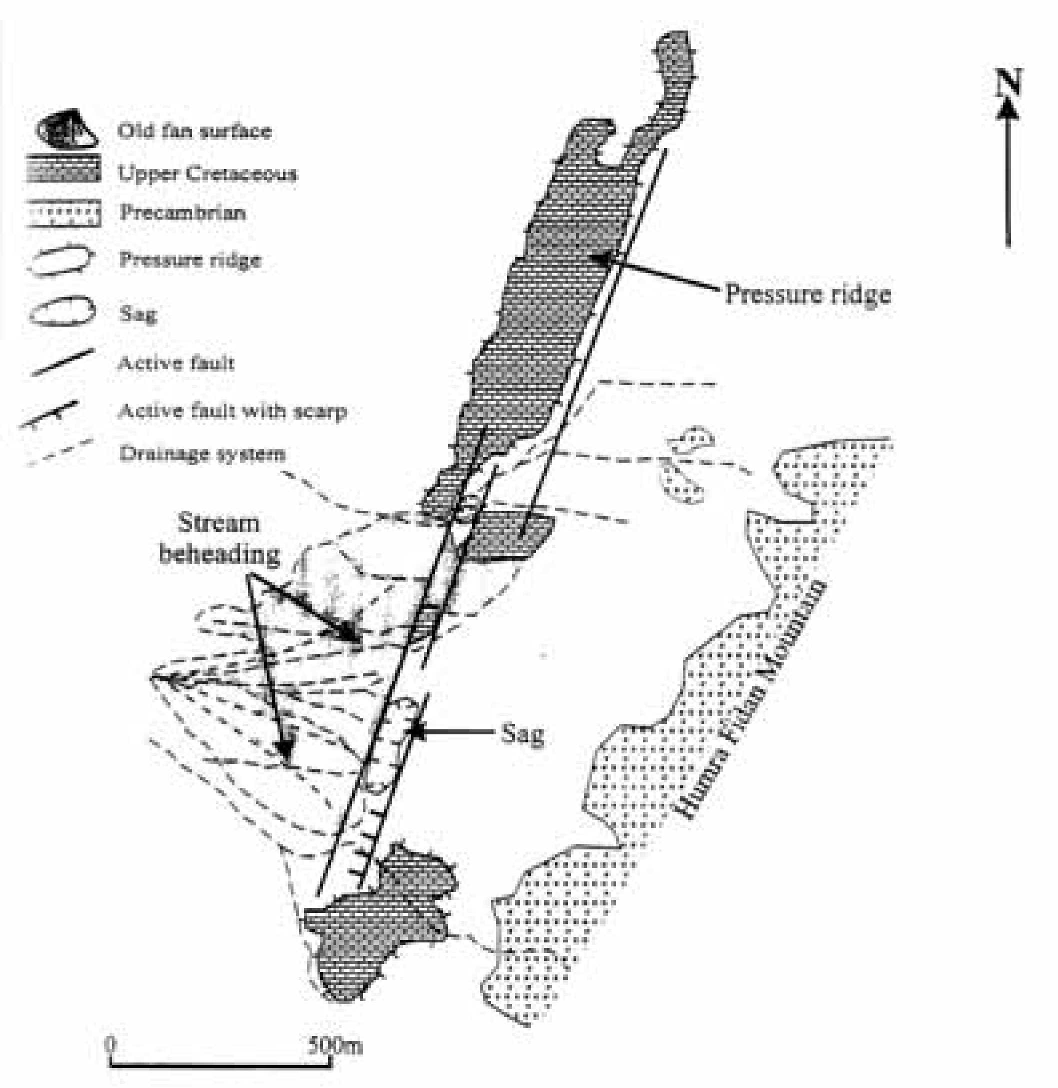



*Figure 22 - Some active morphotectonic features in the Humrat Fiedan, Wadi Araba*

purple, and violet conglomerate, and medium to coarse-grained arkosic sandstone with some thin, reddish-brown and pale green mudstones. This formation was laid down in rivers and channels on the uneven surface of the Bayda porphyry. It is only about 30 m thick in the Wadi Siyyagh.

The Umm Ishrin Formation overlays the Abu Khusheiba Sandstone Formation which overlays the Salib formation in the west, but in the north of our area, they are separated by the Burj dolomite-shale formation. The Umm Ishrin sandstone dominates most parts of Petra with its distinct steep, rugged cliffs along the wadis, and on the eastern scarp slopes (Fig. 25). The Siq itself is cut through this formation, and around the Siq it covers the majority of the Jilf, large parts of the Madrass, and most of the northwest part of the Qantara catchment basins (Fig. 24). It ranges from fine, compact to coarse-grained, loosely-packed sandstone with thin beds of reddish-mauve, very finely laminated micaceous siltstone, with a ferruginous sandstone layer. The formation can be sub-divided into five layers with slightly different characteristics; the lowest member is the

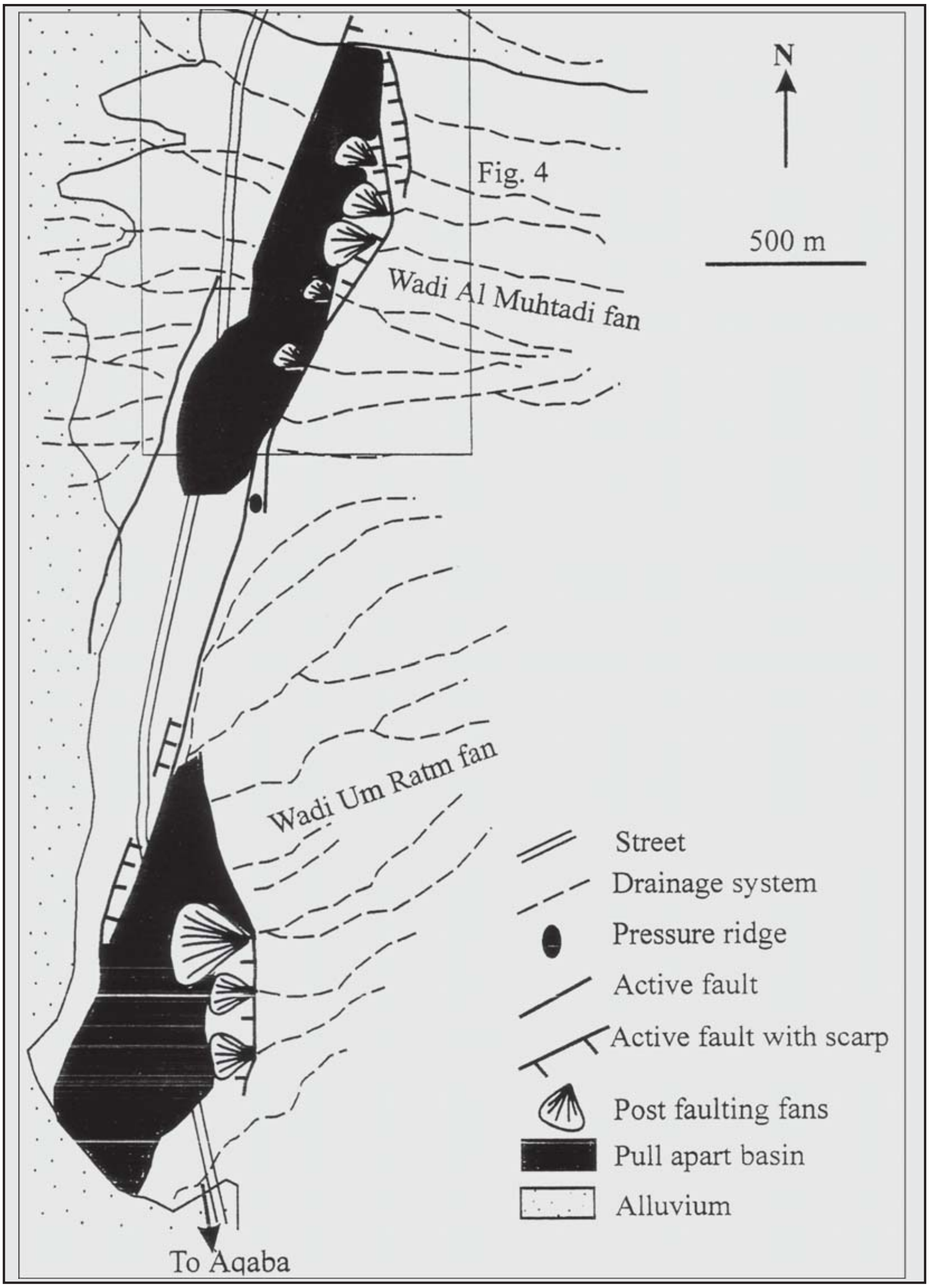



*Figure 23 - Muhtadi and Ratam fans and some active tectonic feature within them*

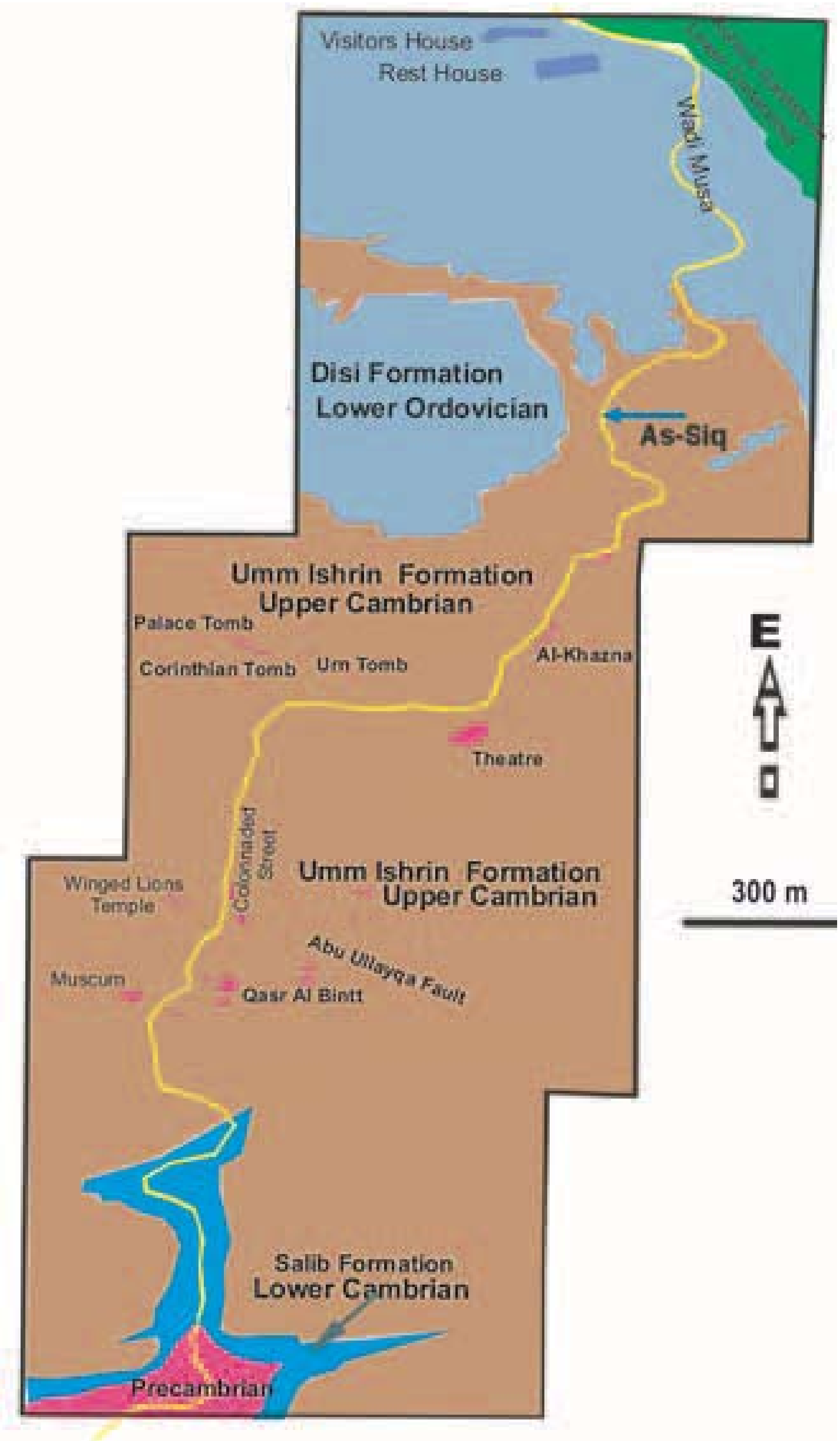



*Figure 24 - A geological map for the trip route in Petra (jaser & Barjous, 1992)*

*Figure 25 - The Umm Ishrin sandstone*

*Figure 26 - Liesegang colour banding in Umm Ishrin*

most solid, and its outcrops along the Wadi Siyyagh and provided the main quarries for monumental buildings such as the Qasr al-Bint (Pflüger 1995). The famous colour banding that characterizes Petra, ranging from yellow to red, mauve and grey and known as Liesegang banding, occurs in a much softer layer. The beautiful swirling and wave-like patterns we see today were formed when water rich in iron and manganese compounds deposited the minerals as it penetrated deep into the formation (Fig. 26). It is into this highly coloured layer that the majority of the monuments in the central basin are cut. Being soft, it was easy to work but, because it is more porous, it is easily eroded. The Umm Ishrin Formation is up to 350m thick in the Petra area, and ranges in age from the Middle to the Upper Cambrian. Like the Salib arkosic, it seems also to have been laid down in a fluvial environment.

The top of the Umm Ishrin grades into the pale grey of the Disi formation which overlays it. The Disi sandstone outcrops mostly to the east of the Siq, and forms the upper parts of Jabal Khubtha and Mataha. It also outcrops in the south and west part of the Madrass, and at the north and south ends of the Qantara catchment areas around the Siq (Fig. 24). The monuments of the Bab al-Siq and Madrass are cut into this formation. It is distinctive because of its grey-white colour, massive rounded weathering pattern, and its lack of colour banding (Fig. 27). The formation consists of medium to coarse grained, thick-bedded sandstone with large-scale cross bedding, and rounded, pale-coloured quartz pebbles dispersed throughout. The Disi formation was deposited in a fluvial and occasionally marine environment and its exposed thickness in the area is only 30 m (it is certainly much thicker to the NNE of the Siq). It is not well-cemented, nor massively-jointed and dates from the Upper Cambrian to the Lower Ordovician.

There was a considerable hiatus before the deposition of the Kurnub sandstone in the Early Cretaceous (c.140-100 million years ago). This outcrops in the central basin and the eastern part of Petra, particularly in the Qantara area above the Disi Formation, from which it is easily distinguished by its multiple colours, ranging from grey and yellow, to pink and violet. It consists of poorly cemented, medium to coarse-grained quartz sandstone with rounded granules and pebbles scattered throughout. However, the lower Kurnub is composed of white, massive sandstone, very much like the Disi Formation, from which it is not easily distinguished. By comparison with the underlying Disi strata, the Kurnub sandstone is friable and has only very low intensity jointing.

The Shara Mountains that loom over the Petra basin from the east are topped by Upper Cretaceous limestones and as they erode, limestone boulders and stones find their way down the wadis to form the main constituent of the wadi beds. The lower layers belong to the Ajlun Group, and the upper ones to the Balqa Group, together having a thickness of around

570 m. They are composed of alternating beds of limestone, dolomite limestone, and marly shale, that were laid down in the shallow waters of a fully marine environment. Bedded chert. chalk, phosphorite, and other rock types are added further upsection in the Balqa Group.

In general, Petra and the surrounding area are covered by Pleistocene and younger superficial lacustrine and fluvial sediments. These are coarse-grained sands, gravels, pebbles and boulders, derived from the older surrounding formations, with locally cross-bedded silt and sands in Wadi Mataha and Wadi Abu Ullayqa. The maximum thickness of these sediments is in Wadi Mataha, where more than 20 m are exposed. Soils that have formed on the surface of the hills consist mostly of silty sand and sandy silty clay, with varying percentages of gravels and cobbles.

In the study area, which is the catchment basins of the Siq, the only formations that outcrop are the Umm Ishrin and Disi sandstones, with locally derived, superficial deposits and soils on top of them.

A major factor in the formation of the landscape is the fault and joint system. The area is cut by two main faults, trending northeast to southwest, which form the sides of a trough of land bordered by two upward-shifting blocks known as a graben. One is the al-Mataha fault, which is a regional fault that has suffered from periodic movements since the Late Cambrian. The second is the Abu Ullayqa fault, also an Upper Cambrian fault that became reactivated during the Miocene. The numerous other, more minor, faults are related to the Dead Sea transform.

One of the most characteristic features of the Paleozoic, Cambrian and Lower Ordovician sandstone in the area, is the net-like joint system. Many straight, individual joints can be traced for up to 500 m, mostly with vertical joint planes. There were two main episodes of joint formation. The early joint systems were controlled by post-Ordovician, pre-Early Cretaceous (the middle Carboniferous Hercynian Orogeny) stresses which affected the Paleozoic rocks (i.e. the basement rocks and Rum sandstone group). Much later, in the Miocene, tectonics within the local Showbak fold belt, and the stresses that created the Dead Sea transform fault system, added new joint planes in all rocks.
The Siq was formed by water erosion, exploiting the weakness along a fracture line in the upper Umm Ishrin sandstones. The process was accelerated by the process known as slab fall, which is a common occurrence on steep sandstone faces where stress relief creates fractures parallel to the rock face. Weathering then plays a major role in releasing the affected block from the parent mass. In the Siq, in addition to the relief fractures, the existing joints parallel to the rock face helped to accelerate this process, which is still active in certain locations.

As well as the major changes brought about by slab fall, the exposed surfaces of the sandstones suffer weathering from both wind and water. The wind is largely responsible for the distinctive domed shapes of the white Disi formation that is so characteristic of the Bab al-Siq area just outside Petra. Rainwater however, plays a greater role in the weathering process, acting both chemically and physically. Water begins by dissolving the cements that bond the sandstone grains, acting more quickly in the more porous, loosely packed layers. The dissolved materials then precipitate out as salts at or near the surface of the rock masses, forming layers that eventually flake off, taking some of the parent rock with them. This process, which intensifies during floods, enlarges open fractures and generally weakens the exposed rock surfaces. Flood waters also carry gravel and stones, sometimes boulders, along with them, which in turn causes physical damage to any rock surfaces against which they may tumble.

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Back Cover:
*field trip itinerary*

32nd INTERNATIONAL GEOLOGICAL CONGRESS

## FIELD TRIP MAP


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